

A Cellular Approach To Optimize The Integration Of Renewable Generation Into Distribution Networks

Von der Fakultät für Maschinenbau, Elektro- und Energiesysteme
der Brandenburgischen Technischen Universität Cottbus-Senftenberg
zur Erlangung des akademischen Grades eines
Doktors der Ingenieurwissenschaften

genehmigte Dissertation

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Tag der mündlichen Prüfung: 30.03.2022

DOI: <https://doi.org/10.26127/BTUOpen-5900>

Kurzfassung

Das stetige Wachstum der auf erneuerbaren Energien basierenden Technologien in den letzten zwanzig Jahren hat den Charakter der Stromsysteme erheblich verändert. Bis heute sind in Deutschland mehr als 112 GW an Photovoltaik- und Windkraftanlagen installiert und rund 90% der installierten erneuerbaren Erzeugungsanlagen sind in die Verteilnetze integriert. Infolgedessen sind die Verteilnetze häufig mit Netzengpässen konfrontiert und es sind mehr Investitionen für die erforderlichen Netzausbaupläne nötig.

Die politischen Entscheidungen in Deutschland, den Anteil der erneuerbaren Energien am Stromverbrauch bis 2030 auf 65 % zu erhöhen, den Ausstieg aus der Kernenergie bis 2022 zu vollziehen und weitere Kohlekraftwerke abzuschalten, gaben Anlass zu ernsthaften Bedenken hinsichtlich der Sicherheit der Stromversorgung und der Realisierbarkeit des Übergangsplans der deutschen Energiewende.

Die vorliegende Dissertation wirft einen Blick auf die jüngsten Entwicklungen der Stromnetze und bietet eine Methodik zur Reduzierung der Kosten, die durch die weitere Integration erneuerbarer Erzeugungsanlagen in die Verteilnetze entstehen. Die vorgeschlagene Methodik basiert auf einem zellularen Ansatz und verschiebt die unnötigen kostspieligen Ausbau der Stromnetze in die Zukunft. Darüber hinaus hilft sie, die erneuerbaren Erzeugungsanlagen auf eine optimierte Weise in die Stromnetze zu integrieren, was einen Mehrwert für die Erreichung der definierten Nachhaltigkeitsziele darstellt.

Die vorgeschlagene Methodik in dieser Dissertation besteht aus zwei Schritten. Der erste Schritt besteht aus dem zellulären Ansatz und der Grey Wolf Optimierung in der MATLAB-Umgebung. In diesem Schritt wird die optimale Kombination von der auf erneuerbaren Energien basierenden Technologien zur Erfüllung der definierten Ziele ermittelt. Der zweite Schritt besteht aus den quasi-dynamischen Simulationen in der PowerFactory-Umgebung. In diesem Schritt werden die vorgeschlagenen Ergebnisse aus der MATLAB-Optimierung in semi-realten Situationen untersucht. Mit der quasi-dynamischen Simulationen wird überprüft, ob die Ergebnisse aus Sicht des Netzbetriebs tolerierbar sind und ob man mit bestimmten Strategien den Netzbetrieb erleichtern kann.

Abstract

The steady growth of the renewable-based technologies in the last twenty years has changed the character of the power systems significantly. Until today, there are more than 112 GW installed photovoltaic and wind parks in Germany and around 90% of the installed renewable generators are integrated into distribution networks. As a result, distribution networks are often facing congestion problems and more investments are needed for the required network development plans.

The political decisions in Germany for increasing the share of renewables in electricity consumption up to 65% until 2030 and the nuclear phase out until 2022 and further shutdowns of the coal power plants raised serious concerns about the reliability of power supply and feasibility of the transition plan.

The present dissertation has a look over the recent developments and offers a methodology for reduction of the resulted costs from further integration of renewable generators into the distribution networks. The suggested methodology is based on a cellular approach and helps also to postpone the unnecessary costly network expansions. Furthermore, it helps to integrate the renewable generators in an optimized way which has an added value to move towards the defined sustainability goals.

The proposed methodology has two steps. The first step is made up of the cellular approach and grey wolf optimization in MATLAB environment. In this step, the optimal combination of technologies for fulfillment of the defined goals are found out. The second step consists of the quasi dynamic simulations in PowerFactory environment. In this step, the suggested results from MATLAB optimization are investigated in semi-real situations. With the quasi-dynamic simulations, it is checked whether the results are tolerable from the point of view of network operation and whether it is possible to facilitate the network operation with certain strategies.

Foreword

This dissertation was written at the chair of Energy Distribution and High Voltage Engineering of the Brandenburg University of Technology Cottbus-Senftenberg. Without the numerous technical and personal supports from colleagues, creation of this work would not have been possible. Therefore, I would like to express my sincere thanks to all the involved supporters.

A special thanks goes to Prof. Dr.-Ing Harald Schwarz, the head of the chair of Energy Distribution and High Voltage Engineering, for his trust, continuous support and supervision.

I would especially like to thank Dr.-Ing Klaus Pfeiffer for the personal technical discussions and the many helpful comments, especially during the promotion time.

My special thanks to Prof. Dr.-Ing Siegfried Lemmer for the technical discussions and interesting rhetorical questioning of the methodology and results.

During the promotion time at the chair of Energy Distribution and High Voltage Engineering, I was able to gain an insight into research projects and participate in some of them. Therefore, I would also like to thank the staff of the chair for the interesting discussions and helpful hints.

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List of Abbreviations

Abbreviation	Meaning
Bn	Billion
CAPEX	Capital Expenditures
DSO	Distribution System Operator
DEA	Degree of Energy Autarky
DLC	Degree of Load Coverage
BNetzA	Federal Network Agency
GDP	Grid Development Plan
GET	German Energy Transition
GHG	Greenhouse Gas
GWO	Grey Wolf Optimization
HVN	High Voltage Network
LEC	Levelized Electricity Cost
LFA	Load Flow Analysis
LFC	Load Flow Calculation
MVN	Medium Voltage Network
NDP	Network Development Plan
NPC	Net Present Cost
OPEX	Operational Expenditure
PR	Performance Ratio
PSO	Particle Swarm Optimization
PUF	Power Utilization Factor
p.u.	per unit
QDS	Quasi-Dynamic Simulation
RE	Renewable Energy
SOC	State Of Charge
TSO	Transmission System Operators
VDE	Verband Deutscher Elektrotechniker (Verband der Elektrotechnik Elektronik Informationstechnik e.V.)

Formula Symbols

Symbol	Unit	Meaning
A	m^2	Area
T	$^{\circ}C$	Unit of Temperature
E	Wh	Energy
$E_{bat.}(t)$	Wh	Stored amount of energy in battery modules
$E_{lack}(t)$	Wh	Lacked amount of energy to supply the loads in one time step
E_t	€	time value of expenses at the year t (OPEX)
E_{e-t}	$[kWh/a]$	Electricity produced over the lifetime t
f	%	Inflation rates
P	W	Active power
Q	var	Reactive power
q	%	Discount factor
S	VA	Apparent power
U	V	Voltage
I	A	Electric current
I_0	€	capital expenditures present value (CAPEX) at initial state
i	%	investment rates
k	% / a	real discount rate
Y	S	Admittance
B	S	Susceptance
G	S	Conductance
I_{ir}	kWh/m^2 or J/cm^2	Solar irradiation
$P_{ch}(t)$	MW	Active power limit for charging of batteries
$P_{dch}(t)$	MW	Active power limit for discharging of batteries
$P_{installed}$	MW	Installed active power
$P_{L,i}(t)$	MW	Active power pattern of the load at connection point i and time step t
$P_L(t)$		
$P_{lack}(t)$	MW	Lacked power to supply the loads
$P_{DG}(t)$	MW	Active power pattern of the decentral generator
T	h	time
U	V	Voltage

V_h	m/s	Wind speed at the height of h above the ground
V_{ref}	m/s	Wind speed at the weather station in
Z_h	m	Height of the wind turbine
Z_{ref}	m	Reference height where the wind data are recorded
Z_0	m	Roughness length
η	%	Efficiency in percentage
%		Percentage
€		Euro
	m	Meter

1. Chapter: Introduction and Motivation

1.1. Introduction

In the face of climate change and global warming national and international communities have defined plans to move towards a sustainable future. According to the assessments of the Economic and Social Council of United Nations, achieving the sustainable goals would only be possible by higher investments and more willingness of the countries to embrace courageous political commitments [1]. In these plans, Renewable Energy (RE) solutions are the building stone to achieve the goals in the electricity sector. However, the countries which promoted RE technologies over several years are faced with serious challenges that concerns the reliability of electricity supply and safe operational management of the power networks with affordable prices.

Germany is a proper example of a pioneer country in promoting RE technologies that introduced challenging national plans to move towards a green future. Ambitious goals of German Energy Transition (GET), also known as “Energiewende”, as a remarkable political decision that projects the national plan over a period of forty years led to massive expansion of RE technologies in the last two decades. As a result, the electricity supply system has undergone drastic changes and experienced serious challenges.

The shift towards a sustainable future might seem very impressive at the first glance, as countries might be able to cover a portion of their electricity demand from clean RE sources. It is discussed that deploying natural energy sources like wind energy or solar radiation creates a chance to reduce the dependency of a country from importing energy carriers or burning of own fossil fuels. Considering heavily industrialized countries which require a high amount of electrical energy, less dependency on conventional energy carriers by means of RE sources is seen as a golden opportunity to take the lead in global markets of the future. However, the serious challenges of the transition process are not profoundly taken into account and bets on technological innovations and a green future are an issue of concern.

Considering Germany, around 41% of the gross electricity consumption in 2021 was produced from RE technologies and 59% from conventional power plants [2]. At the first glance 41% appears to be a huge potential for reduction of CO₂ emissions and partly import of energy barriers like natural gas. Investigation of the foreign trade balance sheets of energy in terms of billion Euros of imports divided by exports manifests the considerable number of 67.9 for fossil fuels in 2018. That is an increase of 20% in a year, which is quite considerable for a country that imports a great portion of its energy carriers. It is clear that small changes in prices of energy carriers have definitely a big impact on economic growth of the country [3]. In Germany significant growth in prices of the imported energy carriers (mostly fossil fuels) was recorded in recent years. Therefore, moving towards implementation of more RE technologies, coupling of the sectors and electrifying the transport sector sounds to have reasonable argumentations.

According to German Federal Government, almost 77% of all Greenhouse Gas (GHG) emissions are originated only from three sectors. Energy sector with almost 38%, industry sector with almost 21% and transport sector with 18% were the record holders in 2017 [4].

Investigation of the trends between the years 2010 to 2017 proves that the energy sector has tolerated a disproportionate burden (in comparison to the other sectors) for reduction of GHG emissions from 369 to 328 Mt of CO₂ equivalents. For the same period, the emissions in the industry sector slightly raised from 189 to 193 and for the transport sector an increase from 153 to 171 Mt of CO₂ equivalents could be identified [4].

It is remarkable that sustainability assessment of the GET forecasted before that the defined goals for 2020 were unachievable without substantial correction of the measures and policies of the recent years [5]. In spite of steady movements toward sustainable targets, it is clear that Germany still has much to do in order to provide acceptable solutions for a reliable and affordable energy transition. In this dissertation, the term GET is referred to the energy policies of the federal government beginning from 2011. The assigned objectives of GET were: nuclear phase out till 2022, boost of RE technologies in electricity generation to at least 80% in 2050 and increasing of electricity efficiency with a growth rate of around 1.6% per year [6]. German Federal Government enacted the conducted new plan under the name of Climate Action Plan 2050 in November 2016 [7].

In the next section, the author outlines the recent developments of RE technologies in power sector on the example of Germany and sketches the challenges and problems arising from the current course of RE expansion policies.

1.2. Requirements and Problems Analysis

The development of RE technologies in German power sector had led to the increased gross electricity generation up to 250 TWh in 2020. This amount corresponds to 45% of gross electricity consumption [8]. Figure 1-1 represents the RE development trends in Germany. According to the reports, about 52% of the produced RE electricity is generated by wind turbines, 20% by photovoltaic modules and 20% by means of biomass technologies. It is clear that the backbone of the German energy transition is based on wind, photovoltaic and biomass technologies [9].

According to Federal Network Agency (BNetzA), as of the beginning of 2021 there were over 128 GW of installed RE generators in Germany. From the installed RE generators almost 47% are wind turbines (offshore and onshore), about 41% are PV installations and around 8% are biomass plants [10]. Figure 1-2 illustrates the spatial distribution of decentral RE generators in Germany until 2021 corresponding to more than 1.7 million of generators [10]. As of the beginning of 2021, the whole installed electrical capacity in Germany was announced to be about 229 GW. Form this amount, about 83 GW are conventional power plants¹ [10].

In Germany almost 90% of all RE generating units are integrated into the power networks of Distribution System Operators (DSO) and only around 10% into the power networks of

¹ Nuclear power plants, coal power plants and gas power plants are considered as conventional power plants.

Transmission System Operators (TSO) [10]. According to the reports, the trend of integrating more RE generators into DSO networks will continue to raise up to 162 GW until 2035. Simultaneously installed capacities of the conventional power plants in TSO networks will continue to decrease down to 19 GW in 2035. It is estimated that in year 2035 around 70% of the generated electricity in Germany will be feeding into DSO grids [11]. Figure 1-3 illustrates the installed capacities of power plants in DSO and TSO levels in Germany.

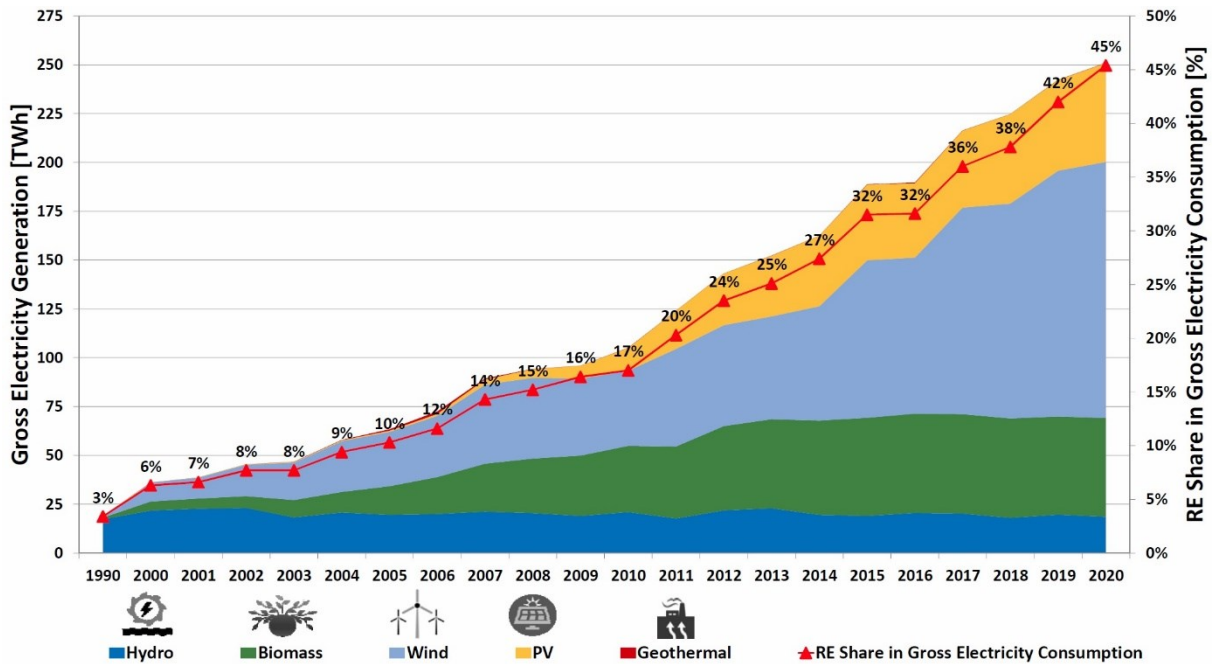


Figure 1-1: Development of RE gross electricity generation in Germany (data based on: [9])

Considering the development trends in power sector, one understands clearly that the electrical supply system is under a massive conversion process. The electrical supply system is no longer centralized in terms of generation and power distribution, but it consists of thousands of decentralized generating units. In other words, the electrical energy is no longer produced mainly at higher voltage levels and transmitted to lower voltage levels for consumption, but it is generated at all voltage levels and electrical power flows bidirectionally between all voltage levels.

The two ambitious decisions of the German Federal Government in 2011 and 2019 for expansion of RE technologies, which will definitely endorse the above mentioned conversion process of the power system. The shut down the nuclear power plants until 2022 was decided in 2011 and in 2019 the shut down the coal power plants until 2038 was enacted [12]. The brief outcome of these decisions can be mentioned as:

- 1) Shut down of the remaining 9.5 GW of nuclear power plants until 2022
- 2) Capacity reduction of the coal power plants to 30 GW by 2022 (12.5 GW reduction from 2019)
- 3) Capacity reduction of the coal power plants to 17 GW by 2030 (13 GW reduction from 2022)
- 4) Shut down of the coal power plants until 2038 (17 GW reduction from 2030)

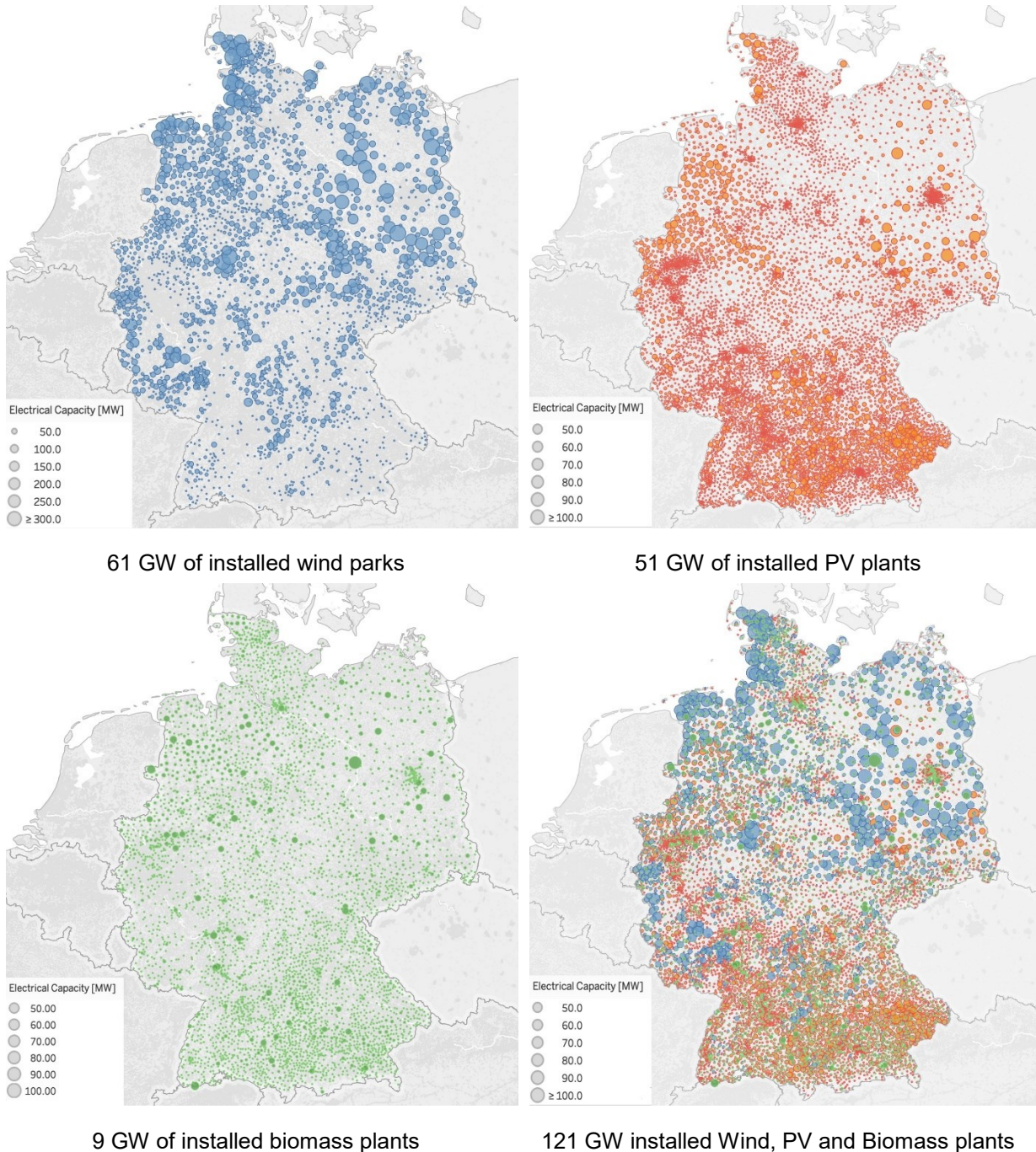


Figure 1-2: MW-scale decentral RE generators in Germany until 2021 (data based on [10])

The electrical power demand in Germany was recorded to be between 36 GW (base load) and 81 GW (peak load) in recent years [13], [14]. These numbers might change in coming years with coupling of sectors and electrification of the transport sector. Nevertheless, as a result of the developments, some of the existing concerns will become more important and shall be taken into consideration. In following the main three concerns are highlighted.

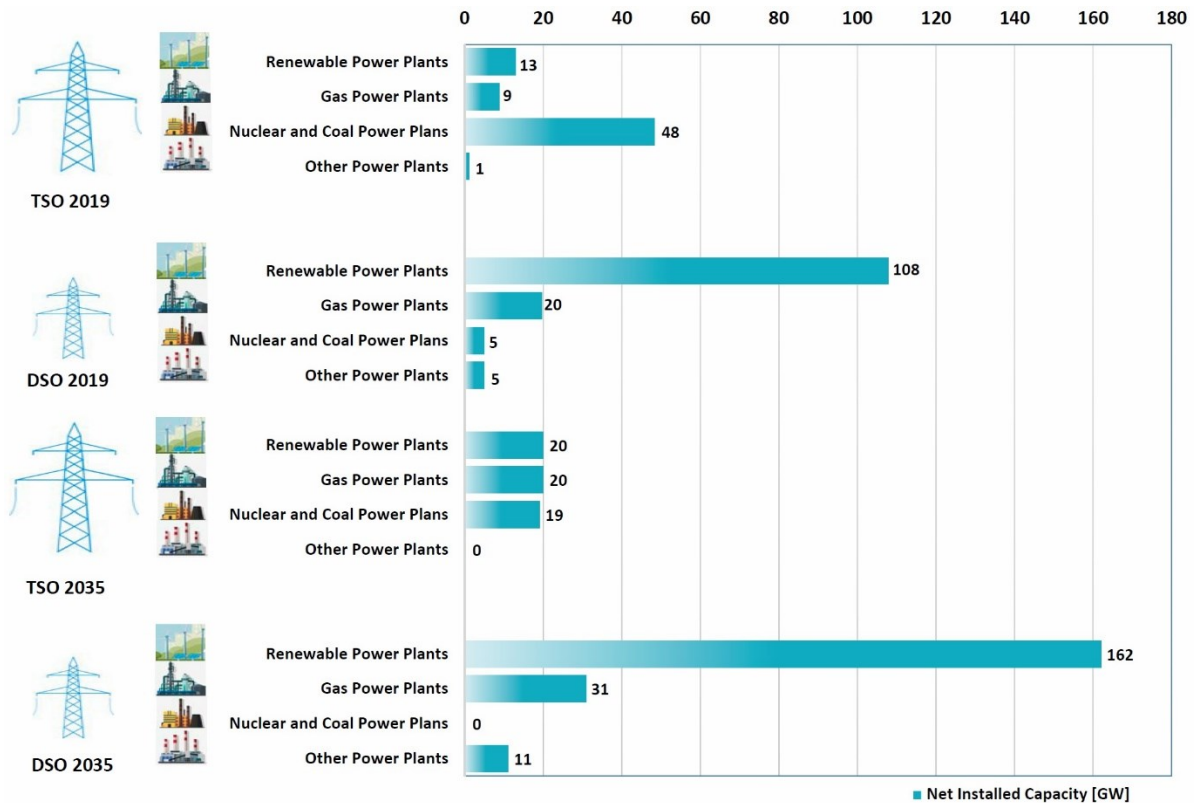


Figure 1-3: Power plants in German networks for years 2019 and 2035 (data based on [10], [11])

Concern Number 1: Reliability of Power Supply

Shut down of conventional power plants seems to be very critical as the reliability of supply in such a huge system is at risks due to volatile generation from RE technologies. Table 1-1 presents the availability and secured power of different types of power plants. As it can be seen from the numbers, the future backbones of the German power system (wind and photovoltaic technologies) with secured power between 0% – 2% has not much to say about contribute in reliability of power supply.

Type of Power Plant	Availability [%]	Secured Power of Plants [%]
Hard coal-fired	91	86
Lignite-fired	95	92
Combined gas and steam cycle	91	86
Gas turbine	56	42
Nuclear	96	93
Biomass	90	88
Wind onshore	95	1
Wind offshore	95	2
Photovoltaic	not mentioned	almost 0

Table 1-1: Availability and secured power of power plants (data based on: [15], [16])

Apparently, in accordance with the political decisions from 2011 and 2019, secured power supply in Germany from 2022 will be a matter of serious concern. The miserable amount of storage technologies can also not be considered as a great support for RE technologies in this manner. Unfortunately, the whole installed capacity of storage technologies in Germany is around 10 GW [10], [17].

Concern Number 2: Rapid Integration Strategy and Neglecting the Requirements and Concerns of the Electricity Network

The promoting green policies were the propulsion engine for integrating thousands of decentral RE units into the distribution grids in recent years. However, the question is whether the integration was matched with the requirements of the electricity network?

The electricity networks and the power plants were formed and designed over decades based on two simple principles: power plants were formed in the vicinity of consumers and electricity networks were dimensioned for transporting the produced power to consumers. Both of these principles are violated with rapid integration of RE technologies. Thousands of decentral generators are located far away from consumers and the pace of network expansions did not match the integration rate. As a result, the electrical networks come very often to their operational limits. Figure 1-4 illustrates the situation in high voltage overhead lines in Germany as of 2020.

The footprint of congestion problems can be seen in the methodology of Grid Development Plan (GDP). Looking at the German GDP, the used methodology in long-term integration plan is formed on the predictions for the availability of land. That means, the RE generators are constructed and connected to the network according to the availability of land and not based on the requirements of the local power network. As a result, many RE generators are built in the regions where there are less consumers for the produced power. The planning and expansion of electricity networks cannot follow this fast integration pace as the process happens over much longer periods. The existing congestion regions in North and East Germany presented in Figure 1-4, are the perfect examples of this process. Accordingly, it can be claimed that the pace of expansion of the electricity networks does not match the RE expansion policy.

In recent years, grid expansion plans are highlighted as counterweights for the network congestion problems. However, it should be noted that grid expansion plans belong to long-term solutions as realization of these plans take up to several years. In this respect, optimization of the electricity grids, application of new grid operational strategies, preparation of power networks for higher loading and capacity utilization are introduced as short-term responses for supporting the long-term network expansion plans and the transition towards a sustainable future. However, the recommended short-term responses have from one side technical limitations and from the other side they require a high level of digitalization and comprehensive monitoring tools in real time. In other words, the intelligent power flow control in electricity networks is a very challenging task and requires huge investments over several years.

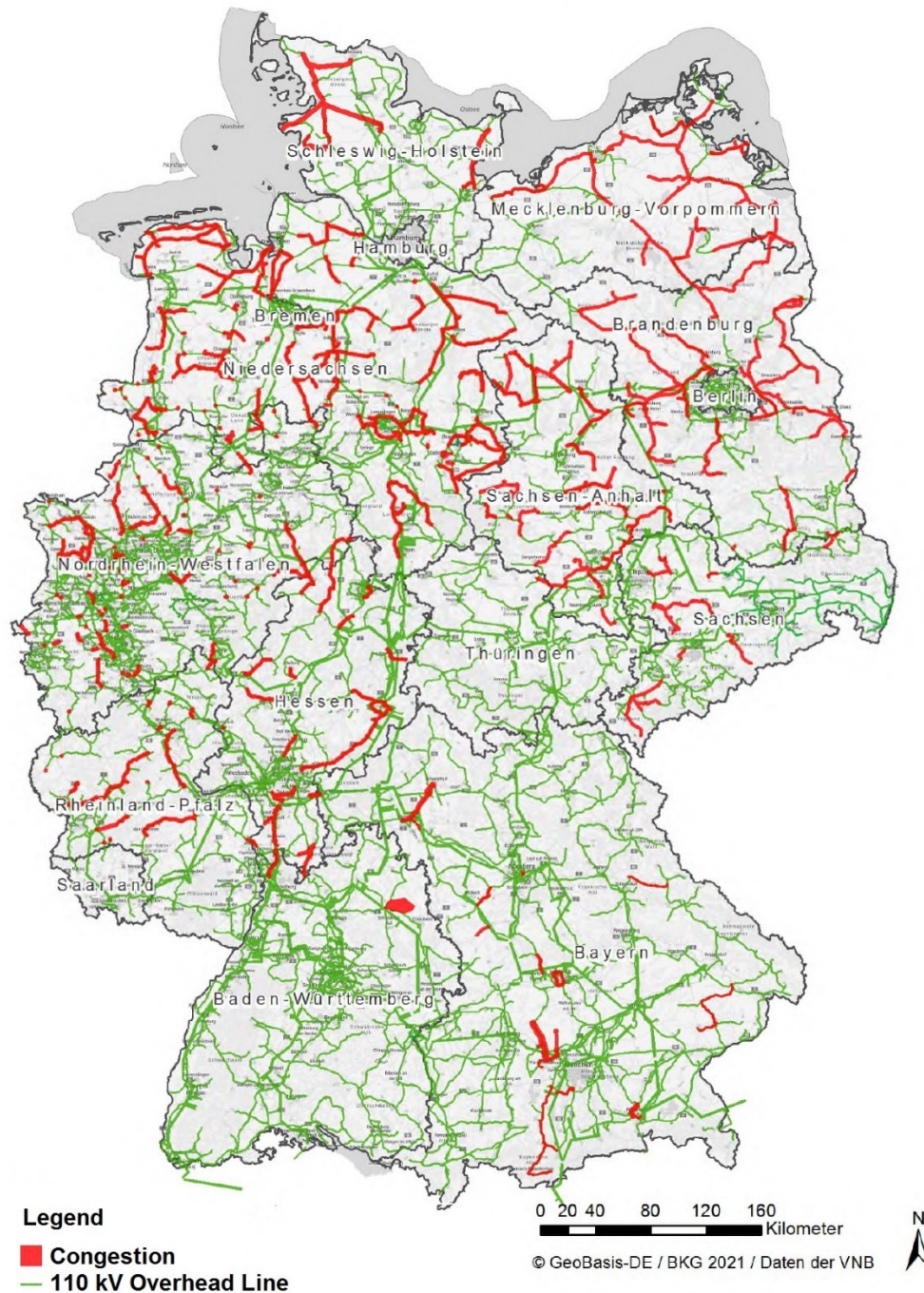


Figure 1-4: 110 kV overhead lines and congestion regions in Germany 2020 (Source: BNetzA [18])

Concern Number 3: Volatile RE Generation and Need for Further Ancillary Services

It is claimed that Germany has to increase its power transportation capacity drastically to be able to guarantee the reliability of power supply. BNetzA confirmed on 20th of December 2019 the last Network Development Plan (NDP) for electricity. According to Federal Demand Plan Act², the total length of the required lines is currently about 5900 km [19]. From this amount, 3050 km is categorized as reinforcement measures for increasing the share of RE technologies in electricity consumption to 65% by 2030. The total investments costs in all NDP scenarios for 2030 are estimated to be over €60 bn [17].

² Bundesbedarfsplangesetz - BBPIG

The author believes that the increasing transport capacities of electricity network is not solely enough to ensure the reliability of power supply. Considering the final goal of the whole transition plan as reducing the dependency on fossil fuels and CO₂ reduction in power sector, the imported power deficiency from neighboring countries in the dark hours of RE generation is in contradiction with the defined goals. The volatile generation from RE technologies leads clearly to increased demand for ancillary services and system stability measures.

In recent years drastic rises in demand of ancillary services were noted. Ancillary services together with system stability measures belong to priorities for further developments in the coming years³. Although due to commissioning of some grid expansion projects the total costs of ancillary services might decrease in some years, but still the total net costs of the ancillary services in 2019 were registered to be the descriptive amount of €1931 million [20]. Detailed costs of the ancillary services in 2019 is provided in Table 1-2.

Type of Ancillary Service	Costs [million EUR]	Type of Ancillary Service	Costs [million EUR]
Frequency Containment Reserve	46.4	Redispatch	227.2
Frequency Restoration Reserve	118.5	Provision of Reserve Power Plants	196.5
Frequency Restoration Reserve	120.7	Engagement of Reserve Power Plants	81.6
Blackout Start Capability	7.7	Provision of switchable loads	28.0
Reactive Power Provision	9.6	Feed-in Management	709.5
Countertrading	64.2	Loss Energy Procurement	321.2

Table 1-2: Costs of the ancillary services in Germany 2019 (data based on: [20])

These rising costs are also indicators of ascending complexity of safe power system operation in Germany. Author's investigations on grid operators' databank of East Germany revealed over-generations in GW scales due to RE technologies. It is clear that the increasing volatility in generation from RE technologies, limited transport capacities, increasing system stability measures and higher costs of ancillary services are serious concerns for German power sector. The mentioned concerns in this section are only a portion of the reality. The mentioned facts can be considered as an alarm on how opportunities can be altered to extra burdens or threats for the whole power system.

³ Ancillary services are classified in different categories and cover a wide range of measures for network operational management, frequency stability, voltage stability and grid restoration.

1.3. Motivation and Goal

The climate problem requires a massive change in the generation structure in a relatively short period of time. As explained in the previous sections, the complexity of transition plan and its exposed high operational costs are good reasons to re-evaluate the next steps in realization of some plans. In public scenes it is often announced with glory that the share of RE technologies is on the record high with around 51% of the generated net electricity mix. Nevertheless, reports about the yearly rising costs are not pleasing to the eye. With electricity prices of almost 0.32 €/kWh for household, 0.23 €/kWh for commercial and 0.17 €/kWh for industry customers in 2020, Germany has one of the highest electricity prices in the world [20].

The mentioned concerns in section 1.2 about the reliability of supply in a power system with the dominance of RE technologies, fast development and integration of RE generators into distribution networks, unmatched pace of RE developments with realization speed of NDPs, volatile decentralized generation and neglecting the requirements of the local power network are the motivations for conducting this dissertation. The central question in this dissertation can be formulated as:

- 1) Is the current strategy helpful in reaching the defined goals for a sustainable, reliable and affordable power supply? Or is it gambling on the security of power supply to a very high price?
- 2) The current RE development strategies have caused operational complexities for power networks. How can we improve the strategies to facilitate the transition process by using the current available potentials?
- 3) How the development strategies can be improved to reduce the rising demand for specific ancillary services and grid stability measures?
- 4) The raising costs of the transition process is a matter of serious concern. What kind of new integration strategies can help to optimally align the future development plans in a beneficial way?

In the current course of time, achievement of the goals is highly tied up to the progress of time-consuming NDPs. The methodology for definition of new NDPs is based on five main steps. In the first step, the frameworks for some scenarios are defined based on the prospect of the grid operators. In the second step, regional planning activities (commissioning and decommissioning of power plants) are taken into consideration. In the third step, the future of the energy market is modeled and forecasts of generation, transportation and consumption of the electricity are defined. In the fourth step, the transportation task and limitations of the electricity network are identified and the results are evaluated. In the last step, the NOVA⁴ principle is applied to optimize the network operation before applying any reinforcement measure or creation of a new network expansion plan [21].

The author believes that the current methodology can be improved by applying some intermediate steps and small tunings which are based on the assessment of the

⁴ Netz- Optimierung vor –Verstärkung vor Ausbau

requirements of the electricity network before integration of RE generators. According to his thesis, the new methodology opens a perspective for utilization of the maximum available potential of the electricity networks and postponing the expensive NDPs as far as possible. The upgraded methodology defines the RE development plans in form of the Degree of Load Coverage (DLC)⁵ as a promising parameter for better evaluation of the usage of the RE technologies. Table 1-3 briefly explains the current state of the art in development of RE technologies versus the suggested methodology. It must be mentioned that the expansion of the RE technologies has a market-driven approach, but theoretically if there could be a way to manage the expansion process in some aspects, there will be a good chance to save unnecessary investments and postpone network developments.

State of the Art	Suggested Methodology
Topic 1: Expansion of RE Technologies	Topic 1: Expansion of RE Technologies
A market-driven approach	A market-driven approach based on definition of the expansion targets in form of the DLC
Topic 2: Network Development Plan	Topic 2: Network Development Plan
Step 1: definition of frameworks of scenario based on forecasts of grid operators	Step 1: definition of frameworks of scenario based on forecasts of grid operators and the cellular approach
Step 2: regionalization plans considering regional plans for commissioning and decommissioning power plants	Step 2: regionalization plans considering regional plans for commissioning and decommissioning power plants
Step 3: market modeling modeling of the development of the future energy market	Step 3: market modeling modeling of the development of the future energy market
Step 4: evaluation of the results identification of the transportation task and limitations of the electricity network	Step 4: Optimal expansion strategy optimization of RE expansion to meet the objectives based on current available network potentials
Step 5: NOVA principle ⁶ network operation optimization before applying any reinforcement or network expansion measures	Step 5: evaluation of the results identification of the transportation task and limitations of the electricity network
	Step 6: NOVA plus principle NOVA principle plus customizing the reactive power strategy for each RE parks

Table 1-3: state of the art vs. the suggested methodology for better integration of RE generators

⁵ DLC defines the degree to which demand is met by generation.

⁶ According to NOVA principle if there are congestion problems, the network can be optimized by: 1- load flow control by changing switching conditions, 2- conductor temperature monitoring. If the network optimization is not enough, the network can be reinforced by: 1- utilization of high-temperature-resistant overhead lines or 2- utilization of compensation facilities. If the reinforcement measures are not helpful, the network must be expanded.

The proposed methodology in Table 1-3 is based on the framework of cellular approach as a method for better evaluation of the performance of a power system. In order to verify the above-mentioned theses, a synthetic DSO power network is designed, investigated and optimized for better integration of RE units. The synthetic power network simulates the behavior of a regional power network and is adorned with RE generators and loads that are connected to 110 kV and 20 kV levels. The RE generators operate based on the historical data from German National Meteorological Service⁷ and standard load characteristic curves from German Association of Energy and Water Industries⁸ are used to model different types of consumers. Moreover, battery models are developed and integrated into the power network as a support for local energy supply.

According to the concept of cellular approach, the synthetic power network is divided into several cells and investigated in details. Then the RE expansion plans are formulated in form of the DLC and the integration plan is optimized according to a novel meta-heuristic mathematical methodology, namely Grey Wolf Optimization (GWO). In this approach the GWO is programmed in a way that considers the power transfer limitations of the power network and aims to smoothen the RE integrations before execution of grid expansion plans. The GWO is programmed in a way that can follow different optimization strategies. In the first optimization strategy, minimizing the Net Positive Cost (NPC) of the RE integrations over 25 years is defined as the optimization goal, subjected to a specific DLC as the constraint. The GWO can also be customized to follow the second optimization strategy. In this strategy maximizing the Power Utilization Factor (PUF) over a year is defined as the optimization goal, subjected to a specific DLC as the as constraint. Furthermore, a weighted discrete distribution algorithm is developed to define the best place of integration for the RE units inside the synthetic power network.

Afterwards, the results of the optimization are validated by Quasi-Dynamic Simulation (QDS) in PowerFactory. By means of that, it is be possible to inspect the stability measures of the synthetic power network, inspect technical restrictions in different operational scenarios and define new controlling strategies for RE units. Moreover, QDS serves in verifying the limitations of the cellular approach as a methodology. Cellular approach can be easily utilized in small energy systems, however its application in a regional power network in this dissertation will challenge the practicability of this approach from a new perspective.

The proposed methodology in this dissertation is developed based on definition of new parameters, a novel optimization strategy for integration of RE generators and QDS as the verification process for the suggested solutions. The author believes that modifying the current development plans (stated in Table 1-3) with the suggested approach, presents better chances for smoother development of RE technologies considering the physical limitations of the power networks, using the current available potentials, postponing unnecessary investments on expansion plans and of course moving toward the sustainability goals in a rational way.

⁷ Deutscher Wetterdienst.

⁸ Bundesverband der Energie- und Wasserwirtschaft (BDEW) e.V.

1.4. Structure of the Thesis

In following the structure of the dissertation is outlined:

Chapter one highlights the effects of recent RE developments on German power networks in terms of costs and new operational challenges. It clarifies the importance of a wise integration plan for RE technologies and suggests modifications for the current development plans. The suggested methodology is based on cellular approach and GWO as a meta-heuristic mathematical methodology for better integration of RE generators in power networks. Furthermore, it outlines the QDS as a methodology for verification of the suggested RE development strategies.

Chapter two introduces shortly the theoretical background of the used methodologies in this dissertation. It starts with the introduction of the cellular approach and its application in energy systems. It presents the concept of autarky in power systems and introduces the economical methods for evaluation of the synthetic power network in this dissertation. Besides, it presents the GWO as the chosen methodology for optimization of the synthetic power network. Subsequently, it introduces shortly the application of QDS in analysis of the synthetic power network and outlines briefly the technical frameworks used for construction of the simulation models in this dissertation.

Chapter three presents the MATLAB optimization and PowerFactory simulation models. It starts with definition of the problem and moves on to the proposed thesis for solving the problem. The proposed solution is a two-steps process in which the first step is the GWO in MATLAB and the second step is the QDS in PowerFactory. Accordingly, it introduces the structure of the optimization model and its details. Furthermore, it presents the structure of PowerFactory simulation models together with the details of the synthetic power network.

Chapter four outlines the results of the MATLAB optimization and PowerFactory simulations. It introduces the outcomes of the developed optimization approaches and discusses the economic feasibility of the approaches. Afterwards, the results of the QDS in PowerFactory for the chosen optimization approach are presented. The QDS also highlights the role of the proper reactive power strategy for the generation units for the better operation of the synthetic power network. Finally, the chosen solution is evaluated by N-1 contingency analysis and the results are discussed further.

Chapter five outlines shortly the final results of the simulation and optimization models. It presents the main outcomes of the dissertation and formulates the answers to the central question of this dissertation. Finally, the evaluation of the author from the current situation and suggestions for future research activities are presented.

2. Chapter: Theoretical Background

2.1. Cellular Approach in Power Systems

In this chapter the theoretical background for the optimization and simulation models are clarified briefly. The optimization and simulation models are later on developed based on the definitions presented in different sections of this chapter and are presented in chapter three.

The indispensable massive changes in the power systems forced new adaptations on the structure of electricity networks which require tremendous balancing capacities for the security of power supply. The required balancing capacities might get relieved lightly by application of storage technologies, possible load shifting strategies or coupling of sectors. Beside the benefits, the new adaptations expose also new challenges. In order to solve the upcoming challenges, the VDE⁹ technical society commissioned a Task Force to address the upcoming issues. The Task Force prepared a list of possible storage options, alternative technologies and energy conversion options in Germany. Based upon that, scenarios for sustainable energy supply via RE technologies were developed. Accordingly, it was realized that balancing of generation and consumption at the lowest local levels might create new opportunities and has a significant importance in raising the share of RE technologies in energy consumption. In this regard, the concept of cellular approach was introduced as a solution for facilitating the implementation of the sustainable development goals. [22]

According to the Task Force, an energy cell is defined as an environment that consists of infrastructures for various forms of energy, in which a cellular energy management system in coordination with other cells organizes balancing between generation and consumption. The cellular approach is not restricted to the size of a system and it can be freely adjusted or customized based on the requirements of systems. It is clear that in this way a cellular energy management system controls the permanent interactions of the defined cells with each other. The concept of cellular approach in literature can be defined as mentioned in Table 2-1 [23].

Definition of the concept of cellular approach in literature	
1)	It is referred to cells with smoothly integrated energy systems; i.e. with integrated infrastructures for electricity, heat, gas and water.
2)	A cell contains an energy management system that is capable of controlling all the components of generation, consumption, storage and energy conversion options.
3)	The energy management system is capable of interacting with neighboring cells or upstream cells to send and receive energy according to requests and offers.

Table 2-1: The concept of cellular approach in literature

At the current course of time, the cellular approach is performed on existing systems in three main steps. In the first step a comprehensive analysis of the generation units, loads and available infrastructures of the system is performed. In the second step a comprehensive potential analysis is performed to determine the flexibility potentials of the system for load shifting or coupling of sectors. In the last step the goals are defined based on previous steps

⁹ Verband Deutscher Elektrotechniker (Verband der Elektrotechnik Elektronik Informationstechnik e.V.)

and accordingly the required restructuring and upgrading measures are identified. As the planning of a cellular system based on the above-mentioned description is very complex and currently only feasible in small energy systems with limited scope (in order of some MW), the author implements simplifications and customizes the concept to be able to extend it to larger scales. The customizations are presented in Table 2-2.

The concept of cellular approach used in this dissertation
1) The concept of cellular approach is prepared for application on high voltage electricity networks in form of a calculation model for virtual cells.
2) The coupling with other sectors is not intended and perused.
3) There is no cellular energy management system to control the interactions between the cells. The cells are created by virtual division of the electricity network. The interactions between virtual cells are only investigated by means of the calculation model.

Table 2-2: Simplifications and customizations of cellular approach in this dissertation

Figure 2-2 represents the schematic diagram of the cellular approach that is used in this dissertation. As it can be seen from the illustration, only medium voltage and high voltage levels are modeled in this dissertation. The details of the calculation models are explained in chapter three.

For more information about the state of art and projects with cellular approach, the reader is encouraged to read the following sources:

- Project C/sells [23], [24]
- Project Energiezelle Max Bögl [25], [26]
- Project IREN2 [27]
- Project SoLAR [25]

All in all, it can be stated that the concept of cellular approach with the current definition and specifications refers to visions for future energy systems. This concept is still in infancy stage and there are no defined standards or directives for design or planning of energy cells. Many aspects are still not clearly discussed or investigated in details. Among them following aspects are important in the view point of the author:

- Feasibility studies for application of such a concept in large scales
- Feasibility studies regarding the economic aspects of the cellular energy systems
- Feasibility studies for supra-regional energy exchange based on cellular approach

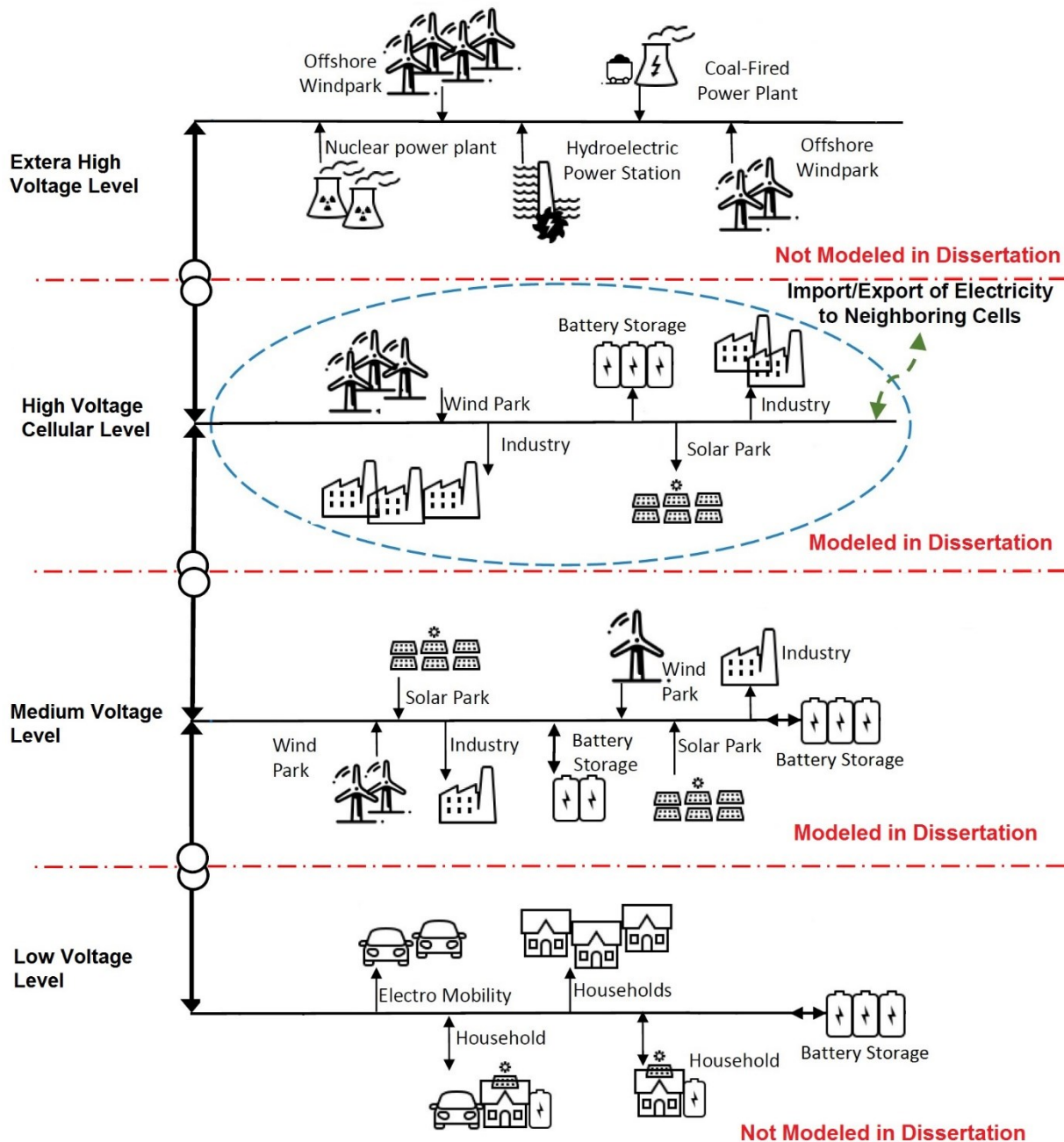


Figure 2-1: schematic diagram of the cellular approach in dissertation

2.2. Autarky in Power Systems

In socio-economic debates terms like “energy autarky” or “autarkic systems” have dominated the discussions and the competition for first autarkic community, village or campus have been running continuously. In the time that the scientists were discussing the evaluation methods of autarkic systems, investors were already realizing projects and selling the idea on the market. In this regard, at the beginning of this era many techno-economic aspects of autarkic systems were not considered or neglected intentionally. Later on, questions were raised about the terms like self-sufficiency, scalability of the concepts and security of power

supply. Moreover, doubts about frameworks of the evaluation methods and indicators were raised from scientific societies.

In literature inconsistent definitions and terminologies are used for autarkic systems. According to the definitions of McKenna et al., most of the existing projects in the field of autarkic systems are classified in categories for systems with a tendency towards autarky or systems with autarky of balance sheet. Except from small islands or very small systems, there are no practical examples for a system with complete autarky in large scales. For a good understanding of the definitions based on clear classifications, the reader is encouraged to study the definitions suggested by McKenna et al. [28].

To recap, the definitions of system autarky depends on the perspective of view and the considered variables. In this dissertation the author defines the following indicators for evaluating the performance of the power system [29].:

Degree of Load Coverage (DLC):

DLC defines the degree to which demand is met by generation. Considering a system with decentral generators, DLC can be measured by dividing the sum of fulfilled demand (numerator) to the sum of demand (denominator) over the given time period as outlined in equation 2-1. The numerator in this equation specifies the demand that is met by summing the minimum value between load and generation at each specific time step. Therefore, this definition allows a time-step-based comparison of the generation and demand.

$$DLC = \frac{\int \min\{P_L(t), P_{DG}(t)\}dt}{\int P_L(t)dt} \quad (2-1)$$

Where $P_L(t)$ is the active power of loads and $P_{DG}(t)$ is the active power of decentral generation units.

Power Utilization Factor (PUF):

PUF is introduced by equation 2-2. It is an indicator to show how effective available generation is being utilized by the system itself. This indicator compares the fulfilled demand (numerator) to the generated power (denominator) over the chosen time period. As a system utilizes more self-produced power to meet its own demand, PUF approaches higher values. 100% is the maximum value which signifies that all the available generation has been utilized by the system.

$$PUF = \frac{\int \min\{P_L(t), P_{DG}(t)\}dt}{\int P_{DG}(t)dt} \quad (2-2)$$

Degree of Energy Autarky (DEA)

DEA is the indicator for autarkic power systems which is used most widely. DEA is principally based on an overall energy balance of generation to energy demand (autarky of balance sheet) and is defined in equation 2-3. The disadvantage of this indicator is that it does not present the balance between generation and demand at each time step. This indicator is not

considered in this dissertation for the development of the optimization model and is stated here as a clarification for the reader.

$$DEA = \frac{\int P_{DG}(t)dt}{\int P_L(t)dt} \quad (2-3)$$

Figure 2-2 illustrates schematically generation and load curves over the time period t and helps in understanding the above mentioned equations.

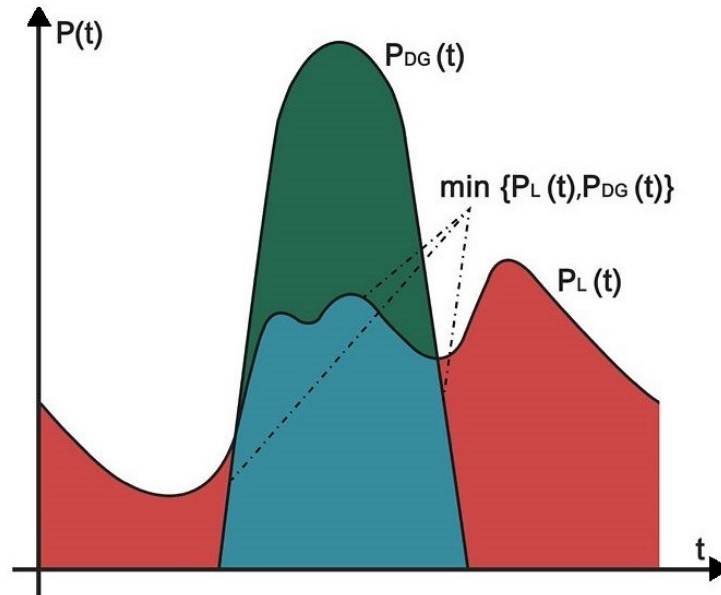


Figure 2-2: Schematic illustration of the curves presented in equations 2-1, 2-2, 2-3

It is worth to mention that for evaluation of a system based on the above mentioned indicators, clear definition of system borders plays an important role. It is clear from the descriptions that the DEA is not a proper indicator for evaluation of the system performance as it is based on the concept of balance sheet comparison that provides only rough information about generation and consumption. In this regard, DLC and PUF are better indicators for evaluation as each time-step plays a role in degradation or improvement of these indicators.

2.3. Economic Model for Power System Analysis

Beside the technical issues related to modern power systems with high amounts of RE technologies, the concept of sustainable development depends to a high degree on macro-economic perspectives of a large-scale power system. In this regard, a detailed techno-economic analysis of a power system over its lifetime is one of the keys towards a successful transition. Techno-economic analysis is also the central topic in cost optimization of the power systems especially by integrating RE technologies.

In this dissertation, techno-economic analysis for integration of RE technologies will be done based on Net Present Cost (NPC) of the system and Levelized Electricity Cost (LEC). It is

clear that in this evaluation method, the least cost approach will be followed by considering the costs, resource life-cycles, maintenance and replacement factors. For a comprehensive understanding of NPC and LEC, the reader is encouraged to refer to the following sources: [30], [31] and [32]. In following the approach is clarified briefly according to the requirements of the dissertation.

The NPC of a power system can be defined by equation 2-4. It can also be expressed in terms of LEC as provided by equation 2-5. In economic evaluations, LEC is seen as a proper criterion for economic feasibility of the projects and is defined as the discounted average of electricity generation cost over a project lifetime.

$$NPC = I_0 [\text{€}] + \sum_{t=1}^{t=n} \frac{E_t [\text{€/a}]}{q^t [1/a]} \quad (2-4)$$

$$NPC = \sum_{t=1}^{t=n} LEC [\text{€/kWh}] \times \frac{E_{e,t} [\text{kWh/a}]}{q^t [1/a]} \quad (2-5)$$

Where the parameters are defined as:

- I_0 : capital expenditures present value (CAPEX) as the initial cash outflow
- E_t : time value of expenses at year t (OPEX)
- $E_{e,t}$: electricity produced over the lifetime t
- q : discount factor
- t : lifetime of the investment project in years

The discount factor q accounts for inflation rates f and investment rates i via variable k as the real discount rate (in % per year), as shown below in equations 2-6 and 2-7.

$$q = 1 + k \quad (2-6)$$

$$k = \frac{(i - f)}{(1 + f)} \quad (2-7)$$

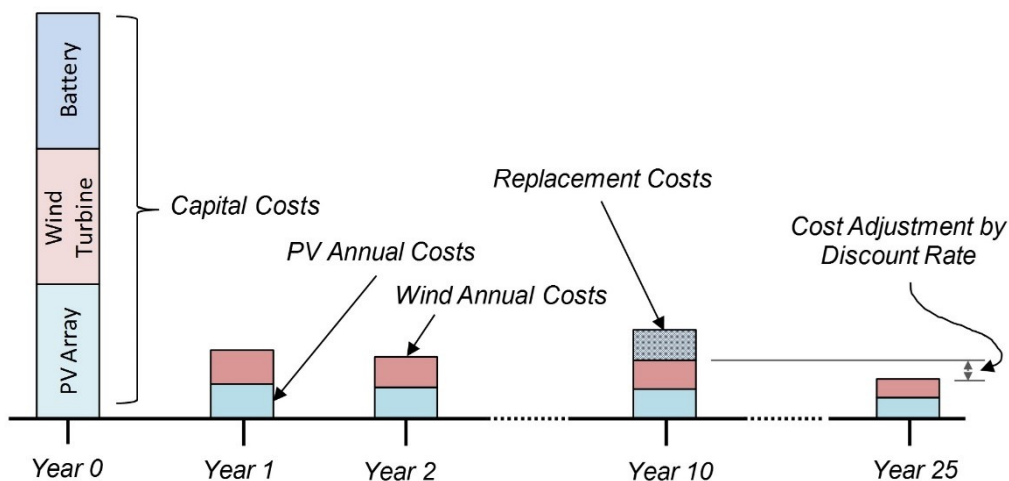


Figure 2-3: Schematic NPC cash-flow-diagram for a RE project with battery modules

For the purpose of optimization (refer to chapter 3), NPC can be calculated based on some assumptions. In this dissertation it is assumed that the anticipated lifetime for photovoltaic plants and onshore wind parks are considered to be 25 years, whereas Li-ion battery banks require cell replacement on a 10 year cycle. Operations and maintenance costs (OPEX) are calculated as annual costs based on installation size. In this regard based on the above mentioned assumptions, NPC cash-flow diagram of a project can schematically be illustrated as in Figure 2-4. As it can be seen, these costs are attributed to the year in which they are accrued as equivalent present costs.

Additionally, annual fixed wind turbine OPEX are calculated based on annual energy output. Table 2-1 clarifies the assumptions in terms of costs.

Technology	Size	CAPEX	Replacement Cost in % of CAPEX	Annual Operational Cost	Annual Fixed Cost	Lifetime
Photovoltaic	1.053 MVA	700 €/kW	-	17.5 €/kW	-	25 years
Wind Turbine	3.5 MVA	1750 €/kW	-	30 €/kW	0.005 €/kWh	25 years
Battery Li-ion	0.375 MWh	200 €/kWh	60%	-	-	10 years

Table 2-3: Economic factors assumed for calculations (data based on: [31] and [33])

For understanding the approach, Figure 2-5 provides the NPC of the introduced technologies in Table 2-1 assuming a 25-year project lifetime. Onshore wind fixed costs are based on annual generation and thus an average 2000 FLH (Full Load Hours) is assumed for this illustration.

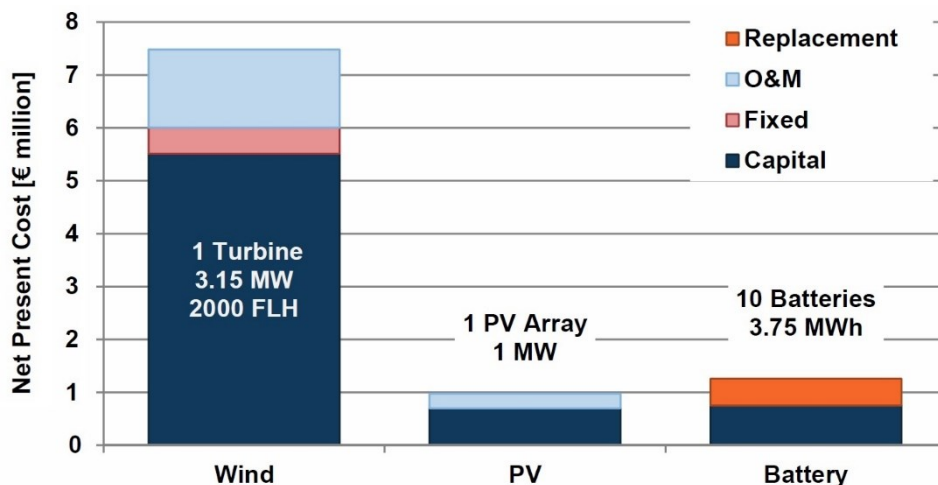


Figure 2-4: NPC of chosen technologies over a project lifetime of 25-years

The above mentioned approach is used in optimization model for minimization of the costs in further steps. The details of the optimization model are clarified in Chapter 3.

2.4. Metaheuristic Algorithm – Grey Wolf Optimization

Reaching reliable electricity supply while maintaining feasible costs in electricity networks with millions of RE-based distributed generators is an extremely challenging and complicated task. In literature, the systems with a portfolio of different types of consumers, generators and storage technologies with or without coupling of sectors are specified as hybrid systems. In hybrid systems, optimization along with the possible constraints belongs to the building stones in designing such systems. As there are several possible configurations of generators (technologies, numbers and sizes of generators) that can be used in system designs.

Due to the complexity of hybrid power system, numerous optimization methods have been proposed and utilized to effectively minimize the costs while maintaining system operation within the defined bounds. Among the optimization methods, meta-heuristic methods are preferred over the classical methods because of the inherent complexity of hybrid energy systems, challenging optimization effectiveness and efficiency of the methods [34]. Meta-heuristic methods are commonly derived from naturally occurring patterns, phenomena or behaviors that express widely varying strategies to finding system solutions. Some examples of these methods are the ant colony optimization which is based on the movement and coordination within the ant colonies, the Particle Swarm Optimization (PSO) which models social patterns as seen in flocks of birds and school of fishes, the cuckoo optimization which is based on nesting, migration and breeding patterns of cuckoo birds, the genetic algorithm which is inspired from the process of natural selection, or the Grey Wolf Optimization (GWO) which is based on hunting pattern of the grey wolves [35], [36], [37].

Problems concerning hybrid energy systems have been studied using numerous meta-heuristic algorithms. In recent years, multi-objective self-adaptive differential evolution algorithms were used for dimensioning the micro-grids consisted of photovoltaic, wind, diesel and battery sub-systems. The methods were implemented and compared in different optimization case. From the view point of the author, all of the above mentioned optimization methods are effective though having different characteristics. Among the possible methods for optimization of a hybrid system, researches indicated that the GWO algorithm shows better conversion rate, higher exploration performance and faster convergence in similar problems in comparison with other methods [34], [38]. The GWO algorithm was developed by Mirjalili et al. in 2014 [39]) and has been used to optimize numerous power system problems, including wind generator controllers [40], combined heat and power dispatch strategies [41], hybrid vehicle engine optimization [42], load-frequency controls in thermal power systems [43] or in optimal reactive power dispatching of generators [44].

Due to the above mentioned advantages of the GWO over the other optimization methods, GWO is applied for optimization of the synthetic power network in this dissertation. Chapter 3 specifies the details of the methodology.

Mathematical Description [39], [38]

The mathematical description of the described search process can be explained in following based on the social hierarchy of grey wolves and their hunting approach. The GWO

algorithm is modelled after the hierarchical authority structures of grey wolves used for hunting and stalking. Packs or groups of grey wolves adhere to strict authority structures, with the alphas (α) at the top of the hierarchy, followed by betas (β), deltas (δ) and omegas (ω). Hunting (optimization) is modeled by considering the best solution to be the alpha (α), the second and third best solutions are the beta (β) and delta (δ) respectively, followed by all others considered as omegas (ω) [39], [38]. In hunting patterns of grey wolves, three main key steps are considered for modeling the algorithm:

- 1) Tracking, chasing and approaching the prey,
- 2) Pursuing the prey, encircling the prey and
- 3) Stopping the prey from movement and attacking.

In GWO optimization process, numerous wolves are generated, each wolf representing a potential solution. With each iteration, the alpha (α), beta (β) and delta (δ) wolves predict the direction of the prey and additional factors promote exploration by causing either convergence to or divergence from the location of the optimal solution. In practice, these factors help the wolves (potential solutions) to define different hyperspheres (assuming a multi-dimensional problem beyond two variable) and to promote exploration towards global optima. After identifying a potential solution, the wolves then encircle the solution area, searching for improved solutions before converging and attacking the final solution.

Accordingly, the searching and encircling behavior can be described as:

$$\vec{D} = |\vec{C} \cdot \vec{X}_p(t) - \vec{X}(t)| \quad (2-8)$$

$$\vec{X}(t + 1) = \vec{X}_p(t) - \vec{A} \cdot \vec{D} \quad (2-9)$$

With the following indicators:

\vec{D} : calculated vector for specifying a new position of a grey wolf

\vec{A} and \vec{C} : coefficient vectors

\vec{X}_p : vector of the prey's position

\vec{X} : vector of the grey wolf's position

t : iteration number

The coefficients \vec{A} and \vec{C} can be defined as:

$$\vec{A} = 2 \cdot \vec{a} \cdot \vec{r}_1 - \vec{a} \quad (2-10)$$

$$\vec{C} = 2 \cdot \vec{r}_2 \quad (2-11)$$

Where \vec{a} , \vec{r}_1 and \vec{r}_2 are:

\vec{a} : vector set that decrease linearly from 2 to 0 over iterations

\vec{r}_1 and \vec{r}_2 : random vectors in [0,1] that allow the grey wolves to reach new random positions inside the space around the prey

Considering the position of a grey wolf and the prey as (X, Y) and (X^*, Y^*) respectively, the next position of the grey wolf can be updated by adjusting the values of vectors \vec{A} and \vec{C} . Possible next locations in a two-dimensional search space can be calculated from equations 2-8 and 2-9 and are schematically illustrated in Figure 2-5.

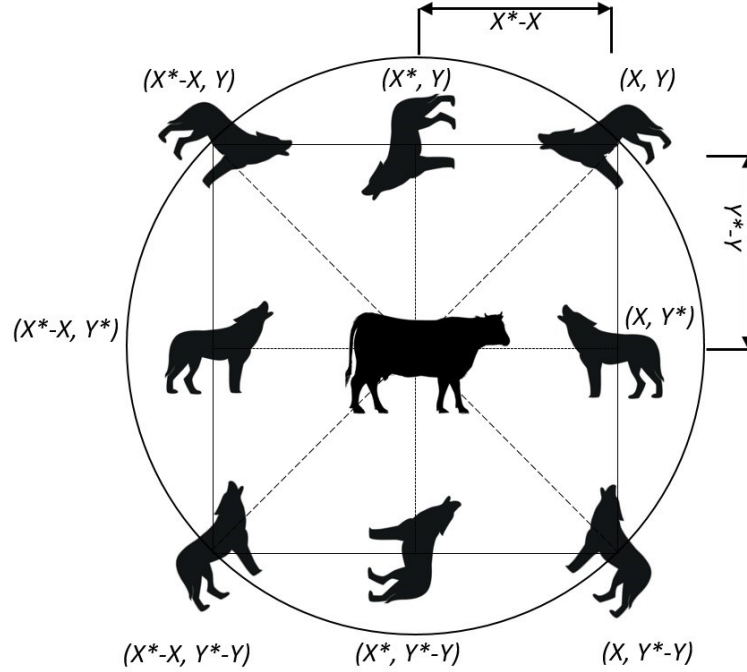


Figure 2-5: Two-dimensional search space in GWO process

Taking the searching behavior of the grey wolves into consideration, it is understandable that the searching agents have the ability to estimate the location of the prey and update their positions in order to encircle it for final attacks. In reality α wolf conducts the mission and hunts as the finishing wolf. However, β and δ wolves might also participate in hunting (final action) occasionally. In optimization, there is a similar approach; i.e. it is considered that the best three candidate solutions (α , β and δ wolves) have better estimations about the potential location of the optimum solution (prey). Therefore, the best three solutions are saved and used as conducting points for updating the positions of other searching agents in a random basis around the prey. Considering Figure 2-6, this approach can be described by following equations for a two-dimensional search space:

$$\vec{D}_\alpha = |\vec{C}_1 \cdot \vec{X}_\alpha - \vec{X}| \quad (2-12)$$

$$\vec{D}_\beta = |\vec{C}_2 \cdot \vec{X}_\beta - \vec{X}| \quad (2-13)$$

$$\vec{D}_\delta = |\vec{C}_3 \cdot \vec{X}_\delta - \vec{X}| \quad (2-14)$$

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1 \cdot (\vec{D}_\alpha) \quad (2-15)$$

$$\vec{X}_2 = \vec{X}_\beta - \vec{A}_2 \cdot (\vec{D}_\beta) \quad (2-16)$$

$$\vec{X}_3 = \vec{X}_\delta - \vec{A}_3 \cdot (\vec{D}_\delta) \quad (2-17)$$

$$\vec{X}(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \quad (2-18)$$

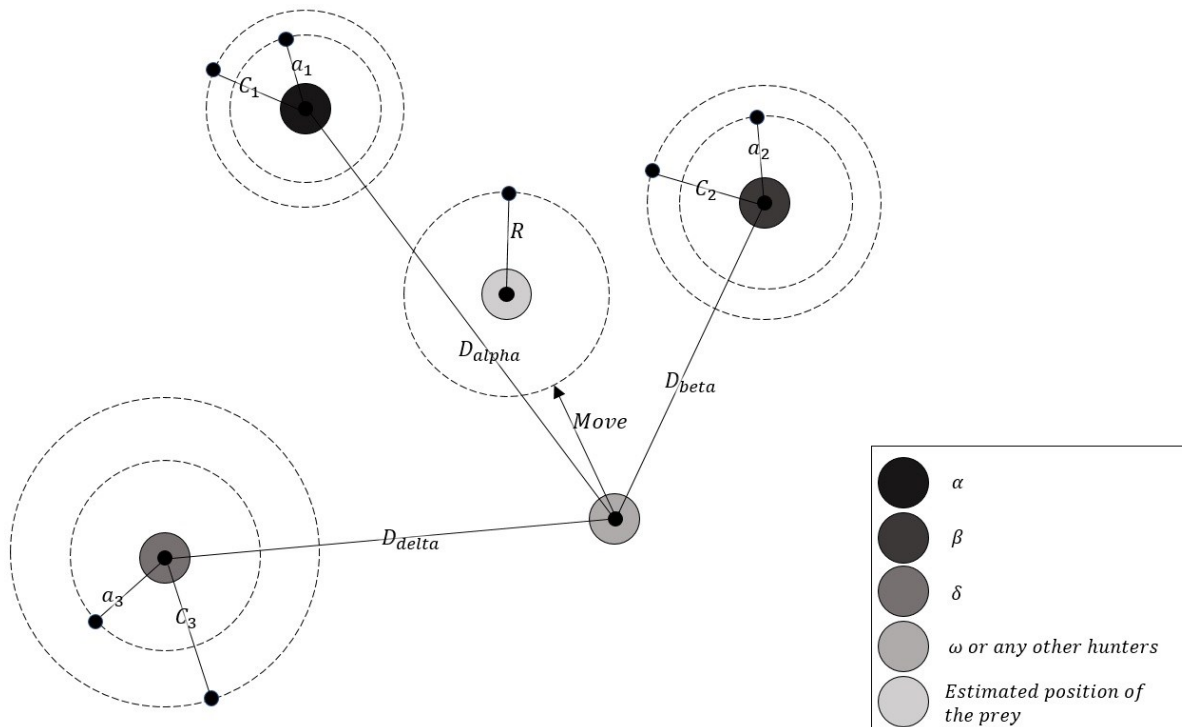


Figure 2-6: Position updating in GWO process

By controlling the vector set \vec{a} , the value of the coefficient \vec{A} can be controlled. Accordingly, the value of $|\vec{A}|$ defines whether searching agents shall attack the prey or they should search further. Values of $|\vec{A}| > 1$ forces the agents to search further by diverging from the prey in the hope of finding a fitter prey and value of $|\vec{A}| < 1$ gives the attacking signal to the wolves. As the coefficient \vec{A} alone can mislead the approach toward a local optima, the coefficient \vec{C} is defined to favor a better exploration in GWO that helps in avoidance of local optima stagnation. Therefore, it is especially important that the coefficient \vec{C} takes over random values. The effect of vector \vec{C} models the effect of obstacles in the hunting path in nature that do not allow the wolves to approach the prey quickly.

Depending on the optimization problem, other factors like the population of searching agents and number of iterations play crucial roles in determination of a successful job. These factors are determined commonly by trial and error approach.

2.5. Power System Analysis and Technical Frameworks

Load Flow Analysis (LFA) is the constituent part in evaluation of power systems. Principally three types of calculations are applied for evaluating the operation of a power system:

- 1) Static Load Flow Calculation (abbreviated also as LFC),
- 2) dynamic simulations and
- 3) Quasi-Dynamic Simulation (QDS).

LFA is principally based on steady-state LFC¹⁰ which is normally conducted for a specific time step. LFCs are carried out for both normal and abnormal system conditions. In this regard, LFC determines the voltage magnitude and the voltage angle of the nodes, as well as active and reactive power flow of branches based on non-linear Newton-Raphson equation systems. LFC is normally performed by engineers for special scenarios at a given point of time (high generation, high load, etc.). The simplicity of LFC in terms of finding a quick answer (convergence or divergence) is an advantage.

RMS simulations are performed to analyze the dynamic behavior of a power system. This type of calculations is basically done for stability analyses, checking the performance of control systems in dynamic situations and transient analysis for planning and design of power systems.

Sometimes it is better to go one step further than simple static LFC and perform QDS which is very practicable for medium and long term assessment of power systems. QDS applies a series of LFCs for simulating the behavior of a power system over a period of time. The simulation step sizes can be defined by the user from some seconds up to hours. Furthermore, by means of QDS it is possible to develop and integrate the detailed model of electrical equipments (if needed) to have better simulation results which is a great advantage in comparison to static LFC. Transient studies are not covered by QDS.

In this dissertation QDS is used to simulate the behavior of the synthetic power network. The simulations are performed in software environment of PowerFactory. The details of the simulation models are presented in Chapter 3. For understanding the mathematical descriptions of the above mentioned calculation methods, the reader is encouraged to refer to: [45], [46], [47].

In order to have trustworthy results from QDS, the developed PowerFactory simulation models must be equipped with the right frameworks. The investigated power network in this dissertation is a synthetic regional distribution network (presented in section 3.4) that consists of electrical equipments in 20 kV and 110 kV. Accordingly, the related technical frameworks can be found in VDE standards for medium voltage and high voltage power networks. The following technical connection rules are used in this dissertation for development of the simulation models:

- VDE-AR-N 4110 – technical connection rules for medium-voltage [48]
- VDE-AR-N 4120 – technical connection rules for high-voltage [49]

Related parts of the technical connection rules are presented in Annex 1. The reader is encouraged to refer to [48] and [49] for more details.

¹⁰ Also sometimes called as static load flow calculation.

3. Chapter: Optimization and Simulation Models

3.1. Introduction

In previous chapter it was outlined that in hybrid networks definition of the size of generators and their optimum place of integration in network is a very complicated task, especially in large scale networks (regional and supra-regional power networks). Considering the cellular approach as an analysis method and GWO as a novel metaheuristic algorithm for addressing this issue, the precise problem definition for optimization is as follows:

Considering a regional power network which is going to be upgraded by RE technologies, how can one integrate efficiently enough number of wind turbines and photovoltaic plants together with battery storage plants, in order to reach a certain DLC with the lowest NPC? Or how can one integrate enough number of wind turbines and photovoltaic plants together with battery storage modules, in order to reach a certain DLC with highest available PUF? Furthermore, what might be the technical obstacles in realization of such plans and where are the system's limits? As it can be understood from the questions, the solution of the problem can have different approaches. In the first approach minimizing the costs plays the key role and in the second approach maximizing the utilization factor of the produced RE power is the sticking point.

In this chapter the structure of the optimization and simulation models for addressing the above questions are introduced on the basis of the developed synthetic network and its requirements. Beyond that, the application of the GWO with cellular approach for better integration of RE technologies in the synthetic network is clarified. Furthermore, the details of the optimization method, its different approaches and goals in MATLAB are pointed out.

At last, it is explained how the results of the MATLAB optimization can be checked by means of QDS in semi-real operational situations. QDS simulations are performed in PowerFactory environment as an excellent simulation program for power networks. The developed synthetic power network and the programmed QDS models for provision of reactive power in PowerFactory are introduced in section 3.4.

3.2. Optimization and Simulation Structure

To start with, Figure 6-7 in Annex 2 presents the overview of the developed synthetic power network. The synthetic power network is constructed based on the structure of 110 kV distribution networks in Germany. In order to have semi-real simulation results of regional distribution grids, three different types of 20 kV Medium Voltage Networks (MVN) are developed and integrated into the simulation models. The MVNs are developed based on benchmark models of CIGRE Task Force and represent industrial, rural and urban 20 kV sub-networks. Details of 110 kV and 20 kV networks are presented in section 3.4. The synthetic network contains ten main substations (double busbar systems in Figure 6-7). It has active power consumption that varies between 153 MW to 750 MW, its reactive power

demand varies between 7 Mvar capacitive to 296 Mvar inductive and it contains almost 900 km of 110 kV and 216 km of 20 kV distribution lines.

It was explained before that the goal of the optimizations and simulations is to find the best solution for integration of the RE technologies into the synthetic network with minimized NPC or maximized PUF, subjected to a certain DLC. In this regard, the author proposes a two-step solution for the problem. The first step of the solution process is optimization in MATLAB and the second step is simulation in PowerFactory. The reason for having a two-step solution in MATLAB and PowerFactory can be explained as follows:

MATLAB has a suitable structure for programming codes and developing mathematical models. Its abundant programming toolboxes, analytical tools and possibilities for creation of high-quality graphical illustration are clear advantages over available comparable software programs. However, development of an extensive power network and programming of LFC or QDS in MATLAB are very time-consuming and complex tasks. Due to this reason, PowerFactory is chosen for performing detailed network analysis as the second step of the solution procedure. PowerFactory is one of the most suitable existing programs for performing network studies. It contains plentiful detailed libraries of electrical equipments, advanced grid calculation tools and well-defined possibilities for creation of operational scenarios in network studies. In the second step, the results from the MATLAB optimization are imported into PowerFactory and investigated by means of QDS.

In the first step of the solution process, the problem is simplified for MATLAB optimization in the way that the GWO considers a cellular structure of a model consisted of its cells and the connection points. The GWO model recognizes the loads connected to each connection point and tries to satisfy the active power demand of loads by means of generators and batteries. The output from generators or batteries are subjected to the weather conditions and the limitations of the connection point. The limitations of the connection points are defined based on available capacities of the connected transformers. This approach has the advantage of limiting the variety of variables in optimization process. It has also the disadvantage of not considering the limitations of other electrical equipments (like distribution lines) or losses within the system. However, the second step of the solution process in PowerFactory abolishes these drawbacks thoroughly in a way that the applicability of the MATLAB solutions can be investigated in semi-real operational situations. It is clear that it is an advantage to perform the QDS in PowerFactory. In this way evaluation of the results and identification of possible obstacles in the way of realization of such complicated solutions can be manifested. In this dissertation, QDS in PowerFactory is used to reveal the technical feasibility of the MATLAB optimization solutions.

In the first step of the procedure, objective function and constraints are defined in MATLAB and the synthetic power network is divided into cells based on the principles of cellular approach (cells are shown in Figure 3-3). Then the problem with its inputs, outputs and constraints is mathematically formulated in form of the GWO algorithm to find the fittest solutions. The optimization algorithm can be prepared based on two different approaches with two different goals. The goal of the first approach can be minimizing the NPC while

reaching a certain DLC. The goal of the second approach can be maximizing PUF while reaching a certain DLC. At the end, results of the optimization are exported for the second step of the solution procedure (simulations in PowerFactory). Figure 3-1 illustrates the overview of the first step of the solution procedure.

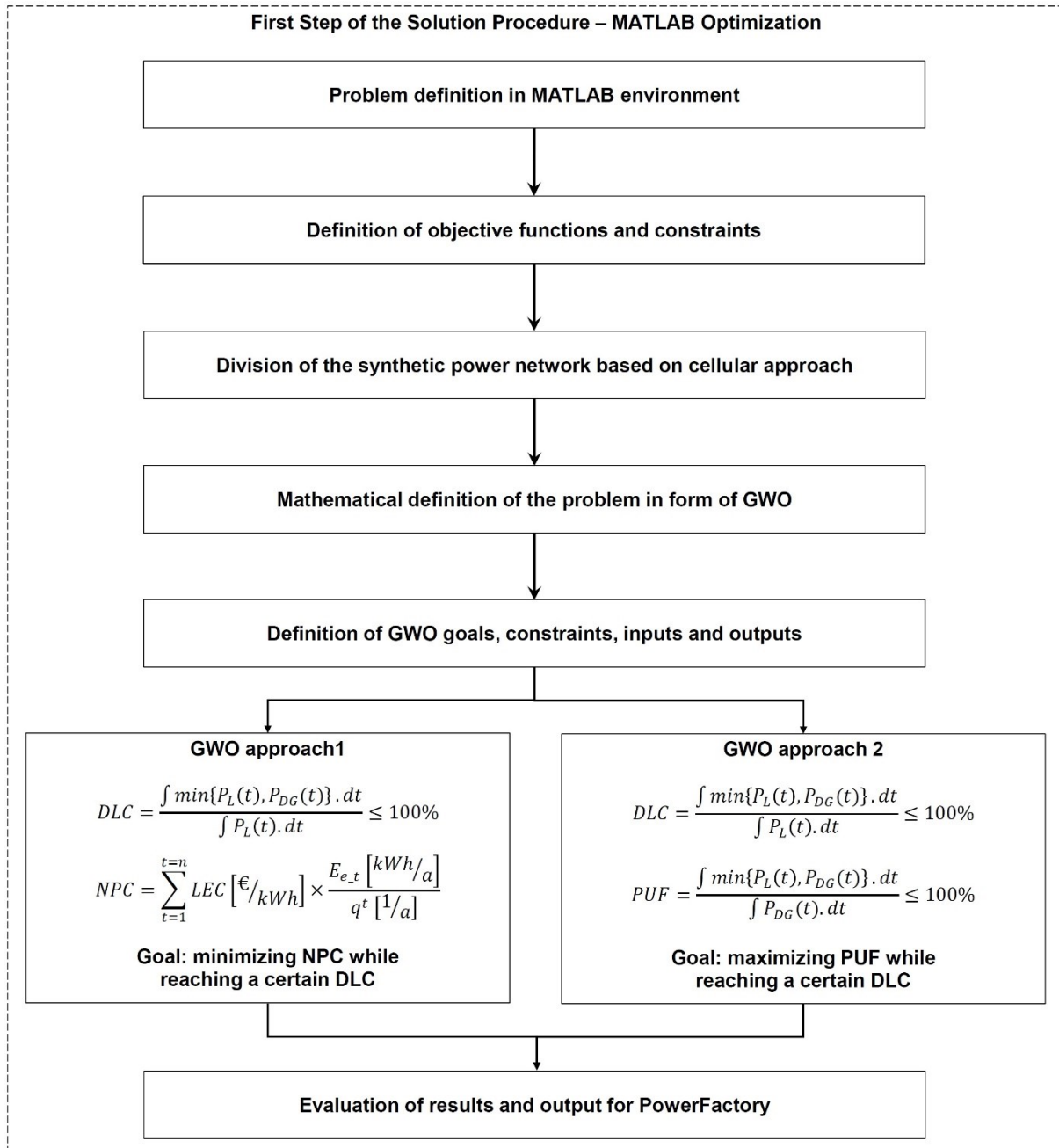


Figure 3-1: Overview of the first step of the solution process – optimization in MATLAB

The GWO solutions specify the exact number of required RE generators or battery units at each specific connection point. Based on these outputs, the synthetic power network is adorned with RE generators and battery modules in PowerFactory. Furthermore, operational scenarios for performing QDS are defined. Based on the preliminary results from QDS and the convergence or divergence results of simulations, an estimation with a good certainty can be made, whether the applied solutions are technically feasible or not. Divergent solutions

are indicators of instability in network operation or extreme overloaded equipments. Solutions with good convergence, are investigated further for possible violation of technical frameworks (introduced in section 2.6.).

Investigation of the results proved that with the proper assigned Q provision strategy for the RE generators, many critical network operation situations can be avoided. Therefore, evaluation of the proper reactive power provision strategy belongs to the important steps in PowerFactory simulations. At last, N-1 contingency analysis is performed to evaluate the effectiveness of the proposed operational strategies in cases where a disturbance results the outage of components. Figure 3-2 illustrates the overview of the second step of the solution procedure in PowerFactory.

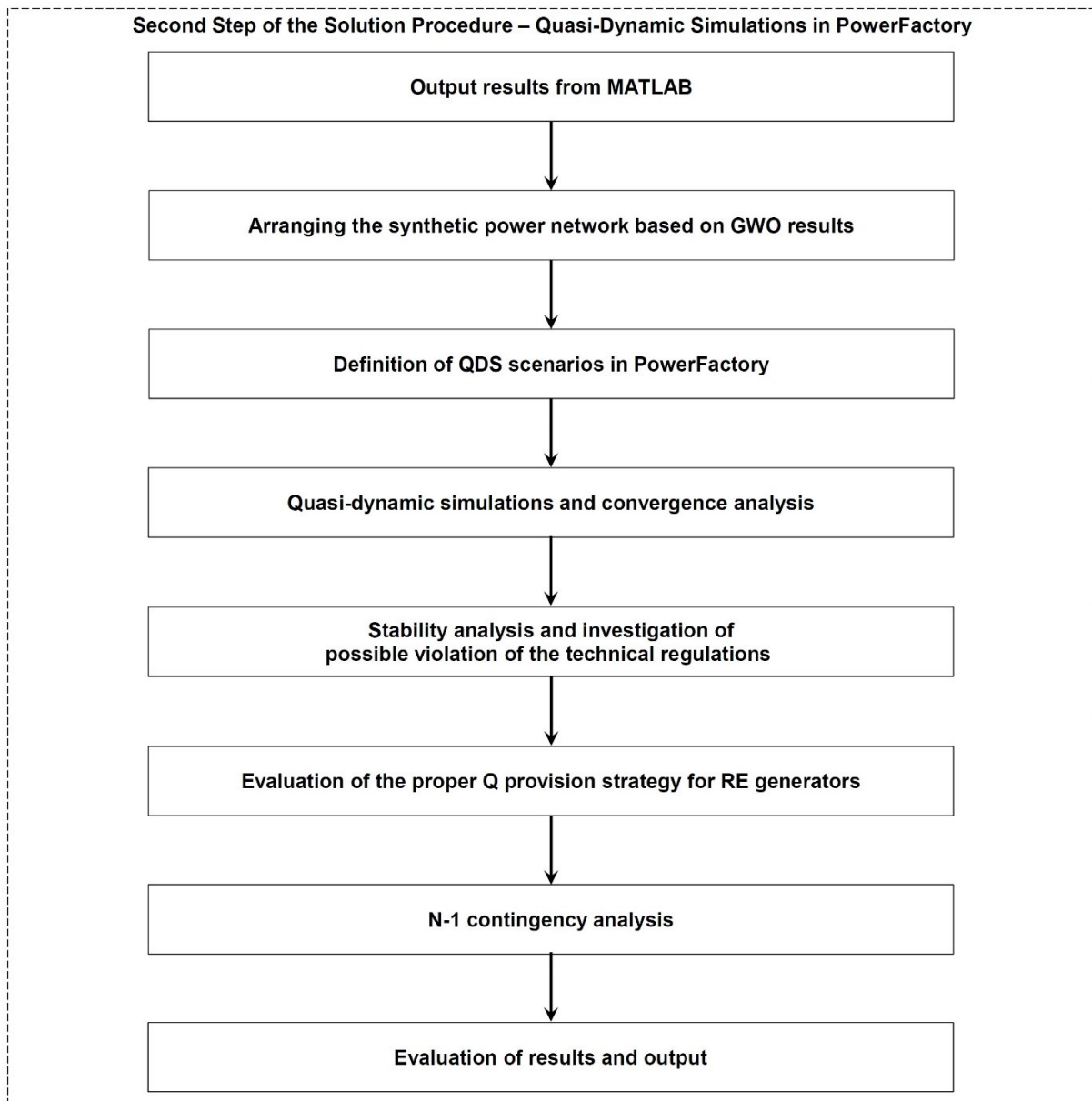


Figure 3-2: Overview of the second step of the solution procedure in PowerFactory

3.3. Optimization Model in MATLAB

3.3.1. Optimization Methodology and Objective Functions

In previous section, the problem definition, goals of the optimization and the MATLAB optimization procedure were introduced briefly. The GWO process used in this dissertation is a pure mathematical optimization method and does not represent any kind of energy management systems for controlling the synthetic power network. In order to start the GWO process, first the introduced synthetic power network (Figure 6-7) must be divided into imaginary cells. Therefore, ten imaginary cells are defined for the purpose of optimization. Figure 3-3 represents the simplified schematic view of the sectionalized synthetic power network which consists of ten cells. Detailed structure of the defined cells are presented in Annex 2 (Figure 6-8 to Figure 6-17). The reason for division of the synthetic power network into ten imaginary cells for optimization can be clarified as follows:

According to the defined methodology in cellular analysis of energy systems, the smaller the defined cells, the better are the results of the analysis. Nevertheless, the analysis which is based on the smaller defined cells, requires a considerable higher computing power. Therefore, the best strategy for choosing the proper size of the cells in a cellular analysis can only be made by means of trial and error. In this dissertation, after several tests, it was observed that definition of ten cells is fully complied with the goals of the optimization and simulation tasks. To be more exact, definition of more cells leads to considerably longer calculation time in optimization process and definition of less cells might has a direct correlation with inaccuracies and incompatibilities of results during QDS simulations.

In order to have optimization results which are calculated based on the semi-real situations, different generation and load characteristic curves were defined and used in GWO process. The applied generation characteristic curves were calculated based on recorded historical data of different weather stations in Germany. The used data for calculation of characteristic curves are the measured solar irradiations and the wind speeds from Germany's national meteorological service in 2018 [50]. The methods for calculating the output power of RE generators are described in Annex 3. The synthetic power network contains also different types of loads with different load characteristic curves. They represent three types of consumers: i.e. household, industrial and rural consumers. The characteristic curves are based on standard load profiles from German Association of Energy and Water Industries and are presented in Annex 4 [51].

Figure 3-4 represents the details of the MATLAB optimization process. The presented GWO algorithm is formed based on the economic model for calculation of NPC (presented in previous chapter) to minimize the costs or to maximize the PUF while reaching a certain DLC. As it can be seen from the flow diagram, the algorithm starts by declaring the GWO parameters. In the first step, it will be indicated which DLC or PUF is to be achieved, how many search agents (grey wolves) will be assigned for this task, how many iterations are allowed to be performed and how many cells for the cellular approach are considered.

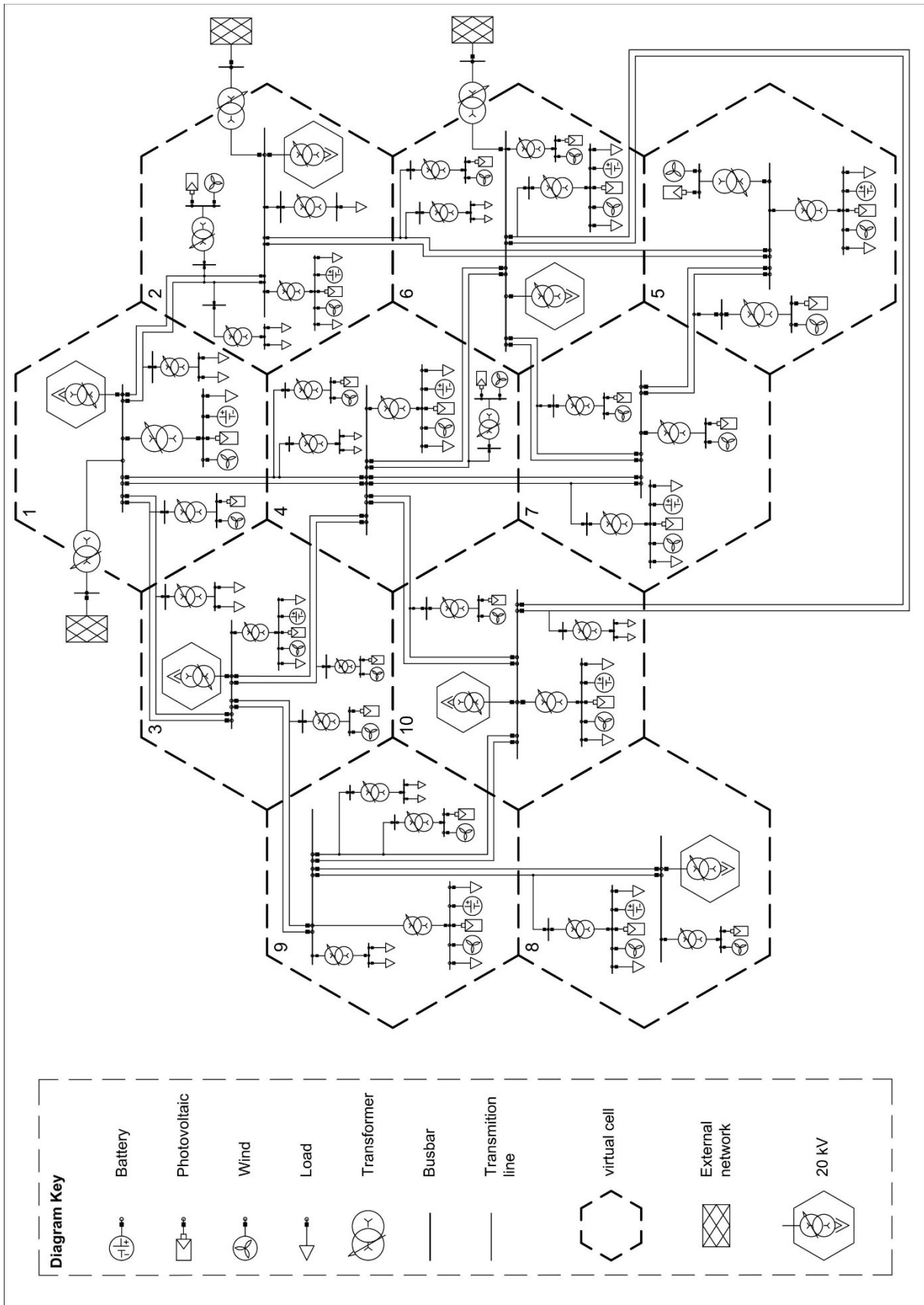


Figure 3-3: Simplified power network for cellular analysis

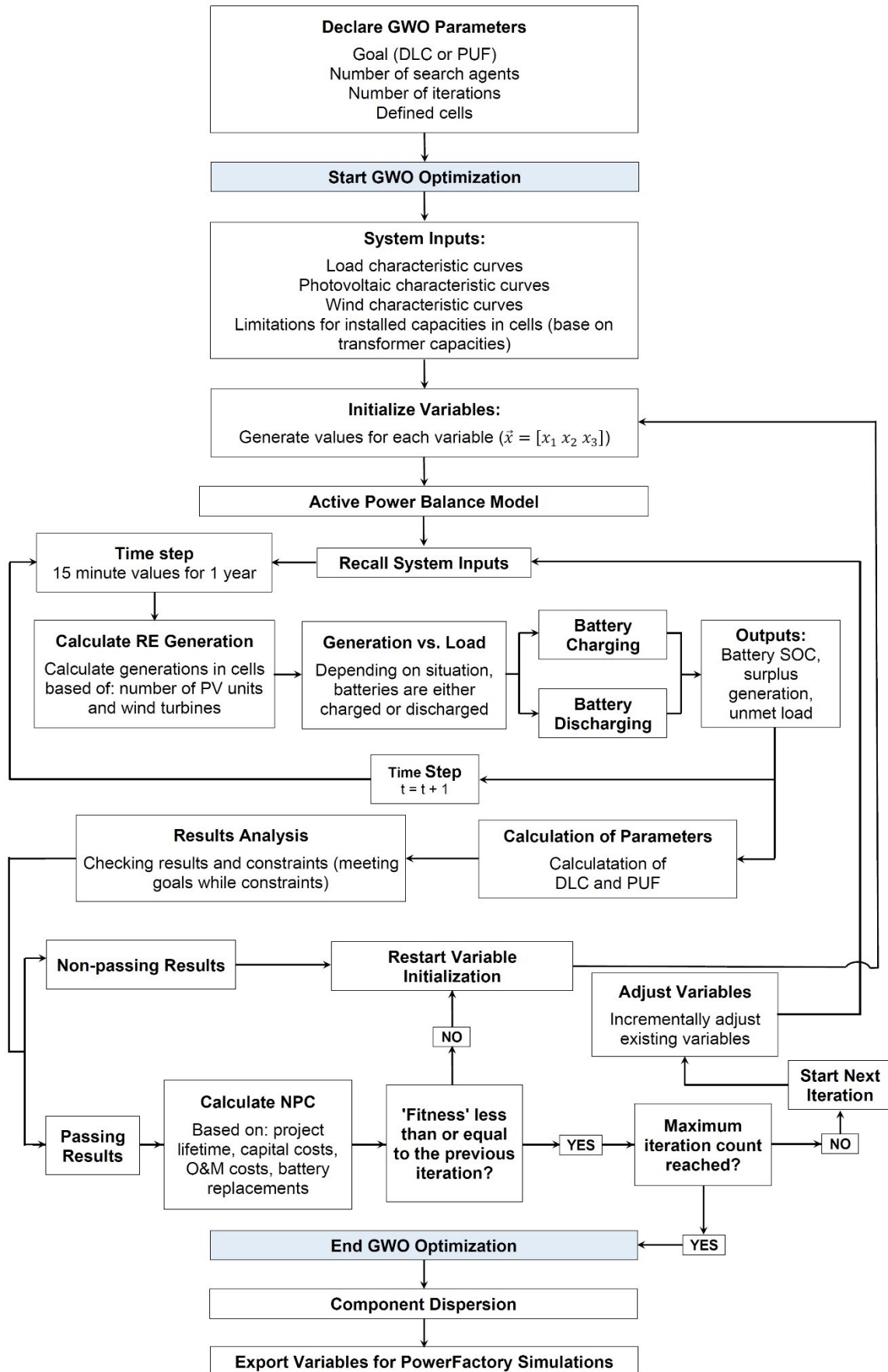


Figure 3-4: Flow diagram of MATLAB optimization model

In the next step the characteristic curves for loads, wind and photovoltaic generation units are defined and limitations of the connection points for new generators in each zone are specified based on transformer capacities.

After that, the search agents are created to search the solution space. By means of that, different combinations of RE generators in combination with battery units are created. Based on the number of units, generation from wind and photovoltaic units are calculated in the corresponding cells. Then the generation profile of each cell over the whole year is separately compared with the load situation of that cell. With the aid of that, charging and discharging procedure of the battery units are calculated. Figure 3-5 presents the charging and discharging logic of the battery modules. Subsequently, parameters like DLC, PUF and NPC are calculated and the results are compared based on the defined constraints.

If the results do not conform to the constraints, variables will be initialized again. If the results comply with the constraints, NPC will be calculated. Here, if the results are better than the previous iteration, the search agents will be ranked accordingly ($\alpha, \beta, \delta, \omega, etc.$) and this solution will be considered as the starting point for the next iteration. Otherwise, the results will be recorded, but the starting point for next iteration will stay the previous solution. After reaching the maximum iterations, it will be clear what combinations of wind, photovoltaic and battery units are needed to minimizing the NPC or maximizing the PUF. It is important to mention that the maximum number of required iterations depends on the defined number of search agents and can only be determined by means of trial and error procedure. In this dissertation, after several tests the author decided for 100 search agents and 5 iterations for a solid search of the solution space.

It must be noted that the GWO outcomes for the combinations of the RE generators and battery modules only underline the number of needed units in each cell and do not specify their place of integration. Therefore, a dispersion strategy is provided which assigns the units to the best possible connection point within the cell. This strategy will be explained in the section 3.3.3.

Mathematical Description of GWO

Considering the point that the power demand is supposed to be covered by three types of technologies (wind, photovoltaic and batteries), the optimization problem can be written in form of mathematical description as follows:

Considering the vector of the three technologies as:

$$\vec{x} = x_1 + x_2 + x_3 \quad (3-1)$$

The objective function to be minimized (optimization approach 1) will be:

$$F(NPC(\vec{x})) = \left(I_0(x_1) + \sum_{t=1}^{t=25} \frac{E_t(x_1)}{q^t(x_1)} \right) + \left(I_0(x_2) + \sum_{t=1}^{t=25} \frac{E_t(x_2)}{q^t(x_2)} \right) + \left(I_0(x_3) + \sum_{t=1}^{t=25} \frac{E_t(x_3)}{q^t(x_3)} \right) \quad (3-2)$$

The objective function can also be defined based on the second optimization approach to maximize the PUF as follow:

$$F(PUF(\vec{x})) = PUF = \frac{\int \min\{P_L(t), P_{DG}(t, \vec{x})\} dt}{\int P_{DG}(t, \vec{x}) dt} \quad (3-3)$$

Subjected to the constraint:

$$DPA = \frac{\int \min\{P_L(t), P_{DG}(t, \vec{x})\} dt}{\int P_L(t) dt} \quad (3-4)$$

For $P_{DG}(t, \vec{x})$ defined as:

$$P_{DG}(t, \vec{x}) = P_{wind}(t, x_1) + P_{photovoltaic}(t, x_2) + P_{battery}(t, x_3) \quad (3-5)$$

With variable ranges defined as follows (N–0 contingency):

$$0 \leq \begin{Bmatrix} x_1 \cdot P_{wind} \\ x_2 \cdot P_{photovoltaic} \\ x_3 \cdot P_{battery} \end{Bmatrix} \leq \text{defined transformer capacity at connection point} \quad (3-6)$$

In the above mentioned equations, the parameters and terms are defined as:

$\vec{x} = [x_1 \ x_2 \ x_3]$ Variables vector for three technologies (wind, photovoltaic and battery), specifying number of considered standard modules

$F(NPC(\vec{x}))$
or $F(PUF(\vec{x}))$ Fitness functions

I_0 CAPEX as the initial cash outflow

E_t OPEX at year t

q discount factor

t lifetime of the investment project in years in Equation 3–2 and time step in other equations

$P_L(t)$ Active power of loads

$P_{DG}(t)$ Active power from decentral generation units

Having the above mentioned description in mind, a model for charging and discharging logic of batteries is developed for the connection point with RE generators. This logic is presented in Figure 3-5. Based on this logic, if the RE generation at a connection point is bigger than the demanded active power of loads, battery modules will be charged, otherwise they will discharge. It is obvious that the charging and discharging behavior of the batteries are subjected to the following variables:

- 1) Available power for charging ($P_{available}(t)$) or lack of power for discharging ($P_{lack}(t)$) at the specific node.
- 2) Charging and discharging limits of batteries ($P_{ch}(t)$, $P_{dch}(t)$, SOC_{max} and SOC_{min}).
- 3) Available stored energy in batteries ($E_{bat.}(t)$) and its limitation ($E_{bat. max}$)

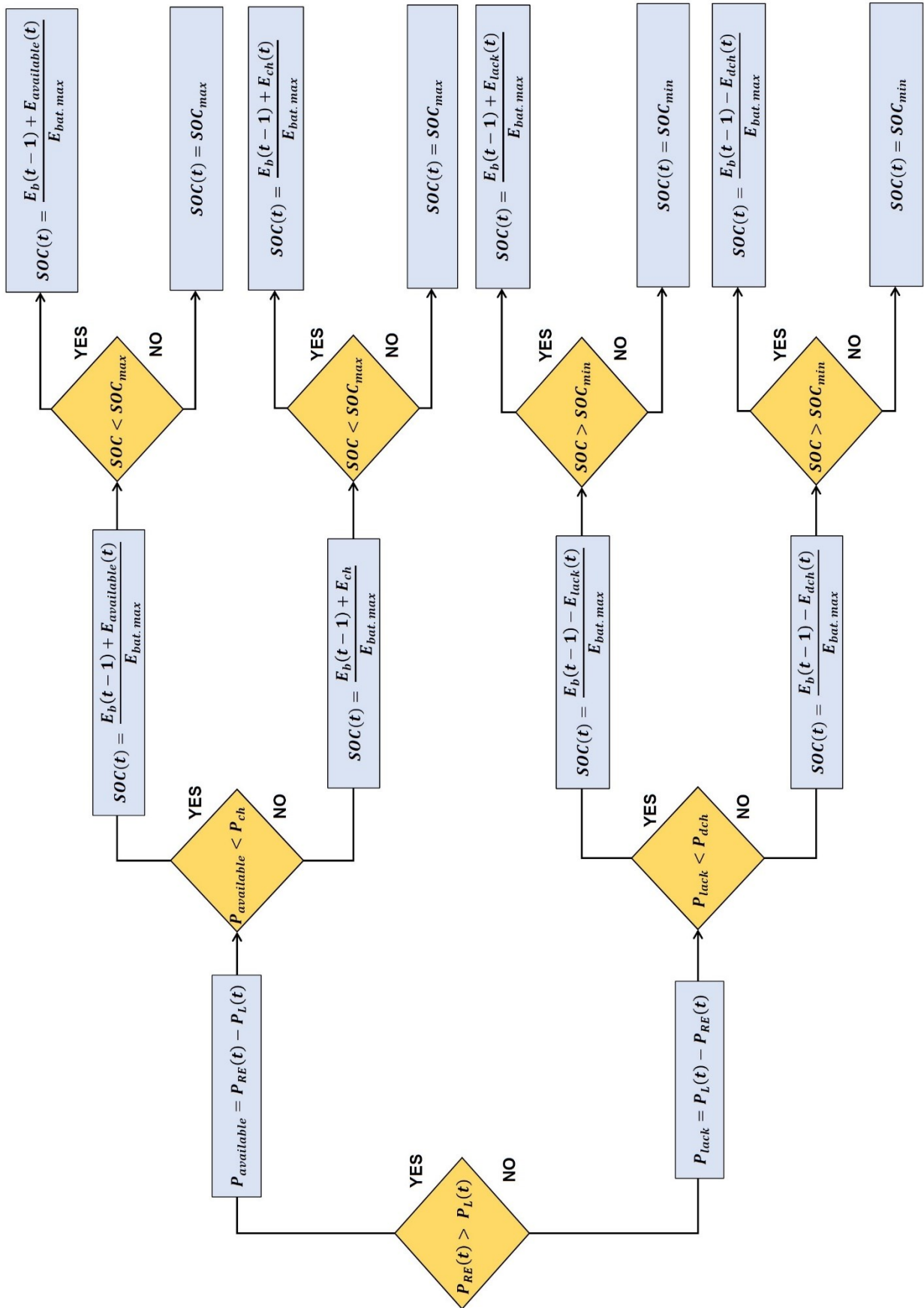


Figure 3-5: Charging and discharging logic of battery modules

Other parameters in Figure 3-5 are defined as follows:

$P_{RE}(t) = P_{wind}(t) + P_{photovoltaic}(t)$	Active power from wind and photovoltaic units
$P_{available}(t) = P_{RE}(t) - P_L(t)$	Available power for charging of battery modules
$E_{available}(t) = P_{available}(t).T$	Available amount of energy that can be stored in battery modules in one time step
$P_{lack}(t) = P_L(t) - P_{RE}(t)$	Lacked power to supply the loads
$E_{lack}(t) = P_{lack}(t).T$	Lacked amount of energy to supply the loads in one time step
$P_{ch}(t)$	Active power limit for charging of batteries
$E_{ch}(t) = P_{ch}(t).T$	Maximum amount of energy that can be stored in battery modules in one time step
$P_{dch}(t)$	Active power limit for discharging of batteries
$E_{dch}(t) = P_{dch}(t).T$	Maximum amount of energy that can be retrieved from battery modules in one time step
$SOC(t)$	State of charge of battery modules in %
SOC_{max}	Maximum limit for the state of charge of battery modules in %
SOC_{min}	Minimum limit for the state of charge of battery modules in %
$E_{bat.}(t)$	Stored amount of energy in battery modules
$E_{bat. max}$	Maximum amount of storable energy in battery modules

3.3.2. Inputs and Assumptions of the MATLAB Optimization Model

In the previous section the optimization methodology was explained in details. In following, the defined inputs and parameters of the GWO process together with the dispersion strategy are listed:

- Definition of load characteristic curves.
- Definition of RE characteristic curves.
- Definition of the cells and the connection points inside them.
- Definition of the exact connection point for loads and preserving N–1 contingency for them. The maximum limit for integration of RE generators is defined base on the transformers' capacities.
- Consideration of N-0 contingency for the connection point without loads and N–1 contingency for the connection points with loads.

- Definition of DLC as constraint.
- Declaration of number of search agents.
- Declaration of number of iterations.

Furthermore, the following assumptions are made to form the optimization methodology:

- It is supposed that the synthetic power network has already integrated RE generators and can cover a portion of its own consumption. This portion accounts to a DLC that equals to 20%. This assumption is made based on the fact that the synthetic power network shall simulate the character of a distribution network in Germany, knowing that there are plenty of RE technologies already in system.
- The optimization is performed for a project lifetime of 25 years. This assumption is needed for calculation of NPC of the project and the economic factors in calculations are considered as presented in Table 3-1.

Technology	Size	CAPEX	Replacement Cost in % of CAPEX	Annual Operational Cost	Annual Fixed Cost	Lifetime
Photovoltaic	1.053 MVA	700 €/kW	-	17.5 €/kW	-	25 years
Wind Turbine	3.5 MVA	1750 €/kW	-	30 €/kW	0.005 €/kWh	25 years
Battery Li-ion	0.375 MWh	200 €/kWh	60%	-	-	10 years

Table 3-1: Economic assumptions for MATLAB calculations (data based on: [31] and [33])

- The initial SOC of batteries is considered to be 25%, the minimum SOC and the maximum SOC are defined to be 25% and 100% respectively.
- Batteries are considered as decentral units at connection points that only support the same connection point in case of lack generation or react to over generations.

3.3.3. Outputs of MATLAB Optimization Model

In the previous sections the GWO model was described in details. At this point, the optimization model revealed the number of required generators or batteries inside each cell. In the next step, the output results shall be prepared for integration in PowerFactory simulation models. In this regard, the RE generators and batteries must be assigned to a specific connection point and it is realized by the dispersion strategy. The dispersion of components within the discrete busbars inside the cells is based on relative electricity consumption and the available capacity of transformers using discrete weighted random variable distribution. In the case of generators and battery banks, each variable is discrete, meaning the distribution will be integer-based and countable. The discrete weighted random distribution of components throughout each cell is performed in three stages as explained below [52]:

- 1) Weighted discrete distribution of photovoltaic (N_{pv}) and wind generators (N_{wind}) by relative annual electricity consumption.
- 2) Weighted discrete distribution of photovoltaic (N_{pv}) and wind generators (N_{wind}) by transformer limitations.
- 3) Weighted discrete distribution of battery modules ($N_{battery}$) by relative annual electricity consumption.

The first stage compares the annual electricity consumption at the specific busbar to the total consumption of the cell. This is shown as an example of a cell with six busbars in Figure 3-6. It is clear that the busbars with a higher annual electricity consumption have also a higher probability for receiving RE generators in the dispersion process. It must be noted that allocation of RE generators with this method is for reducing the overall losses of the system. In other words, the smaller the distance of the generators from the consumers, the less power must be transported (lower power flow in the system) and therefore there are less losses in the whole system.

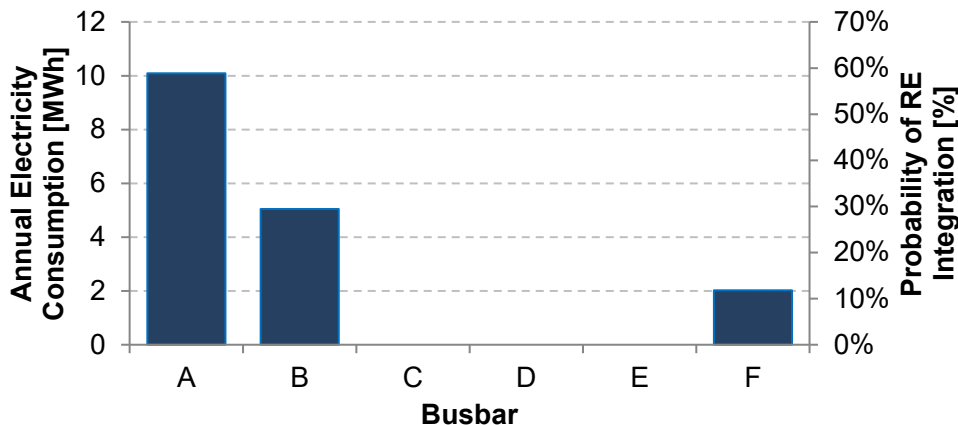


Figure 3-6: Bar diagram of the annual electricity consumption for a cell with six busbars

At the first stage, only busbars containing both conditions, i.e. annual electricity consumption and the free transformer capacities for integration of RE generators, are considered. The dispersion of components is then performed by the generation of random numbers and the weighted probabilities. If the components are integrated at a specific connection point up to the maximum available capacity (transformers limits), then the distribution probability of that busbar will be defined as zero. In result, the remaining busbars receive the additional components based on their probabilities.

In the case that all busbars with loads are filled with integrated components up to their transformer limits and there are still components remained for allocation, the first stage ends and the second stage of the dispersion process begins. At the second stage, the remaining components are distributed based on the weighted discrete distribution of the free transformer capacities. Following the previous examples, busbars A, B and F with loads are disqualified Re generators are integrated up to their limits. Therefore, busbars C, D and E can be allocated for remaining components and thus have positive probabilities of allocation as shown in Figure 3-7.

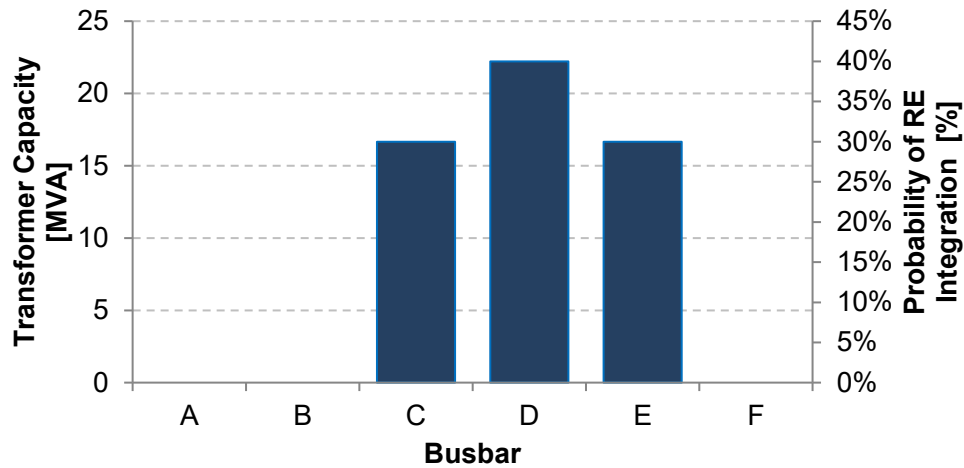


Figure 3-7: Distribution diagram based on transformer capacity for a cell with six busbars

Finally, stage 3 distributes the total number of batteries (N_b), using weighted discrete distribution probabilities based on relative annual load among busbars with both connected load and generators. Table 3–2 illustrates the example results of the dispersion method with exact number of units from each technology that must be connected to a special connection point.

Busbar	N_{pv}	N_{wind}	$N_{battery}$	Remarks
A	0	0	0	Busbar A has already reached its limits.
B	0	1	0	Busbar b has only a free capacity for integration of a wind turbine.
C	5	27	15	-
D	0	5	0	-
E	0	2	0	-
F	2	9	16	-

Table 3-2: Dispersion results for a cell with six busbars

After the dispersion process, the allocated capacities for each specific busbar are defined and the results are used as inputs for the PowerFactory simulation models.

3.4. PowerFactory Simulation Model

In previous sections, the overall structure of the synthetic power network is pointed out and the topology is presented in Annex 2. The synthetic power network in this dissertation is developed in PowerFactory to simulate the behavior of real distribution power networks in Germany. The QDS in PowerFactory is the second step of the solution process. The purpose

of the QDS simulations is to evaluate and validate the MATLAB optimization results in terms of feasibility and applicability in real situations.

Each MATLAB solution from the previous step, is different from the other solutions. It is unique and specifies the number of RE generators and batteries with their exact place of integration in the synthetic power network. Therefore, for each solution a new corresponding PowerFactory model is defined. In the first step, QDS for a period of one year (in 15-minute steps) is executed for PowerFactory models and critical months and situations are identified. Critical months and situations are defined by author as situations where the components of the synthetic power network are overstrained. Overstraining of the synthetic power network shows itself in QDS in form of severe convergence problems. It can happen due to several reasons; for instance: very high or very low RE generation, critical changes of power flow direction within a short period of time, voltage stability problems or overloading of the equipments. Based on the preliminary results of the QDS, two different critical months are chosen for profound analysis in next steps. The reason for choosing critical months for detailed analysis is the fact that performing the QDS over the period of one year is very time consuming. Based on the experiences of the author in simulations, if the evaluations of the QDS for critical months are passed successfully, the evaluations of the QDS over the whole year will also pass the tests.

The first QDS results in PowerFactory manifest considerable differences and doubts in practicability of MATLAB results and the necessity of a deep grid analysis. The reason for differences are understandable as the MATLAB optimization model is developed based on active power balance between generation and consumption within the cells of the synthetic power network. However, the reactive power demand within the cells can drastically affect the results of PowerFactory simulations. Therefore, recognition of the appropriate reactive power strategy by means of QDS in PowerFactory is one of the most important goals.

In this regard, the reactive power demand of the synthetic power network is analyzed firstly and minimum requirements are defined. Based on the results of the analysis, two different QDS-models (Q(U) and Q(P) models) for controlling the reactive power provision of the RE generators are developed in PowerFactory and integrated into the simulation models. The const. Q and Cos Phi controlling strategies are here neglected as these strategies could not meet the minimum Q provision requirements of the complex power system which results in severe convergence problems in simulations. The QDS are then performed with both Q controlling strategies for critical months. The power flow situations, interactions with the external networks, loading of the equipments and voltage stability at main connection points are stored for further analysis. Furthermore, sensitivity analyses (dU/dQ and dU/dP) around the operational points are carried on to identify the connection points that are more sensitive than others to changes in infeed-power, as it is the case with volatile generating units. The analyses also helps to verify the voltage stability problems in connection points.

Based on the results of the QDS with Q(U) and Q(P) controlling strategies and the sensitivity analyses, it can be said which Q controlling strategy is more suitable for each specific cell. In this regard, a hybrid Q controlling strategy (consisted of Q(U) and Q(P)) is assigned to the

RE generators. In other words, each cell receives a specific Q controlling strategy based on its specific requirements.

In the next step, QDS with the hybrid Q controlling strategy is performed and the results are evaluated. If the new simulations show better convergence than the previous simulation results with Q(P) and Q(U) strategies, then the results can be viewed as solid solutions. If the new simulations face more convergence problems than the previous simulations, then it is tried to find and solve the source of the instabilities by means of small modifications in simulation settings or Q controlling strategies. If the convergence problems are solved, the results can be viewed as solid. If not, it is clear that MATLAB optimization could not deliver a feasible solution.

In the last step, the N-1 contingency analysis is performed. The contingency calculations show the behavior of the synthetic power network under outage of transformers or distribution lines. If the contingency calculations ensure the N-1 safety of the operation, the results can be considered as acceptable. Otherwise, the suggested solution from MATLAB can be considered as a solution with high operational risk. Figure 3-8 represents the steps of the PowerFactory simulation process.

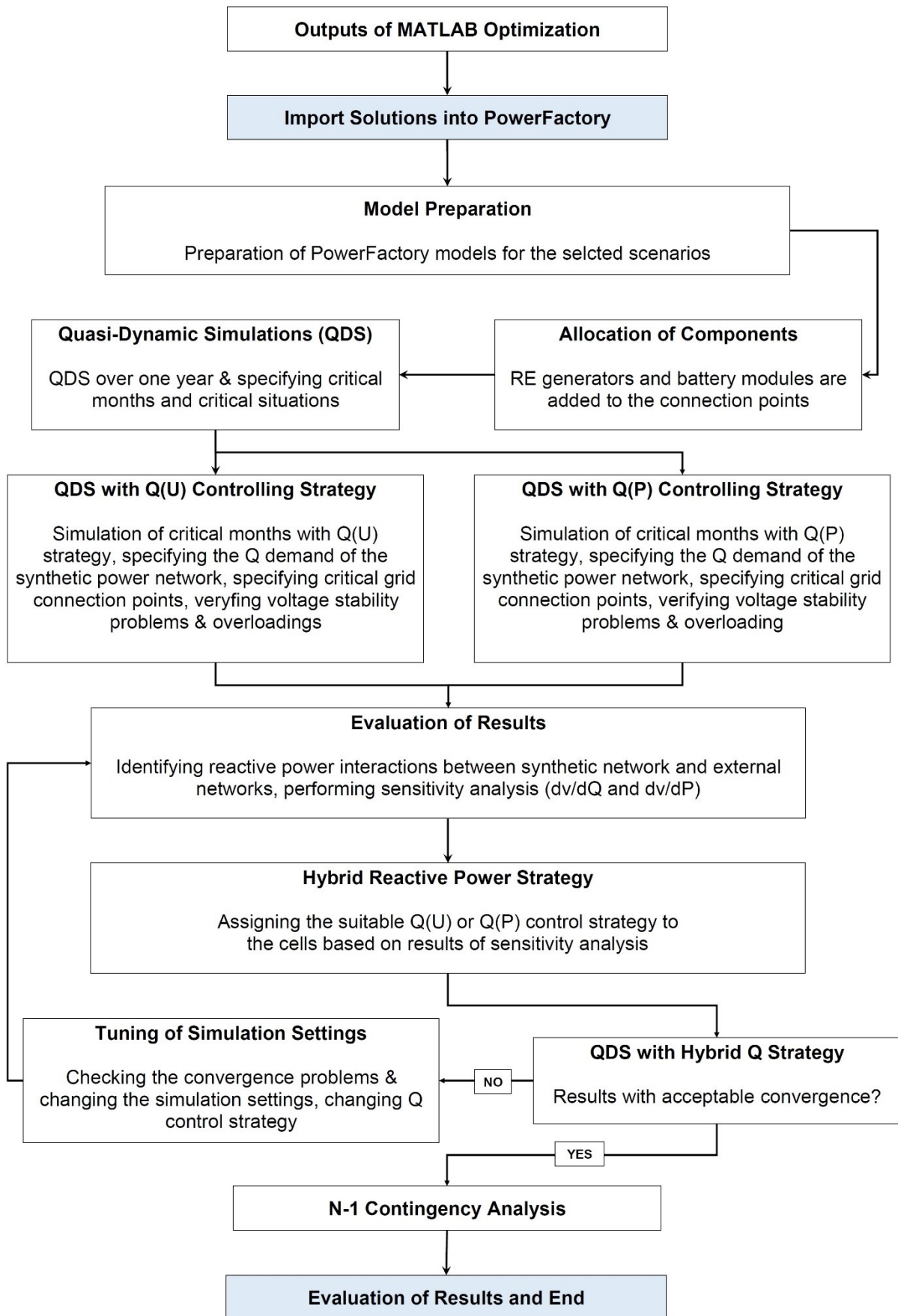


Figure 3-8: Flow diagram of PowerFactory simulation model

3.4.1. Synthetic Power Network

The 380 kV voltage level in PowerFactory models is realized as external connections to the synthetic power network. There are three 380 kV connections to the synthetic power network which play key roles in stability and support of the whole power network. These connections are established throughout 380/110 kV transformers in cells one, two and six. The connection points can be seen in Annex 2 where the topology of the synthetic power network is presented.

It is important to mention that the arranged external networks (380 kV grids) are modeled as slack connections. In other words, the external networks control the voltage and angle of the reference busbar in QDS. The reference set point for the reference busbars is considered as 1 p.u. with the angle of 0 degrees.¹¹ In this regard, the external network connections interact actively with the cells in provision of P and Q.

From the presented network topology in Annex 2, it is clear that the 110 kV distribution network builds the most visible share of the synthetic power network with almost 900 km of overhead lines. The substations with double busbar systems are considered as the central points of the ten virtual cells. These substations are interconnected via overhead lines to each other and via 110/20 kV transformers to 20 kV sub-networks, consumers and RE parks. Apparently, the 110 kV distribution network in this dissertation shapes a well-interconnected synthetic power network.

The 20 kV voltage level in this dissertation plays a special role in understanding the effect of the RE technologies on Medium Voltage Networks (MVNs). In this regard, three different types of 20 kV distribution networks were developed and connected into six different cells inside the synthetic power network. The structure of the MVNs is developed based on European configuration of CIGRE benchmark for medium voltage distribution networks [53], [54]. This type of network has two connection points to High Voltage Network (HVN) via 110/20 kV transformers. The feeders are connected to each other via switches which enable the operation as two radial feeders or as a ring network. In this dissertation, the ring configuration of the 20 kV sub-networks will be considered for simulations. It must be mentioned that the benchmark allows the flexibility in design of this type of network. In this regard, the author has integrated different load characteristic curves to shape three different types of 20 kV sub-networks. By means of that the behavior of a rural, an industrial and an urban sub-network can be simulated. Principally the difference between these types of sub-networks are in the length of cables and types of consumers. The rural sub-network has a length of 51 km with maximum 24 MW of active and 2.4 Mvar of reactive power consumption. The industrial sub-network has a length of 27 km with maximum 40 MW of active and 18 Mvar of reactive power consumption. The urban sub-network has a length of 30 km with maximum 22 MW of active and 1.3 Mvar of reactive power consumption. The topologies of

¹¹ In special cases where the power network has a strong inductive or reactive character, the set points might deviate from the standard values which are mentioned here.

the 20 kV sub-networks are presented in Annex 2. Details of the components and their internal parameters are provided in digital Annex under PowerFactory models.

3.4.2. Components of the Synthetic Power Network

The wind, photovoltaic and battery units in PowerFactory simulation model are defined as three-phase static generators. The RE units are featured with the following capacities in simulation models:

- Apparent power of wind turbines is equal to 3.5 MVA
- Apparent power of photovoltaic units is equal to 1.053 MVA
- Battery units with a storage capacity of 0.375 MWh

Based on the required capacity at a specific connection point, the number of parallel units is defined in the simulation models to form a wind park, a photovoltaic park or a storage plant. Depending on the place of integration in the synthetic power network, the RE units might have different outputs. Annex 3 presents the methodology for calculation of generators outputs which are based on statistical data from Germany's national meteorological service. The calculated outputs are stored and integrated as characteristic curves into the simulation models.

Furthermore, the technical connection rules for MVN and HVN, namely: VDE-AR-N 4110 and VDE-AR-N 4120, define the operational limits for the RE generators inside the simulation models. The technical frameworks and the operational limits are presented in Annex 1. It is clear that the active power production of the RE generators depends on the calculated characteristic curves and the reactive power production depends on LFC, the assigned Q controlling strategy and the operational limits of RE generators.

Reactive power provision via RE generators is realized through Q(P) or Q(U) controlling strategy. In Q(P) controlling mode, a characteristic curve is calculated and integrated into generator models which is based on Q requirements of the whole synthetic power network. For Q(U) controlling mode, a QDS model is developed and integrated into the generators model. This QDS model is programmed in a way that reacts to voltage discrepancies at grid connection point. The high voltage side of transformers at connection point is considered as the setpoint and the Q provision is arranged in a way to compensate the discrepancies. The developed QDS model provides the opportunity to adjust parameters like reference voltage, dead band and gradients in provision of reactive power. These parameters play a crucial role and irrational values threaten the convergence of simulations. Figure 3-9 presents the working mechanism of the Q(U) controller.

It is worth to mention that in using of the Q(U) strategy special attention should be paid to the adjustable parameters of the local controller at generators. As provision of reactive power from generators must not contradict the tap changing of transformers. If the parameters are not adjusted correctly, the QDS model and tap changer might operate against each other which causes convergence problems in simulations.

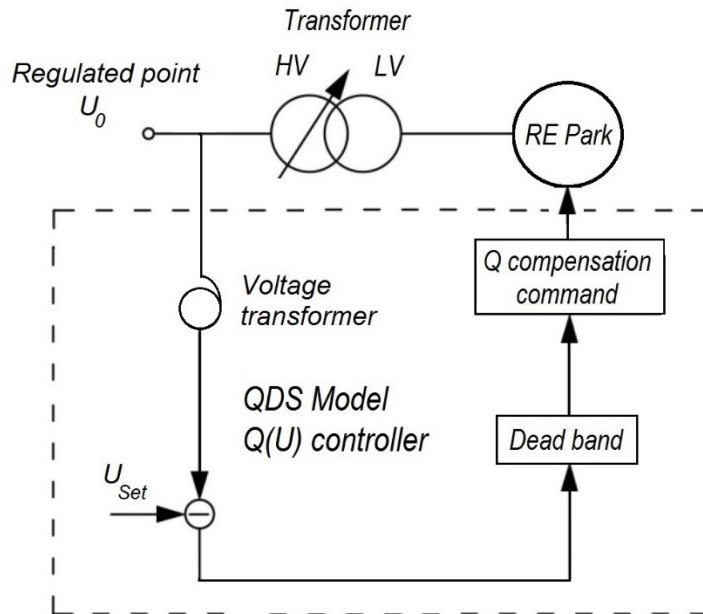


Figure 3-9: Q(U) controlling strategy in generators (QDS model)

Tap changers are located at high voltage side of the transformers which react to voltage discrepancies on lower voltage side. The tap changing mechanism of transforms is schematically illustrated in Figure 3-10.

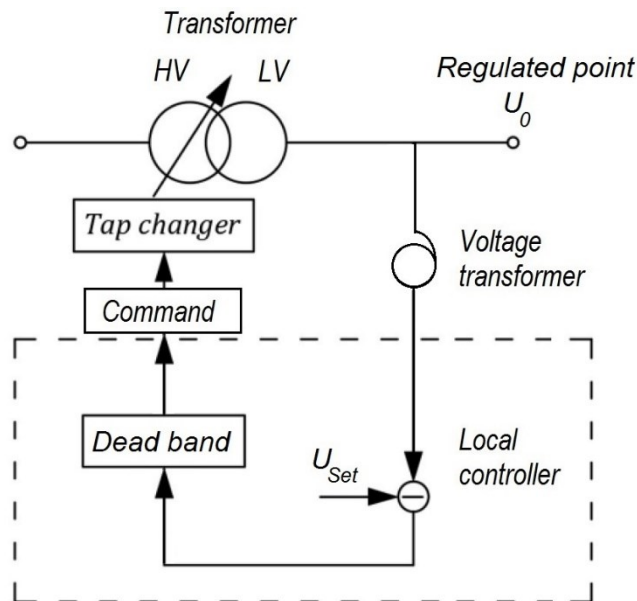


Figure 3-10: tap changing mechanism in transformers

The battery modules in simulation models are developed as local storage facilities which exist beside RE generators. The battery modules support the network in case of lack of production at the connection point. In this regard, a QDS model is developed to control the charging and discharging of the battery modules. The battery modules in PowerFactory simulations are considered also as static generators which were equipped by the developed QDS model. Figure 3-11 illustrates schematically the working mechanism of the developed QDS model. In the first step the AC power flow through the connection line is measured.

Then based on the amount of power flow and its direction, the charging or discharging strategy of the battery modules can be defined. In case of the excess active power production (power flow from T1 to T0), the battery modules will be charged and in case of deficiency (power flow from T0 to T1), the battery modules will be discharged. Figure 3-12 illustrates schematically the behavior of batteries during charging and discharging.

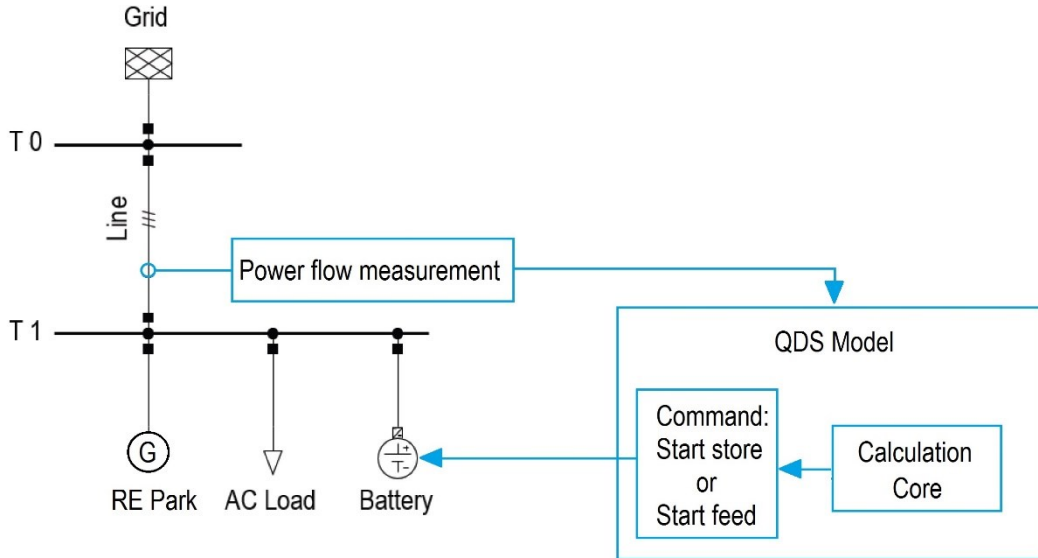


Figure 3-11: QDS model for controlling of batteries charge/discharge process

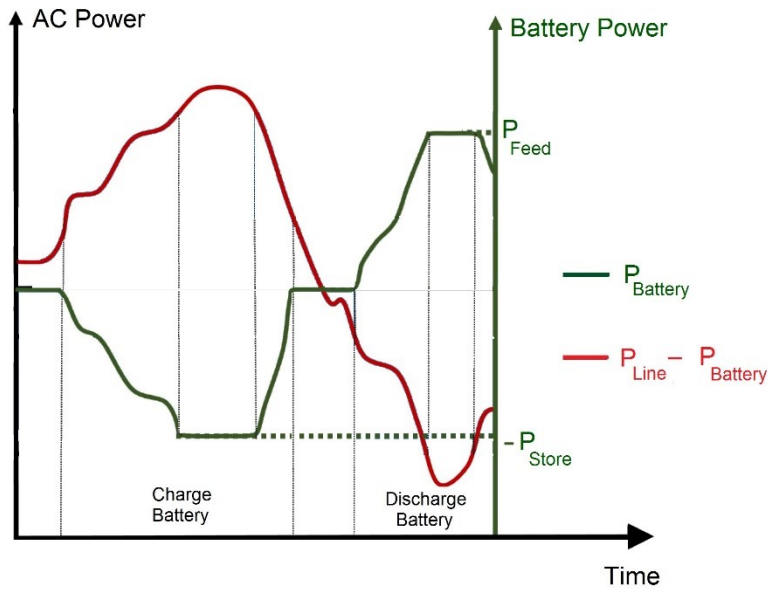


Figure 3-12: Charging and discharging logic of battery modules

According to Figure 3-11, for the measuring point it can be written:

$$P_{measurement}(t) = P_{RE\ Park}(t) + P_{Load}(t) = P_{Line}(t) - P_{Battery}(t) \quad (3-7)$$

Based on this correlation, equation 3-8 defines charging and discharging behavior of battery modules. Parameters of the QDS model for a standard battery module (with the storage capacity of 0.375 MWh) are presented in Table 3-5.

$$\begin{cases} P_{\text{measurement}}(t) > 0 & \rightarrow & \text{charge battery modules} \\ P_{\text{measurement}}(t) = 0 & \rightarrow & \text{battery modules inactive} \\ P_{\text{measurement}}(t) < 0 & \rightarrow & \text{discharge battery modules} \end{cases} \quad (3-8)$$

Parameter	Description	Value
E_{ini}	Battery storage capacity [MWh]	0.375
SOC_{ini}	Initial state of charge [%]	25
SOC_{min}	Minimal state of charge [%]	25
SOC_{max}	Maximal state of charge [%]	100
P_{Store}	Rated charging power [MW]	0.1
P_{Feed}	Rated discharging power [MW]	- 0.1
P_{Battery}	Power that flows to/from the battery [MW]	Calculated

Table 3-3: Parameters of a standard battery module used in QDS model

In the developed QDS model internal losses of the battery modules and losses during AC/DC conversion are considered to be zero. The initial SOC of batteries is assumed to be 25%. The charging and discharging behavior are also limited to 25% and 100% as minimum and maximum permissible values. It is clear that in case of having parallel battery units, parameters E_{ini} , P_{Store} and P_{Feed} will be updated accordingly.

3.4.3. Outputs of PowerFactory Simulations

Based on the structure of the simulations (presented in Figure 3-8), the QDS are performed. The first outputs of the simulations are the overview about the LFCs and the convergence state of simulations. The number of failed LFCs (not converged time steps) and calculations hours are solid criteria in the first moment to evaluate the practicability of the proposed solution. Few numbers of failed LFCs in simulations are acceptable and the solution can be considered as a potential option for practical implementation. However, the time periods around the failed LFCs are simulated and investigated further to detect the reason for failed LFCs. Sometimes small adjustments of the simulation parameters can change the results.

In the next steps, the saved results from QDS are processed and different types of diagrams are created. The diagrams provide a great contribution in further investigation and evaluation of the results. At the end, the clear outcome of the PowerFactory simulations is the answer to one question: whether the suggested solutions from the MATLAB optimization are practical and tolerable in real operational situations? Inspection of the PowerFactory outcomes reveals clearly the answer to this question. Details about critical situations in network operation and violation of the technical boundaries are found by the results of QDS in PowerFactory.

4. Chapter: Optimization and Simulation Results

4.1. Optimization Approaches and Results

In section 3.3 of the previous chapter, the MATLAB optimization methodology was introduced extensively. It was expressed that the GWO is programmed for two different approaches with different goals. In the first approach, GWO follows the strategy to minimize the NPC while reaching a certain DLC. In the second approach, it pursues a strategy to maximize the PUF while reaching a certain DLC.

It is obvious that both of the approaches have something in common that is reaching a certain DLC as a determining condition. The results of the simulations show that due to different characteristics of the cells (different types of loads and generators) and power transmission limitations (limited capacities of transformers), some cells reach their highest possible DLC level earlier than the others. Simulations of both approaches prove that battery modules have a central role in achieving higher DLC values. However, solutions with higher DLCs correspond to significant higher costs in comparison to solutions with lower DLC goals. Figure 4-1 represents the status of the achieved DLC versus the goal DLC in each cell and the entire synthetic network. Simulations with both GWO approaches show almost similar DLC results, though having different cost factors. The reason for the similarity is the fact that DLC is the defined boundary condition for both approaches. The differences of the two approaches manifest themselves in form of costs and number of components.

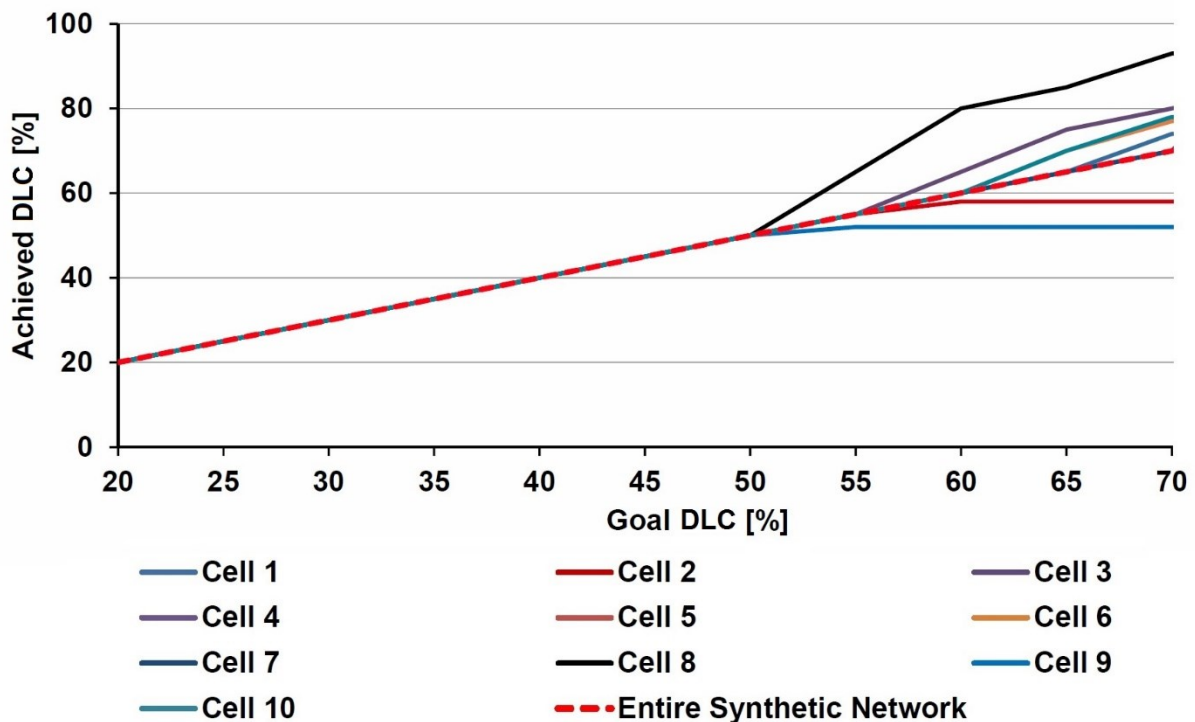


Figure 4-1: Achieved DLC versus goal DLC in GWO approaches

Table 4-1 represents an overview of the cells and the entire synthetic network in achieving a certain DLC. As it can be seen, some cells reach their upper limits after 50% DLC. However, the algorithm can be programmed in a way to continue the calculations to reach higher DLC values. For this purpose, the neighboring cells might support the cell which has already

reached its maximum installation limit. For instance, it can be seen from Figure 4-1 or Table 4-1 that the maximum achievable DLC value for cell 9 is 52%. From this point, cell 8 is the chosen neighboring cell in the calculation model for supporting cell 9 to fulfill its power deficiencies for achieving higher DLC values.

Cell Number	Goal DLC [%]										
	20	25	30	35	40	45	50	55	60	65	70
	Achieved DLC [%]										
Cell 1	20	25	30	35	40	45	50	55	60	65	74
Cell 2	20	25	30	35	40	45	50	55	58	58	58
Cell 3	20	25	30	35	40	45	50	55	65	75	80
Cell 4	20	25	30	35	40	45	50	55	60	65	70
Cell 5	20	25	30	35	40	45	50	55	60	65	70
Cell 6	20	25	30	35	40	45	50	55	60	70	77
Cell 7	20	25	30	35	40	45	50	55	60	65	70
Cell 8	20	25	30	35	40	45	50	65	80	85	93
Cell 9	20	25	30	35	40	45	50	52	52	52	52
Cell 10	20	25	30	35	40	45	50	55	60	70	78
Entire Synthetic Network	20	25	30	35	40	45	50	55	60	65	70

In this table, the blue color shade is a representative of simplicity of convergence and the red color shade is a representative of difficulty of convergence for GWO algorithm in finding solutions for a certain DLC.

Table 4-1: MATLAB GWO process in searching a certain DLC in different scenarios

The results of the MATLAB GWO for the first approach is illustrated in Figure 4-2. As it can be seen from the diagram, photovoltaic parks have the dominance in most of the solutions. By increasing DLC goal value, wind technology contribution starts to gain importance. The reason for obtaining of importance of Wind technology in higher DLC solutions is the fact that in general the yearly production per installed MW is relatively higher than the photovoltaic

technology¹². However as stated in the second chapter, the related expenses of wind technology in comparison to photovoltaic over the calculated time span of 25 years are relatively higher. The battery modules also start to gain importance in an exponential pattern with increasing DLC values. This behavioral pattern is comprehensible as achieving higher DLC values is only possible with the contribution of storage technologies. Though this contribution brings about more rapid increase of the NPC values. Figure 4-3 represents the NPC for the scenarios of the first GWO approach.

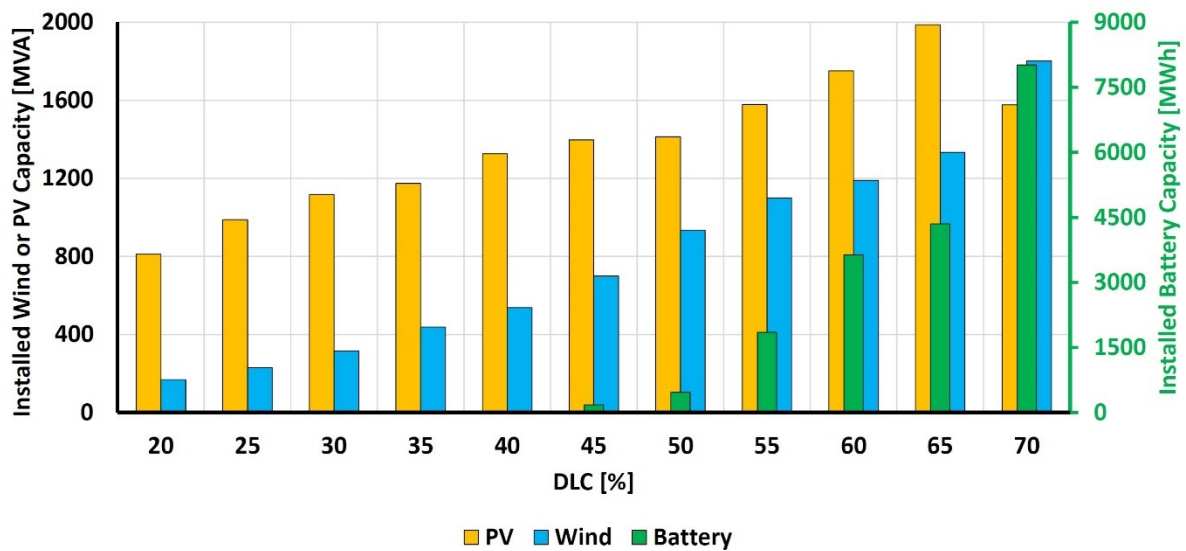


Figure 4-2: Installed capacities in first approach scenarios of MATLAB GWO

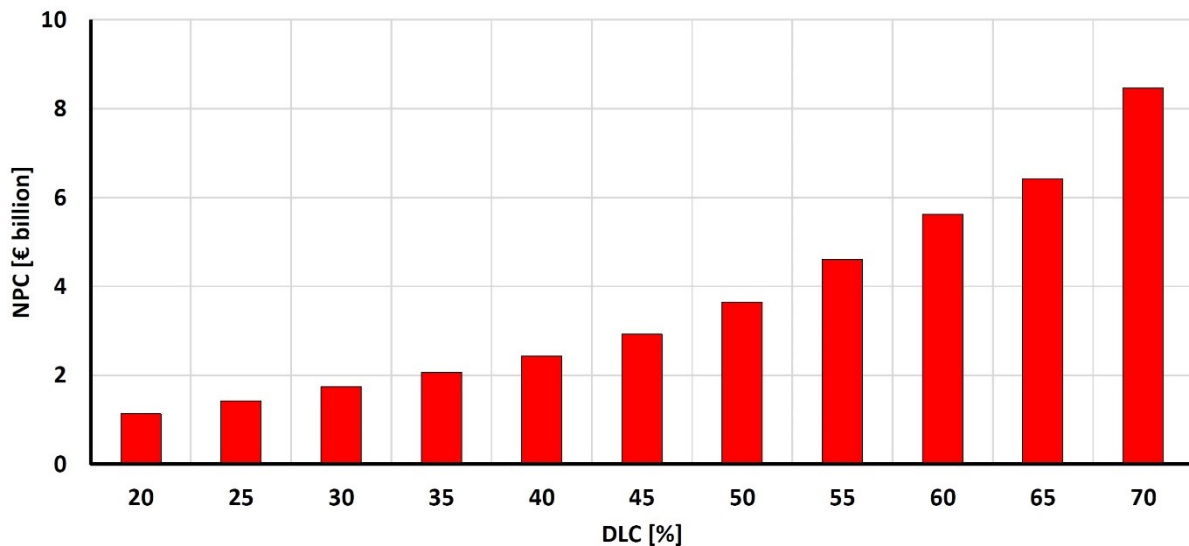


Figure 4-3: NPC in first approach scenarios of MATLAB GWO

GWO simulations are also performed for the second MATLAB GWO approach. In the second approach maximizing PUF for each scenario is the defined goal of the optimization. It is expected that the second approach experiences more contribution of battery storage in comparison to the first approach. Figure 4-4 illustrates the installed capacities of each

¹² Power duration curves of wind and photovoltaic technologies can be found in Annex 3.

technology in the second optimization approach. As it can be seen from the diagram, battery storage plays a dominant role in all scenarios. This is due to the reason that with few battery modules, then surplus generated power in a cell must be exported to the neighboring cells. Power exports from a cell means having lower PUF values. Integration of more battery modules for having higher PUF values has also a direct relation with generating higher NPC values. Unlike the first optimization approach, in the second optimization approach NPC does not play a role in achieving final results. It must be mentioned that the presented results in Figure 4-4 and Figure 4-5 are one of the possible combinations of the technologies to achieve the highest PUF and does not represent the best feasible solution. Considering the points that maximizing the PUF correlates with minimizing the surplus generation for each virtual cell and days without generation demands more installation generation capacities than the peak load inside each cell, justifies the reason for high amounts of batteries in the second approach.

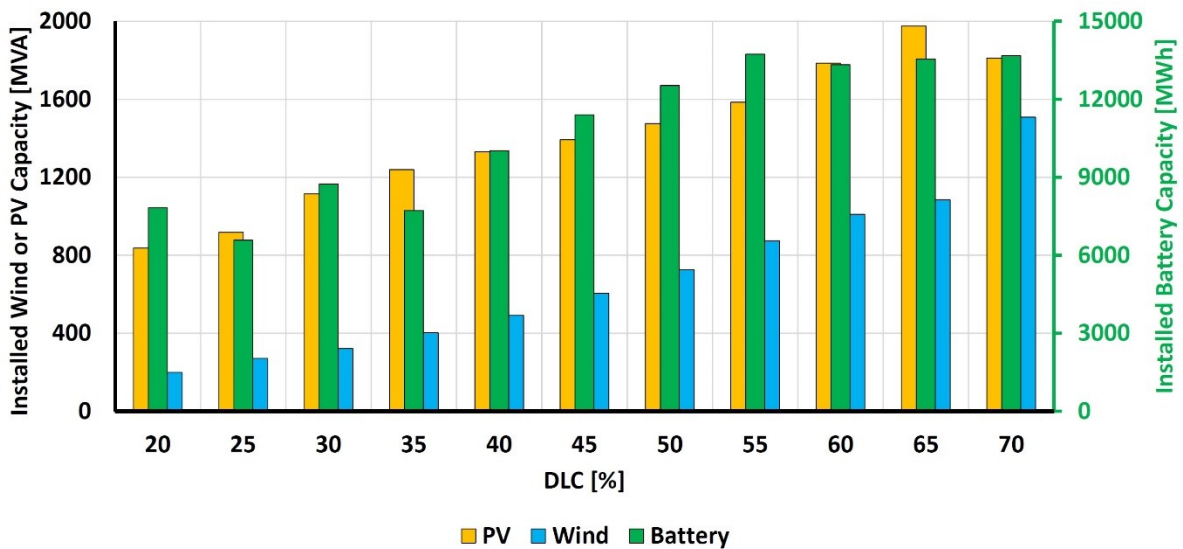


Figure 4-4: Installed capacities in second approach scenarios of MATLAB GWO

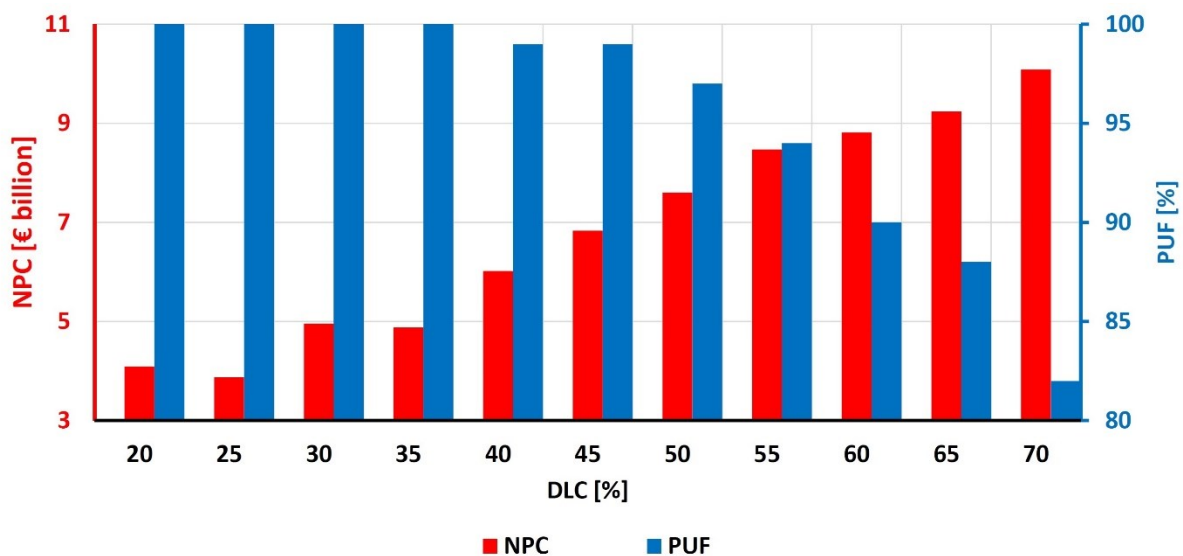


Figure 4-5: NPC and PUF in second approach scenarios of MATLAB GWO

Although more battery storage symbolizes higher PUF values in all scenarios of the second GWO approach, anyhow by increasing DLC values the surplus generated power can also not be stored fully by decentral storage solution of the calculation model. Consequently, the PUF value starts to drop by increasing DLC values as illustrated in Figure 4-5. However, efforts to keep the PUF value at its maximum value results in rising NPC values.

4.1.1. GWO Example: First Approach with 50% DLC

The goal of the GWO algorithm in this scenario is to minimize the NPC subjected to DLC value of 50%. According to the GWO simulation results, the entire synthetic power network will be capable of achieving 50% DLC value by having the total installed capacities of 1414 MVA photovoltaic and 934 MVA wind together with 467 MWh of battery storage. The corresponding NPC value of the project over the period of 25 years is calculated to be over €3.6 bn which is relatively very high for a regional distribution network. Figure 4-6 represents the results of the GWO scenario with details about loads and required capacities of wind and photovoltaic generators together with battery storage in each cell.

As it can be seen from Figure 4-6, the required installed capacities of wind and photovoltaic generators are significantly higher than the peak load in all cells. Cell 9 is the only cell which is on the verge of reaching its highest DLC value (52%). This is due to the limited remained transportation capacity of this cell. Based on the calculation model, further integration of RE generators after 52% DLC value in cell 9 is only possible with new integrated transformers in this cell. Otherwise N-1 contingency for loads or N-0 contingency for RE generators cannot be satisfied. The other solution for achieving higher DLC values in cell 9 is only possible by using the support of neighboring cells. For this purpose, cell 8 which has sufficient free transport capacity can be chosen and new RE generators can be integrated into this cell to compensate the power deficiency in cell 9 for reaching higher DLC values. This decision is reasonable as new integrated generators in cell 8 have also the shortest spatial distance to cell 9. This point is interesting from the view point of load flow calculations as less power flow in the entire synthetic network corresponds to lower losses or further problems in the system. However, the results in MATLAB are based on GWO calculation model which is based on active power balance between load and generation. The practicality of the suggested solutions must be evaluated by QDS simulations in PowerFactory.

Figure 4-7 provides an overview of the loads and NPC values of each cell for achieving the DLC value of 50% in the first GWO approach. It is remarkable that cell 9 has significantly higher NPC values in comparison to the other cells. This is for the reason that cell 9 requires a huge battery storage capacity (448 MWh) in comparison to other cells to come up with its assigned DLC goal within its limited transport capacity. Cell 2 is also on the way to meet its maximum transport capacity (58% DLC). In current example, cell 2 requires 13 MWh of battery storage which justifies having a bit higher NPC value in comparison with other cells.

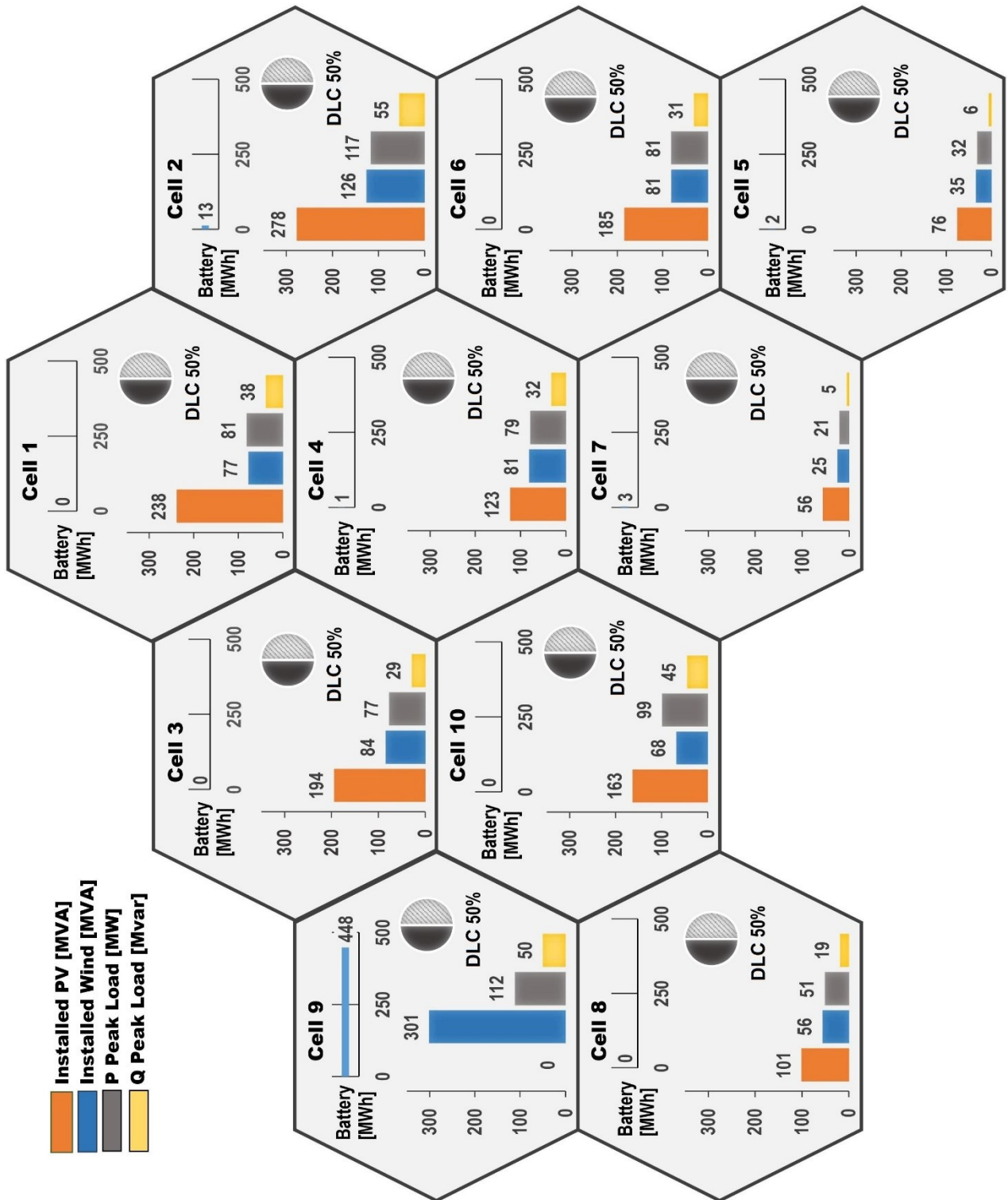


Figure 4-6: GWO scenario for the first approach with 50% DLC

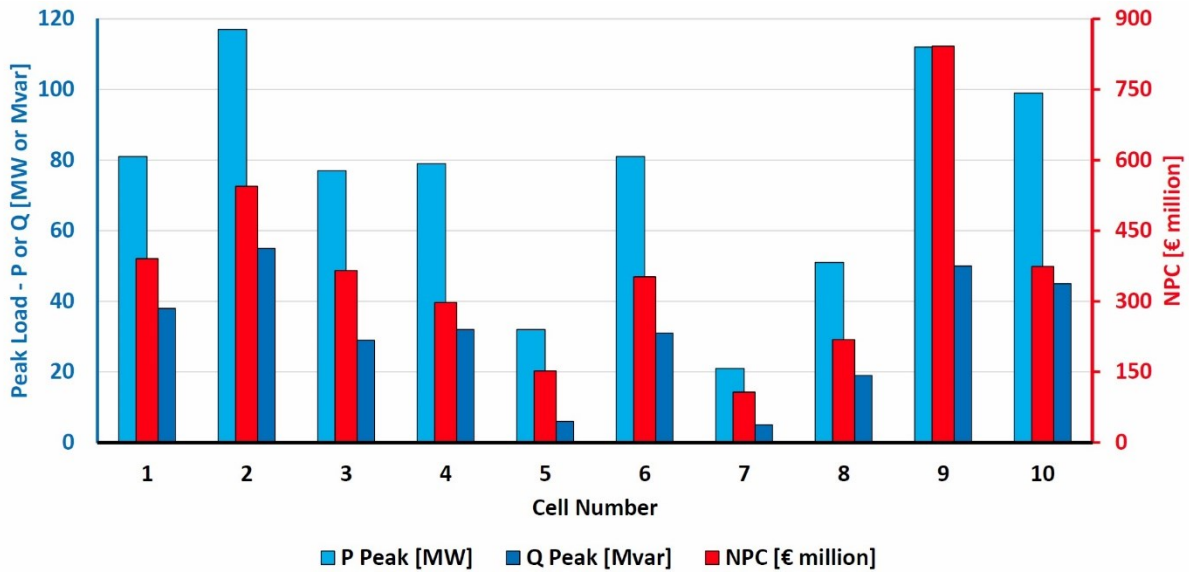


Figure 4-7: Peak load and NPC of cells in the first approach scenario with DLC of 50%

4.1.2. GWO Example: Second Approach with 50% DLC

The goal of the GWO algorithm in this scenario is to maximize the PUF value subjected to the DLC value of 50%. According to the GWO simulation results, total installed capacities of 1475 MVA photovoltaic and 726 MVA of wind together with 12528 MWh of battery storage are essential to achieve the goal. The corresponding NPC of the project over the period of 25 years is calculated to be almost €7.6 bn which is more than the twice expenditure of the similar scenario in first approach with 50% DLC value. It is clear that the price for having a higher PUF value is modification of the cells with more battery modules which can store a great portion of the surplus power production. The stored energy is then utilized in power deficiency moments. Figure 4-8 represents the results of this scenario in its cellular structure.

As it can be seen from Figure 4-8, in comparison to the results of the first optimization approach with 50% DLC, photovoltaic installations have slight changes within the cells. Although the overall photovoltaic capacity in the entire synthetic network is almost the same as the previous example. Nevertheless, the necessity for increasing battery storage modules results in the reduction of almost 23% of the installed wind capacities (208 MVA) to keep the PUF value at 96%. It is clear that without drastic increase of the installed battery capacity, achieving higher values of PUF is not possible.

The NPC values of each cell in this scenario are presented in Figure 4-9. As it can be seen from the illustration, NPC values of almost all cell have raised drastically in comparison to the first approach which is obviously a consequence of integration of more battery modules. Cell 9 is the only cell with very slight change of the NPC value. As mentioned before, this cell is on the verge of meeting its maximum DLC limit (52%) and not enough maneuverability is left for the GWO algorithm. It must be mentioned that in cells which are reaching their transport

capacity limits, N-1 contingency for connected loads and N-0 contingency for generators are obstacles in the way of integrating more RE generators or battery modules into the cell.

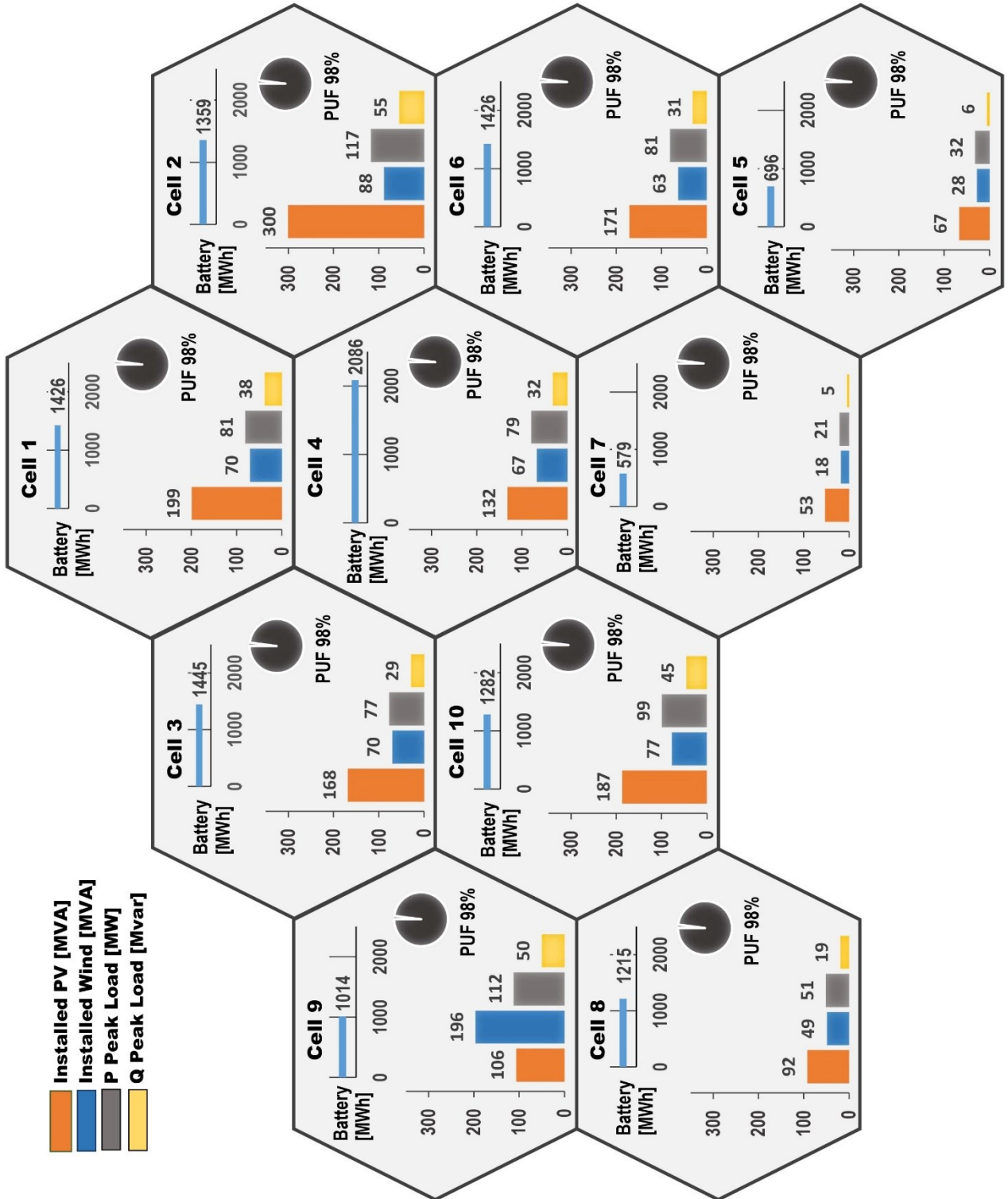


Figure 4-8: GWO scenario for the second approach with 50% DLC

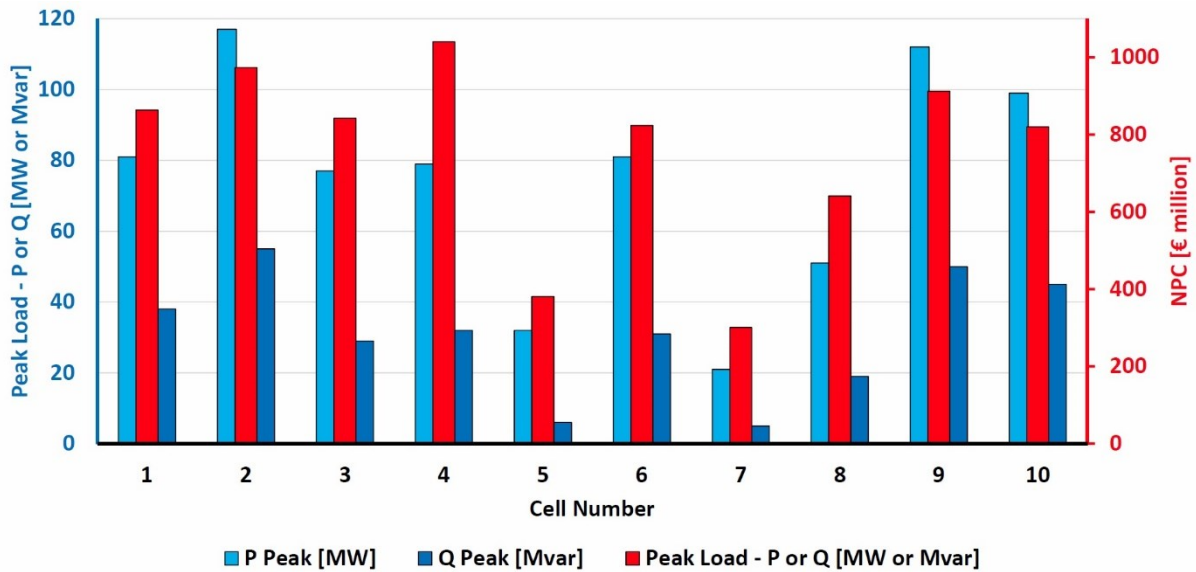


Figure 4-9: Peak load and NPC of cells in the second approach scenario with DLC of 50%

As mentioned before, the overall PUF of the synthetic network is equal to 96%. If instead of maximizing the PUF value minimizing the NPC is defined as the goal for the GWO (first approach instead of second approach), the calculated PUF value would be around 81%. This value signifies that according to the GWO calculation model, in the first approach around 19% of the generated power in the entire synthetic network cannot be absorbed by batteries or consumed by the loads. However, this number might change in real operation as from one hand there exist neither cell management systems nor a management system for the entire network that controls the power flow within the cells. From the other hand the reactive power demand of the network is not considered in MATLAB model. In light of these aspects, the power flow in real operation influences these numbers. Figure 4-10 illustrates the PUF versus NPC values for each cell in the second optimization approach. It is obvious that the increased expenditure is to raise the PUF values in each cell.

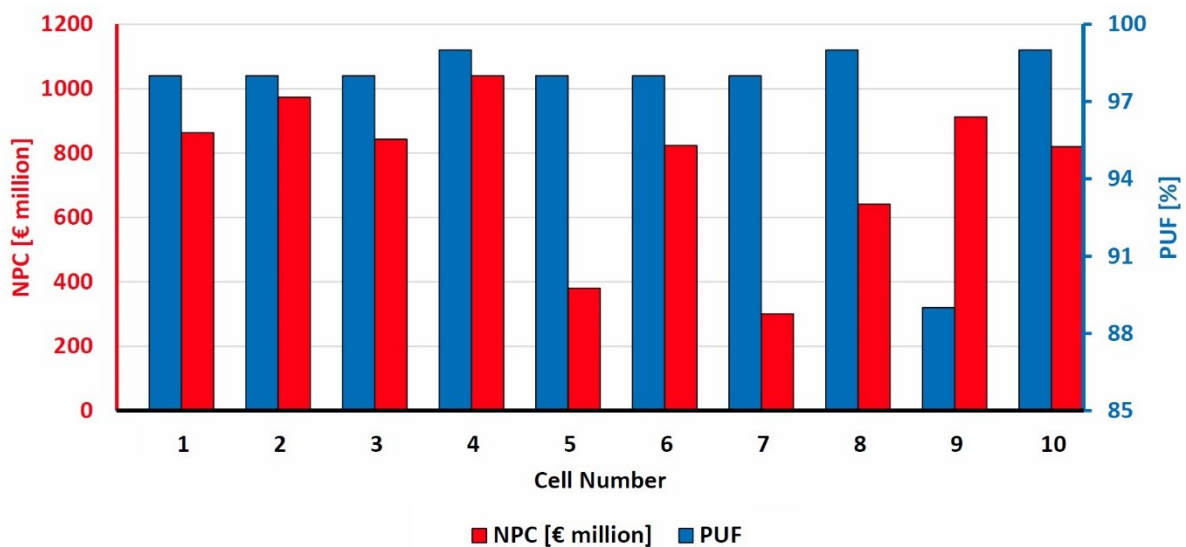


Figure 4-10: NPC vs PUF in the second approach scenario with 50% DLC

Overview of the GWO Results:

In previous section the general results of the GWO were introduced and the optimization approaches were explained using two examples. The detailed results of the both optimization approaches are illustrated in Annex 6.

Considering the results of the two optimization approaches, it can be seen that the second optimization approach has almost the double NPC values for the similar DLC values in comparison to the first approach. The reason for the tremendous differences in NPC values is the fact that for maximizing the PUF value in the synthetic power network higher amounts of battery modules in the cells are required. The integration of higher amounts of batteries has also a direct correlation with significant higher NPC values.

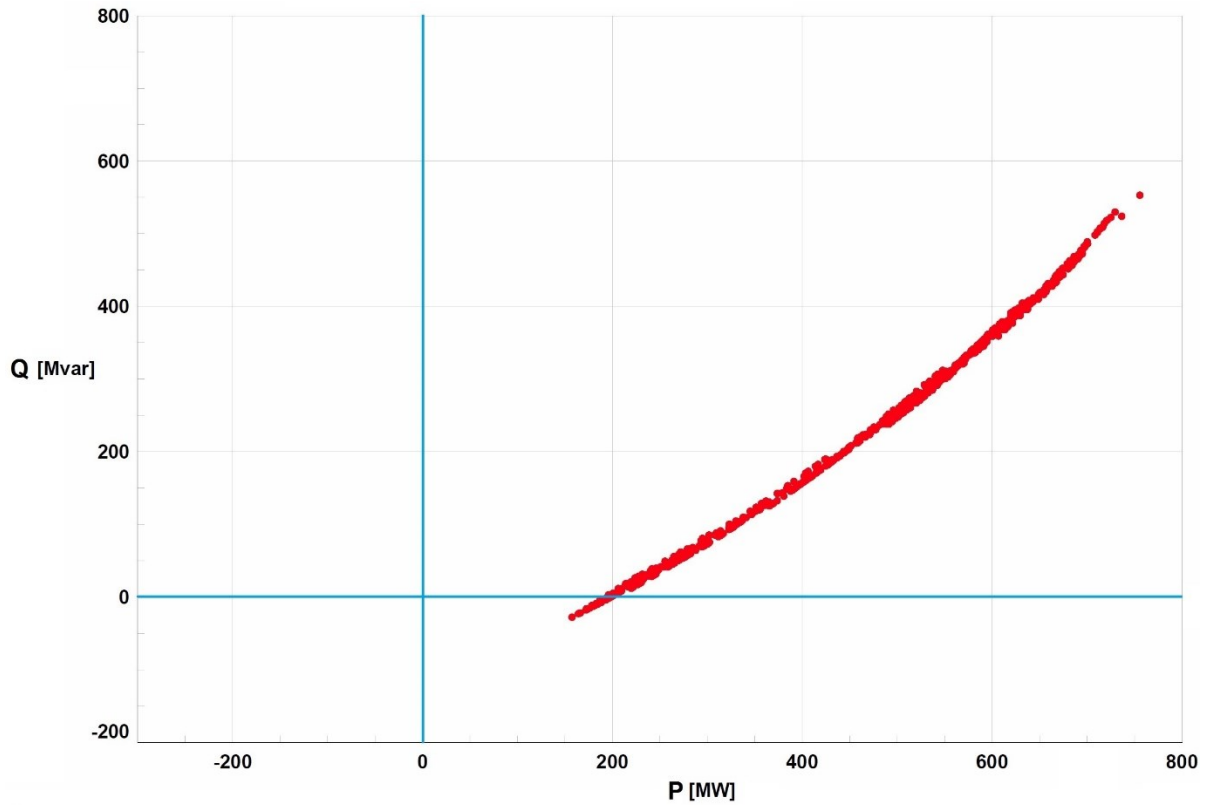
The higher NPC values of the second optimization approach are not economically feasible for such a regional network in reality. In other words, solutions for maximizing the PUF value can only make sense if a breakthrough in battery storage technologies is achieved which suppress the production costs. Due to this reason, the results of the second approach are not investigated by PowerFactory simulations. In the coming section the focus remains on investigating the results of the first optimization approach and its possible challenges for operation of the synthetic power network.

4.2. Simulation Scenarios and Results

In the first step of the simulation process, it is important to evaluate the active and reactive power demand of the synthetic power network in the absence of RE generators and battery modules. Because after integration of the new components, the power flow status and respectively the active and reactive power demand of the whole synthetic network are changed. In the second step, RE generators and battery modules are integrated into the synthetic power network based on the results of the first optimization approach and different simulation strategies are investigated.

Performing QDS for the synthetic power network without generators and battery modules, reveals the minimum requirements of the synthetic power network under normal operation. In this type of simulation, the active and reactive power demand are fulfilled via the connection points to external networks. Figure 4-11 illustrates the PQ operating points of the external networks for this simulation. The power flow values from the external networks reveals the amount of required active and reactive power for the preservation of the synthetic network. The operating points are obtained by QDS over the period of one year and are presented in generator-reference arrow system.

Figure 4-12 presents an example of the active and reactive power demand of the synthetic power network over the period of one week in February.



Legend:

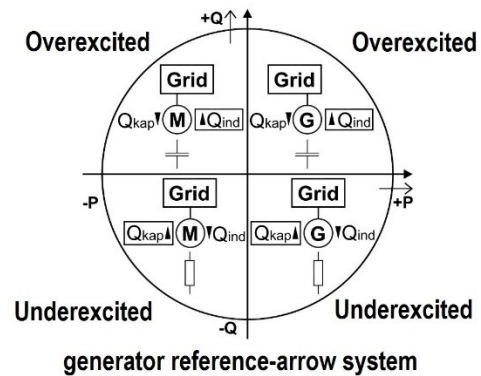
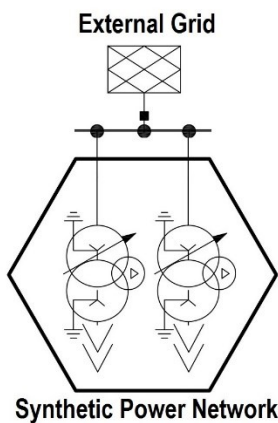


Figure 4-11: PQ diagram of the external networks; QDS without generators and batteries for one year

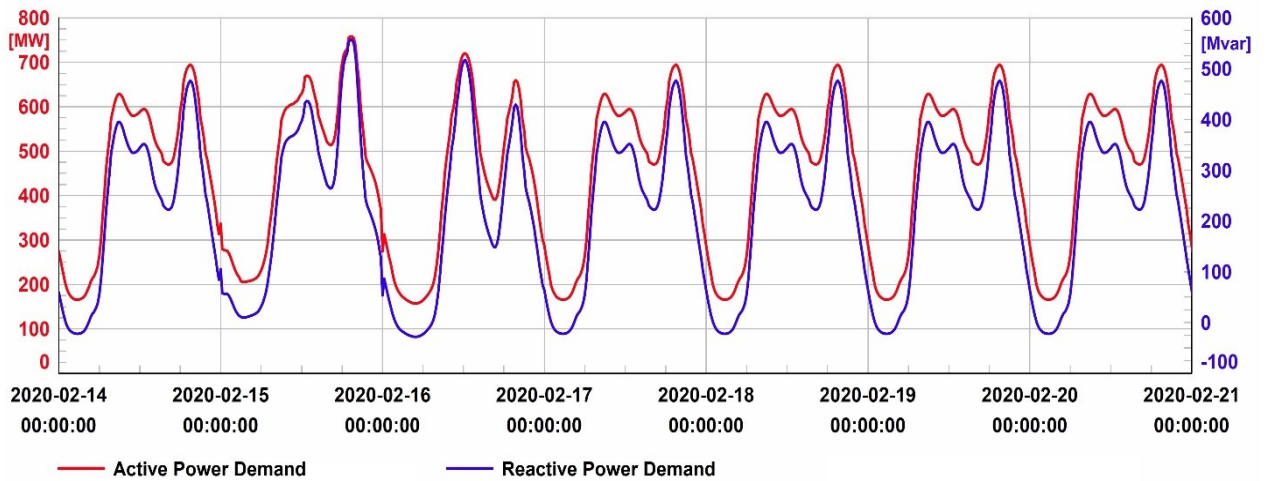


Figure 4-12: active and reactive power demand of the synthetic power network

The preliminary results of the QDS reveals that the months February and July are the months with the most drastic fluctuations in RE generation and therefore with the greatest number of failed LFCs. Hence, these months are considered as critical months for further investigation. The simulation also reveals that the assigned reactive power controlling strategy in the synthetic network plays a significant role in convergence of the QDS. To be more exact, the tap changers of the transformers, the defined frameworks for generators in provision of reactive power and their corresponding Q provision strategy (dead band and droop) are important points in convergence of the QDS. In order to find out the best reactive power strategy for the RE generators, following series of scenarios are prepared for investigation in PowerFactory:

- Simulation scenarios with Q(U) controlling strategy
- Simulation scenarios with Q(P) controlling strategy
- Simulation scenarios with hybrid strategy (combination of Q(U) and Q(P) controlling strategies)

All the investigated scenarios show serious convergence problems without automatic tap changing control of transformers. This is due to the strong changes in power infeed from the RE generators. Therefore, all the scenarios are equipped with automatic tap changer for transformers. In this strategy the tap changer is located at high voltage side of the windings. The control mode is voltage controlling with the bus target voltage assigned as the setpoint of the controller. The results of QDS for the above-mentioned scenarios are presented in the next sections.

4.2.1. QDS Scenarios with Q(U) Controlling Strategy

Table 4-2 presents the QDS results for the first optimization approach with different DLC values. In simulations, different voltage Q-droop values are assigned to the Q(U) controllers of the RE generators. The droop values are chosen between the permissible limits of 3% and 12%¹³ and the simulations are performed for the chosen months. The results in Table 4-2 are presented in form of the percentage of LFC failures. It can clearly be seen that the droop value of 12% delivers the better results. Beside the droop value, the voltage dead band plays also an important role in convergence of the QDS. The simulations with different values of dead band prove that with a dead band value of 0 p.u. the RE generators are very sensitive to small changes which in instability of calculations. Whereas a dead band value of 1 p.u. is not fast enough to react properly to the drastic infeed changes inside the synthetic network. Therefore, the value of 0.5 p.u is assigned to the Q(U) controller as a proper dead band value for regulation of voltage in QDS. Figure 4-13 illustrates a glimpse of the results with the proper configurations for Q(U) controller in QDS.

¹³ Droop value of 3% means that by voltage deviation of 0.01 p.u. the generator provides an additional reactive power of $(\frac{100\%}{3})$ of the rated apparent power of the generator. Accordingly, the additional reactive power for the 12% droop is $(\frac{100\%}{12})$ of the rated apparent power of the generator.

		Percentage of LFC Failures with droop value of 3%		Peak Load [MW]	Peak Generation [MW]
DLC [%]	February	July			
20	8%	23%	572	380	
30	31%	25%	572	543	
40	29%	28%	572	725	
50	No Convergence	No Convergence	572	971	
60	No Convergence	No Convergence	572	>1200	
		Percentage of LFC Failures with droop value of 6%		Peak Load [MW]	Peak Generation [MW]
DLC [%]	February	July			
20	2%	5%	572	380	
30	16%	8%	572	543	
40	14%	10%	572	725	
50	14%	7%	572	971	
60	No Convergence	No Convergence	572	>1200	
		Percentage of LFC Failures with droop value of 9%		Peak Load [MW]	Peak Generation [MW]
DLC [%]	February	July			
20	1%	3%	572	380	
30	1%	5%	572	543	
40	9%	4%	572	725	
50	7%	5%	572	971	
60	No Convergence	No Convergence	572	>1200	
		Percentage of LFC Failures with droop value of 12%		Peak Load [MW]	Peak Generation [MW]
DLC [%]	February	July			
20	<1%	1%	572	380	
30	7%	3%	572	543	
40	4%	2%	572	725	
50	5%	4%	572	971	
60	No Convergence	No Convergence	572	>1200	

Table 4-2: Overview of the QDS results with Q(U) controller

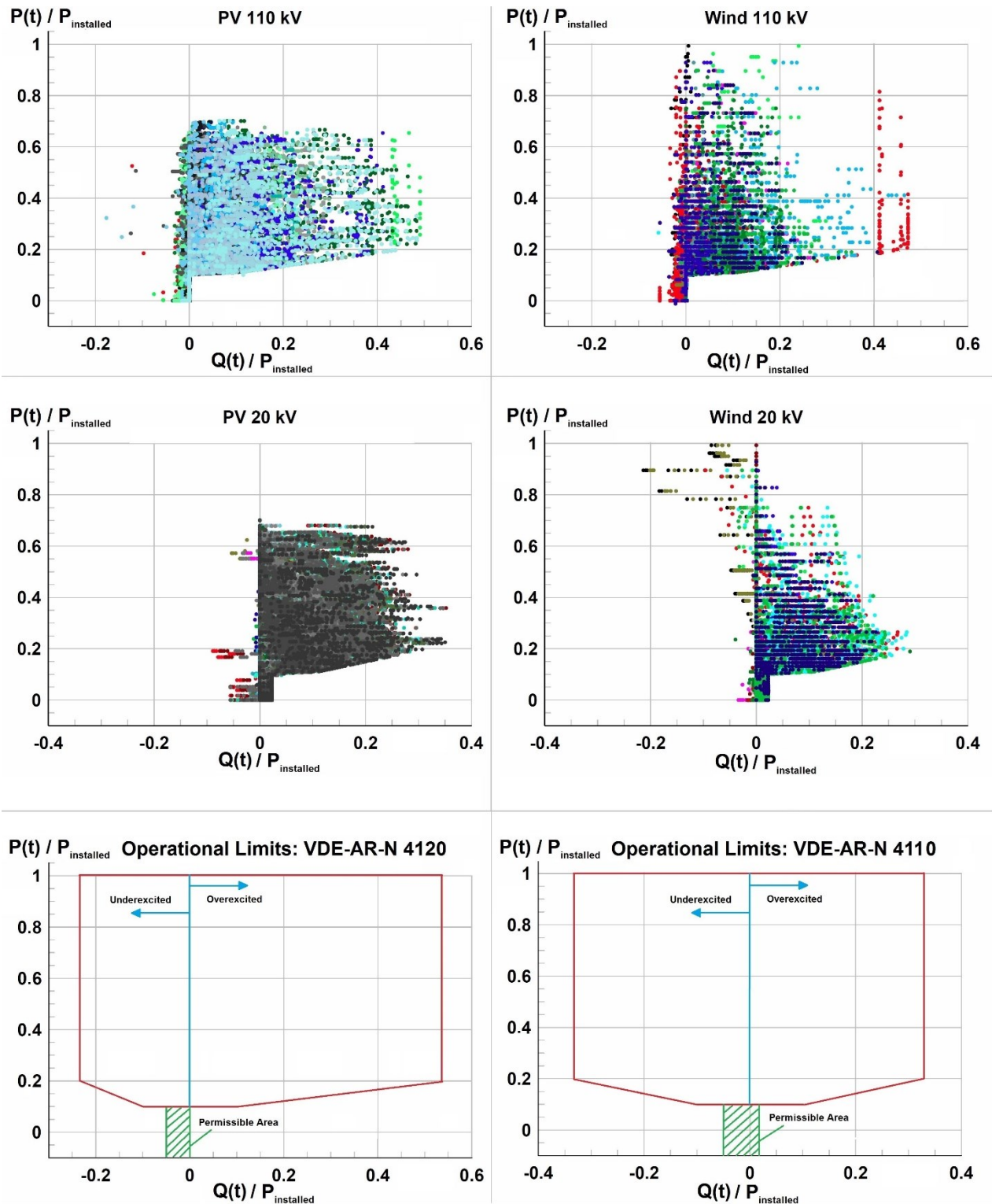


Figure 4-13: Operating points of RE generators; scenario: first optimization approach with 50% DLC, critical week in July, Q(U) controller with 12% droop and voltage dead band of 0.5 p.u.

In Figure 4-11, it was illustrated that the synthetic power network has a strong inductive reactive power demand due to the types of the existing loads. According to VDE-AR-N 4120 for HVNs, there are three variants of the requirements for generation plants in provision of reactive power at the grid connection point (operational limits in form of PQ diagram). It is

clear that the first variant with more tendency towards overexcited region is the most suitable choice for the RE generators connected to the synthetic power network [49]. The requirements for generation plants in provision of reactive power at the grid connection point of MVNs is also defined by the VDE-AR-N 4110. The explained variants are the defined operational limits of the RE generators for QDS and are illustrated in Figure 4-13.

Figure 4-13 also presents the operating points of different RE generators connected to 20 kV and 110 kV voltage levels for the case scenario: first optimization approach with DLC value of 50%, Q(U) controller with 12% droop and 0.5 p.u. dead band. The operating points of the RE generators are illustrated in different colors, where each color represents a specific wind park or photovoltaic plant. As it can be seen from the diagrams, RE generators in this scenario are mostly working in overexcited area to provide inductive reactive power for the synthetic network. In this scenario the RE generators are limited by the defined operational limits which leads in some cases to LFC failures in several hours of simulations due to lack of provision of reactive power and voltage stability problems. Figure 4-14 illustrates an example over a critical week in July how the lack of reactive power provision and changes in infeed power results the voltage deeps at main busbars of each cell.

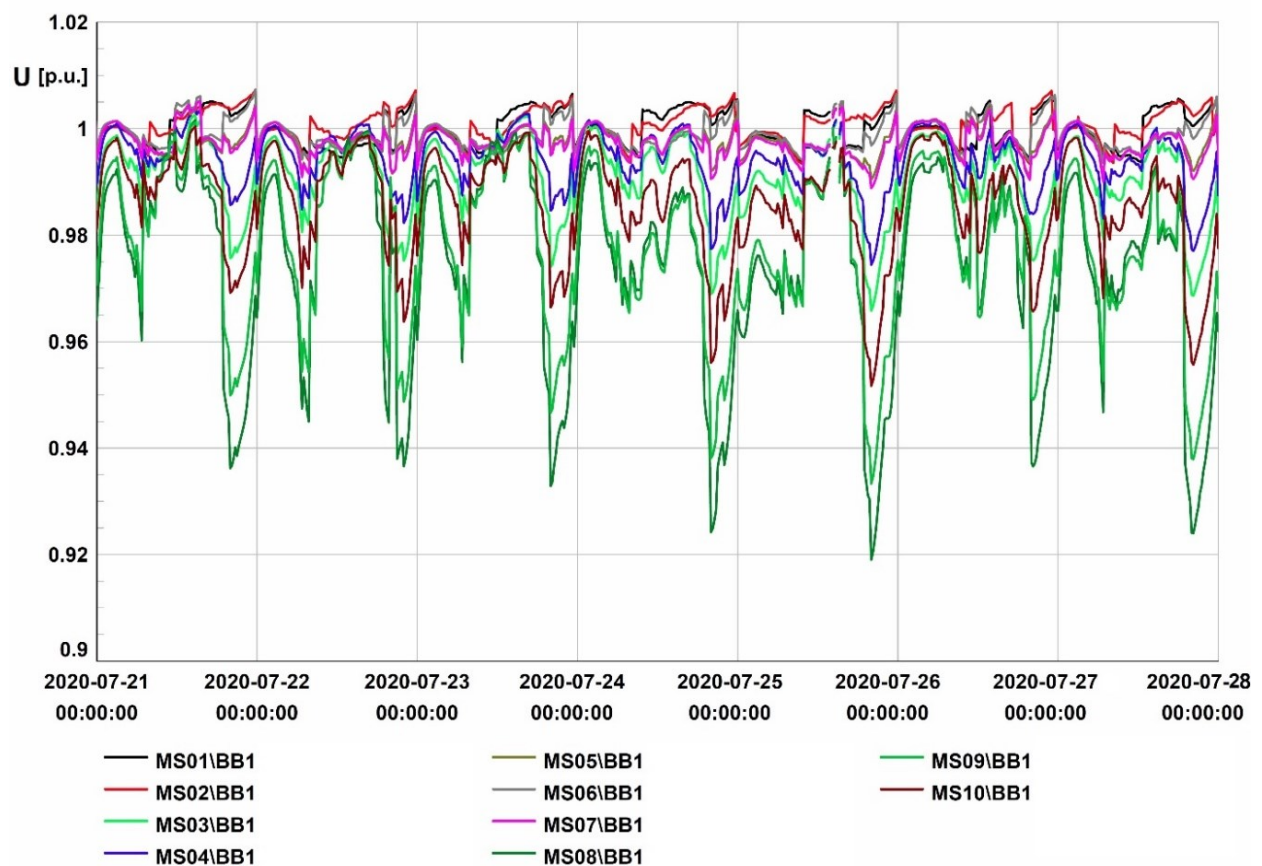


Figure 4-14: Voltage variations at main busbars of each cell; scenario: 50% DLC, Q(U) controller with 12% droop and voltage dead band of 0.5 p.u.

It is clear that lack of reactive power provision from the RE generators and strong changes of the infeed power from RE generators within hours can lead to serious operational problems. In these scenarios transformers play a crucial role as the on-load tap changers have effective

contributions in regulation of the voltage deeps in the critical moments. The small peaks in Figure 4-14 are resulted by tap changers. The results of the QDS show that due to dramatic changes in the infeed power from RE generators, transformers have to change the position of taps very often to compensate the dramatic voltage changes at connection nodes. The changes in tap changer position of transformers are illustrated in Figure 4-15 over a chosen critical week in July (the same time span as Figure 4-14). The steady tapping of all transformers is remarkable in this illustration. It is obvious that without automatic tap changing controller of the transformers, serious convergence problems would appear in QDS.

Tap Position

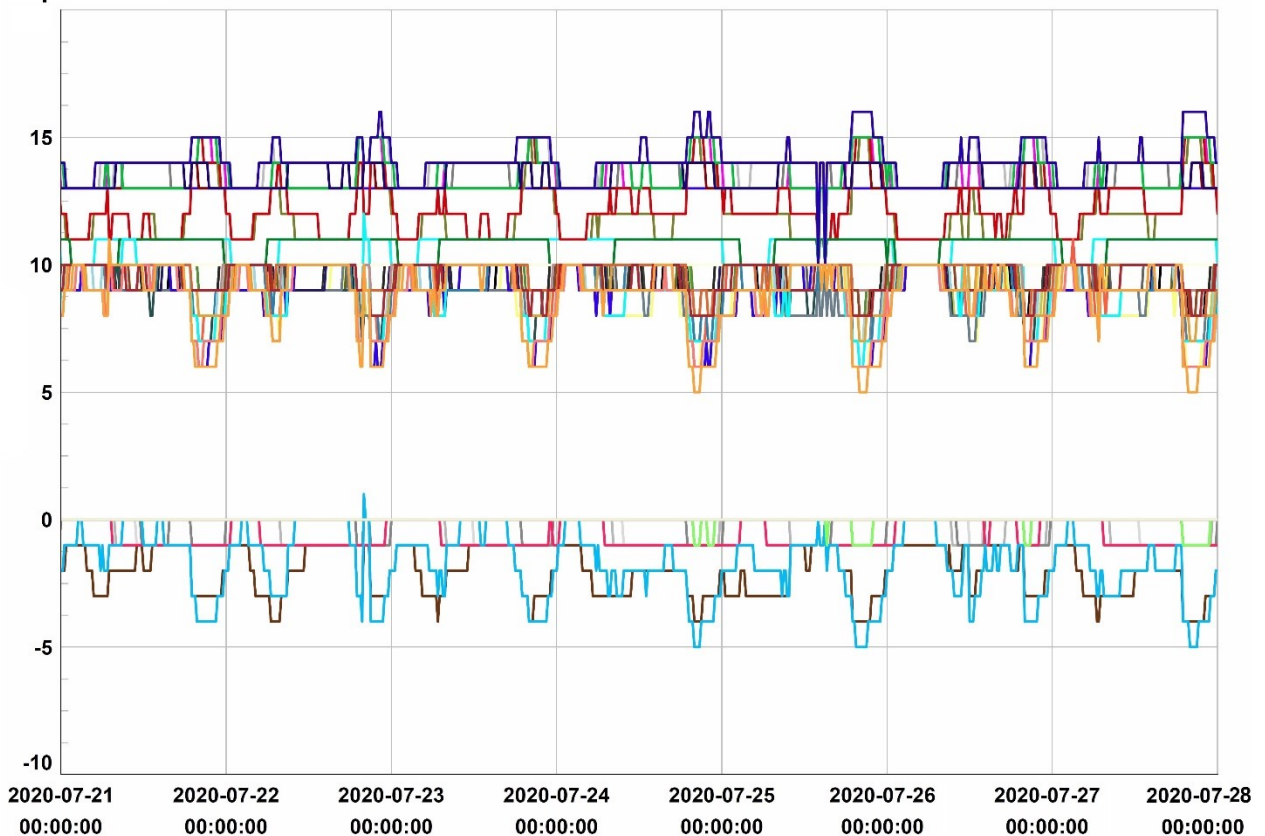


Figure 4-15: Tapping of the transformers¹⁴ in first optimization scenario: 50% DLC with Q(U) controller, 12% droop and voltage dead band of 0.5 p.u.

The voltage-based heatmap illustration of the main busbars of each cell is presented in Figure 4-16. This figure is a snapshot of the synthetic power network in a voltage deep situation.

As stated before, the Q(U) controller with the droop value of 12% and the voltage dead band of 0.5 p.u. delivers the results with the minimum number of LFC failures. However, there are still serious convergence concerns that can be interpreted as critical operational moments for the synthetic power network. It is clear that the operational challenges could not be answered only with Q(U) controlling strategy.

¹⁴ The tap position in some transformer models changes between 1 to 19 steps (10 as neutral position) and in some transformer models changes between -13 to 13 steps (0 as neutral position).

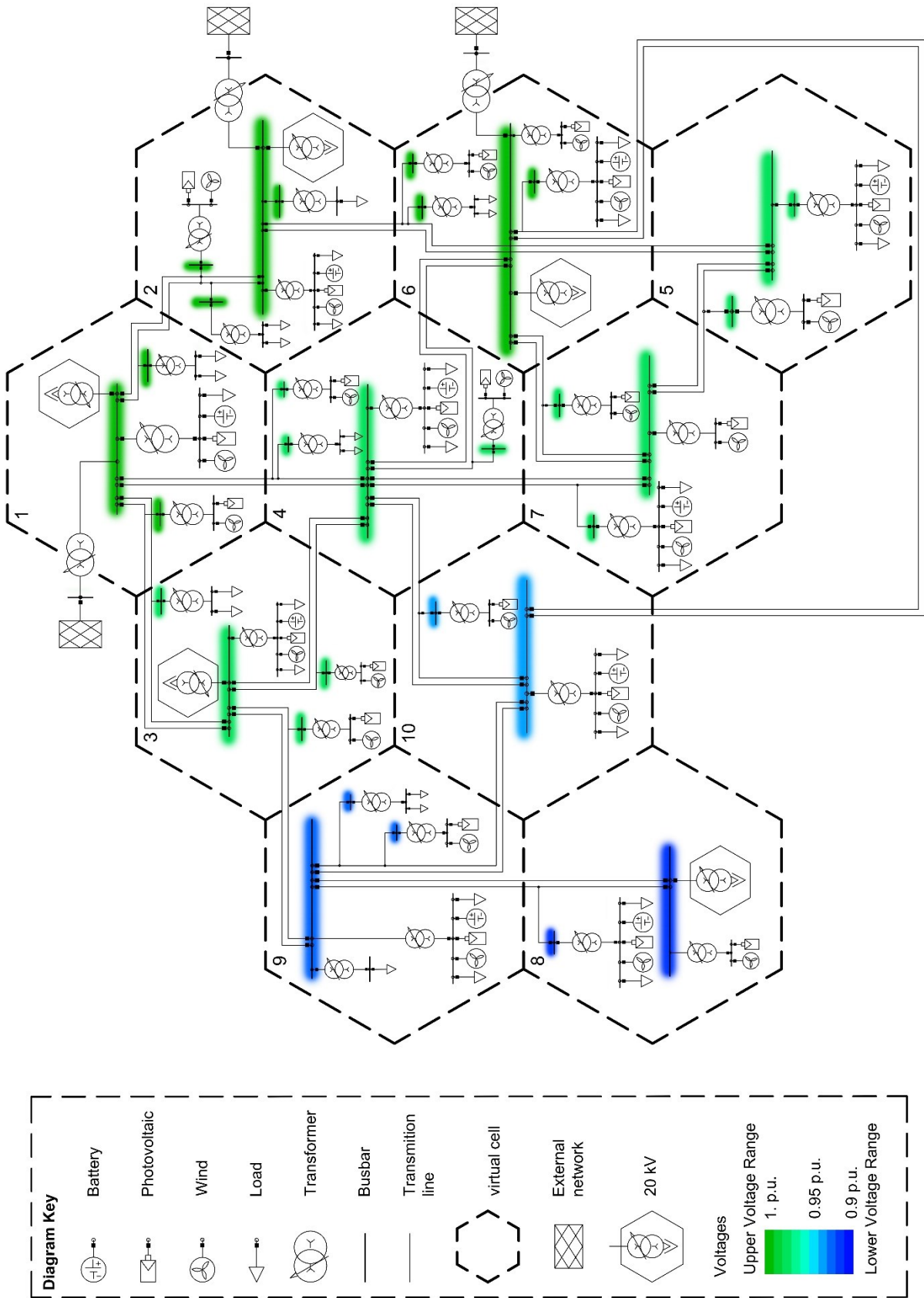


Figure 4-16: Voltage-based heatmap for the first approach with 50% DLC, critical moment in July, Q(U) controller with 12% droop and voltage dead band of 0.5 p.u.

4.2.2. QDS Scenarios with Q(P) Controlling Strategy

In these scenarios the Q(P) controller operates based on a fixed defined characteristic curve. The setpoints of the characteristic curve are calculated based on the requirements of the synthetic power network. In this regard, the following points are taken into consideration:

- 1) Active and reactive power demand of the whole synthetic power network
- 2) Operational limits of RE generators in provision of reactive power according (defined by the technical guidelines VDE-AR-N 4120 and VDE-AR-N 4110)

The active and reactive power demand of the synthetic power network was illustrated in Figure 4-11 in form of the PQ operational points and the operational limits of RE generators were shown in Figure 4-13. The following steps describe the proper guideline for formation of the Q(P) characteristic curve for RE generators:

- 1) Step 1: performing the QDS of the whole synthetic network without RE generators over the period of one year to acquire the net P and Q demand.
- 2) Step 2: ascending sorting of the P demand of the synthetic network and noting the corresponding Q demand.
- 3) Step 3: dividing the sorted data by maximum active power demand (P_{\max}) to obtain the P/P_{\max} and Q/P_{\max} values.
- 4) Step 4: the outcome can be considered as per unit values of a single generator which feeds the entire synthetic network and shows the guiding points to form the Q(P) characteristic curve for RE generators.

Undertaking the above mentioned steps, the Q(P) characteristic curves for the generators connected to the HVN and MVN can be defined. Figure 4-17 and Figure 4-18 illustrate the guiding points in formation of the Q(P) characteristic curves.

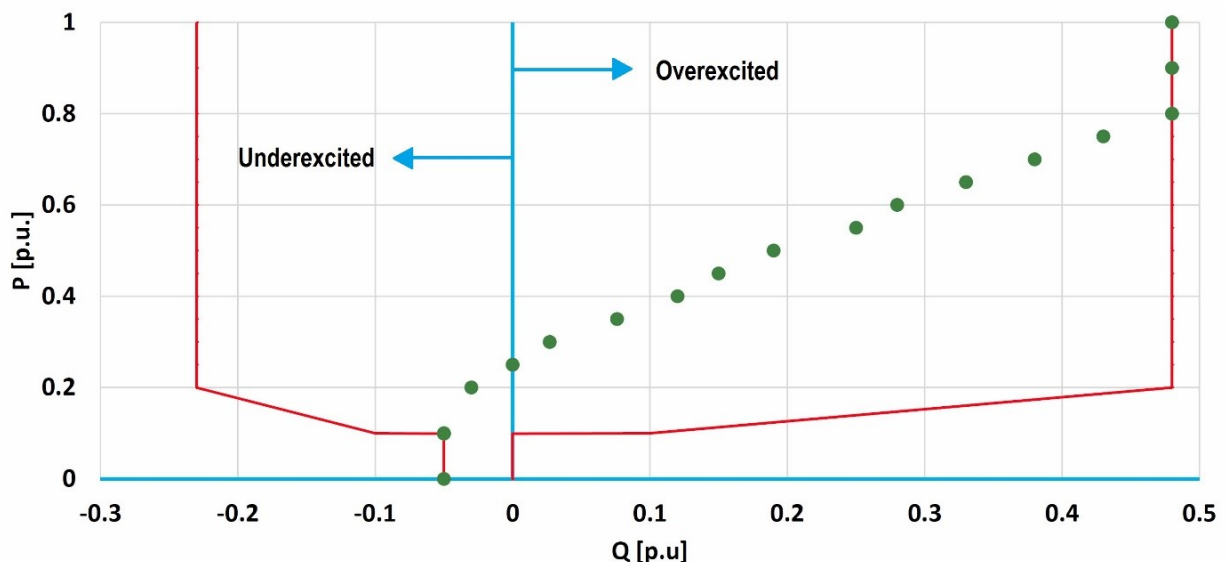


Figure 4-17: Guiding points in formation of the Q(P) curve for generators connected to the HVN

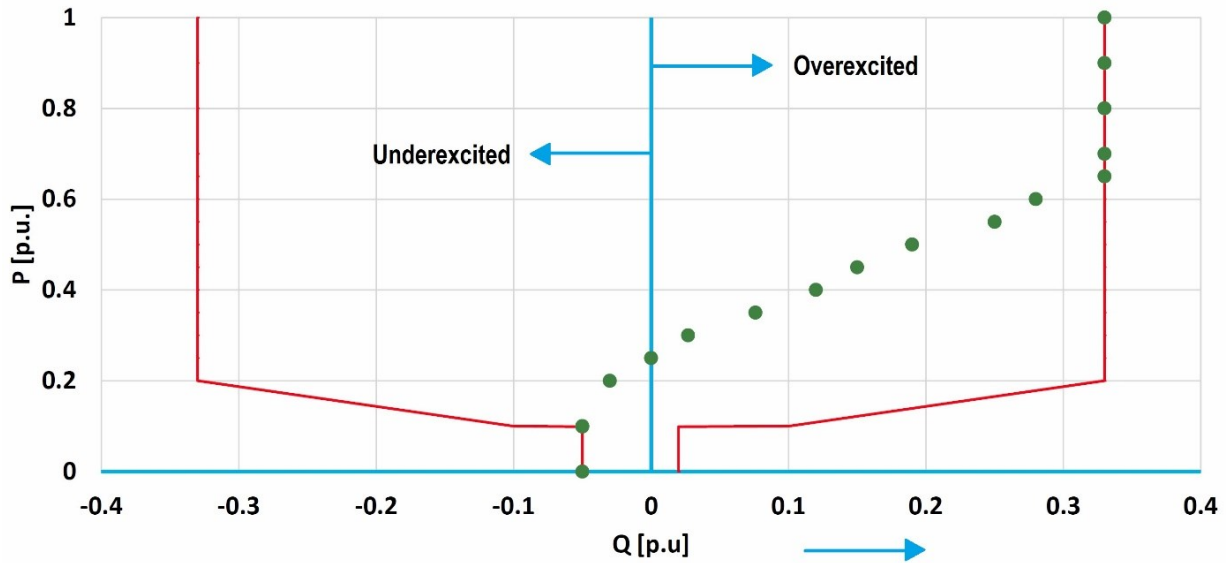


Figure 4-18: Guiding points in formation of the Q(P) curve for generators connected to MVN

Looking into the generation profiles of the RE generators, it is easy to understand that the infeed power during the day is much higher than the night hours. In other words, the high infeed hours of the RE generators coincide in many operational days with the peak loading hours of the synthetic power network.

The obtained curves presented in Figure 4-17 and Figure 4-18 are then assigned to the Q(P) controllers of RE generators and QDS for critical months are performed. The results of QDS for the first optimization approach with the assigned Q(P) characteristic curve are presented in Table 4-3.

DLC [%]	Percentage of LFC Failures in February	Percentage of LFC Failures in July	Peak Load [MW]	Peak Generation [MW]
20	0%	0%	572	380
30	0%	0%	572	543
40	~0%	~0%	572	725
50	~1%	~1%	572	971
60	~7%	~7%	572	>1200

Table 4-3: Overview of the QDS results for the first approach with Q(P) controlling strategy

Comparing the results of the simulations for the both reactive power controlling strategies, it is obvious that the overall results of the Q(P) controller show better performance by having much less number of LFC failures in comparison to the results of the Q(U) controller. Due to this fact, the QDS with Q(P) controller converge also relatively faster than the QDS with Q(U) controllers. However, precise investigation of the results reveals new facts which must be taken into consideration:

- 1) The advantage of using Q(P) strategy comparing to Q(U) strategy comes from the point that by applying the Q(P) strategy, less reactive power interactions between the synthetic power network and the external networks is required.
- 2) The Q(P) controllers promote the RE generators to provide reactive power according to the requirements of the whole synthetic network. However, the Q(U) controllers limit the reactive power provision to the requirements of the local connection point. Generally, it can be seen that less reactive power is provided via Q(U) controllers in comparison to the Q(P) controllers. Therefore, the difference in import of reactive power from the external networks is justified.
- 3) The voltage stability problems look very similar in both Q(U) and Q(P) controlling strategies. The voltage deeps and convergence problems in challenging operational situations of the synthetic network remains as an open point. Considering low infeed hours of the RE generators as challenging operational situations, one can understand how the defined operational limits for RE generators dampen down the reactive power provision. In high infeed hours, overloading of the distribution lines and transformers are the challenging operational situations.
- 4) The Q(P) controlling strategy has a disadvantage which can be describe as direct dependence of the reactive power provision to the active power infeed of the RE generators. The fixed defined Q(P) characteristic curve is directly coupled to the active power production of the RE generators and indirectly coupled to the total demand inside the synthetic network (the four step methodology for gaining the Q(P) characteristic curve). Therefore, the calculated Q(P) characteristic curve is suitable for the synthetic network in most of the time steps. However, it does not apply 100% to all of the time steps.

Figure 4-19 illustrates an example of the voltage changes at main busbar systems of each cell over a chosen critical week in July. It can be seen that, the voltage deep problems in cells 8, 9 and 10 remain and the voltage curves at critical hours have similar patterns as the patterns of the QDS with Q(U) controller. With the Q(P) controller the voltage deeps break down up to 0.02 p.u. and the voltage raise go up to 0.03 p.u. more than the Q(U) controller in critical moments. The reason for the voltage deeps and raise at specific busbars and the specific moments is the inappropriate value of the Q(P) characteristic curve for these special moments.

As it can be seen from the QDS results, assigning a solo reactive power provision strategy to all the RE generators inside the synthetic power network does not satisfy the requirements of the complex network. In the next section, a hybrid reactive power controlling strategy is presented which contains the advantages of both controlling strategies.

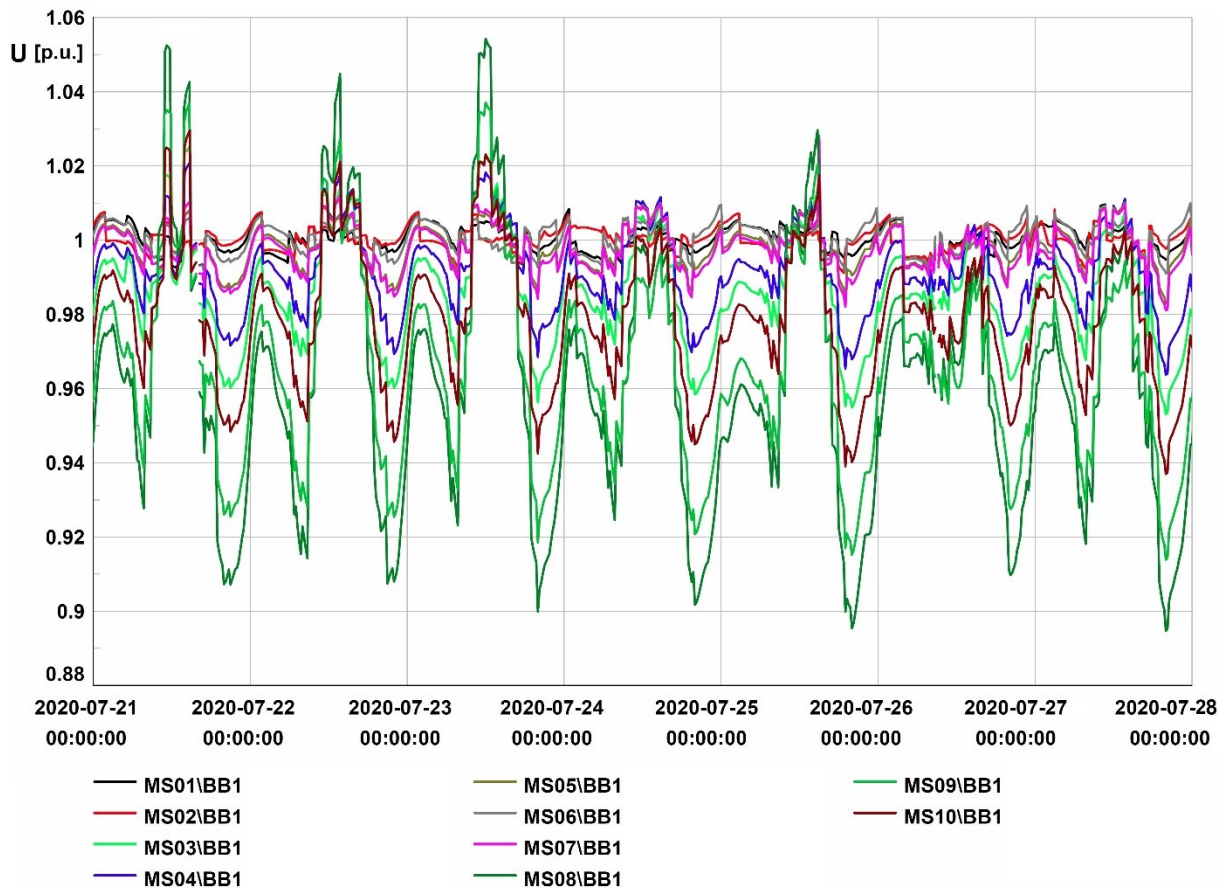


Figure 4-19: Voltage diagrams of main busbars from each cells; scenario: 50% DLC, Q(P) controller

4.2.3. QDS Scenarios with Hybrid Controlling Strategy

In previous sections it was stated that both Q(U) and Q(P) controlling strategies encounter voltage problems in critical situations of extreme low or extreme high RE generation. Based on the presented results in Table 4-2, it is clear that the solo reactive power provision strategy with Q(U) controllers cannot comply with the operational challenges for scenarios with DLC values bigger than 30%. The similar situation happens to the solo reactive power provision strategy with Q(P) controllers with DLC values bigger than 50%. In this regard, the hybrid controlling strategy is practiced on scenarios with DLC values of 50% upwards.

The Q(U) controlling strategy has the advantage that the reactive power provision is aligned with the requirements of the local connection point of the RE parks. However, it is identified that in many calculation steps the RE parks inside a specific cell are potentially able to provide more reactive power which is needed and theoretically can be used for supporting the neighboring cells. It is obvious that by limiting the Q provision from RE parks in such situations, the advantage of the Q(U) controlling strategy at the local level can be changed into an obstacle at the global level.

The simulations show that the Q(P) controlling strategy has better results at the global level in comparison to the Q(U) controlling strategy. Nevertheless, the global advantage of the

Q(P) controlling strategy can be a drawback at the local level as the reactive power provision is not aligned with the requirements of the local connection point of the RE parks. It is aligned with the general requirements of the whole synthetic network.

Considering the advantages and drawbacks of the both Q(U) and Q(P) controlling strategies, the author believes that a proper combination of the both controlling methods forms the best reactive power strategy which is aligned with both local and global requirements inside the synthetic power network. However, the crucial question is: which controlling method is to be assigned to which RE park inside which cell?

The best methodology for allocating the proper Q controlling strategy for RE generators is realized in two steps. In the first step, the results of Q(U) and Q(P) strategies are investigated to determine the following points:

- Identifying the reactive power interactions between the synthetic power network and the external networks by means of QDS and the QP diagrams.
- Performing sensitivity analyses for the selected connection points inside each cell which encounter voltage problems due to lack of reactive power provision.

The inductive character of the synthetic power network was discussed in previous sections and illustrated in Figure 4-11. The QP operating diagrams for both Q(U) and Q(P) controlling strategies are gained by QDS for the synthetic network over the period of one year and are presented in Figure 4-20 and Figure 4-21 respectively.

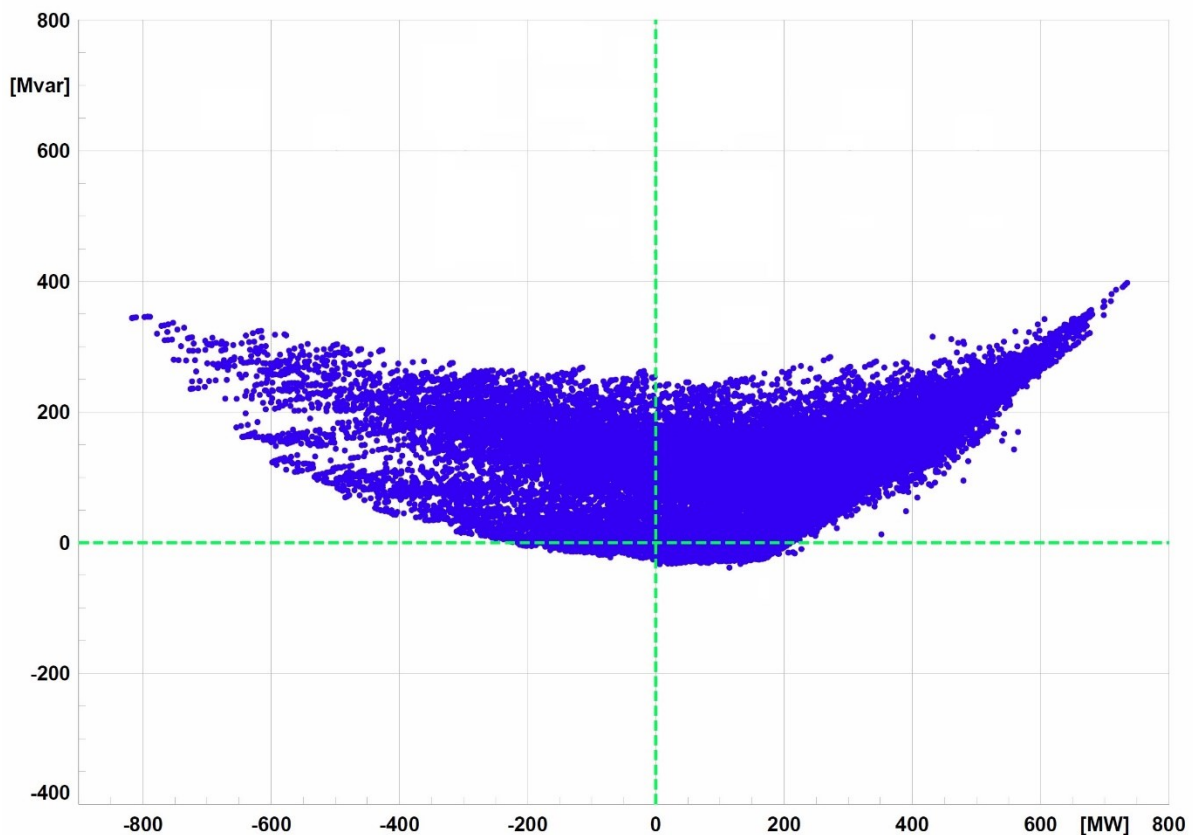


Figure 4-20: PQ operating points of the external networks; QDS with Q(U) method, 50% DLC, 12% droop and voltage dead band of 0.5 p.u.

Considering Figure 4-20 and Figure 4-21, the distribution of the operating points above the horizontal green line specifies the inductive reactive power import from the external networks. Respectively, the operating points under the horizontal green line correspond to exporting inductive reactive power into the external networks. The working points on the right side of the vertical green line correspond to the hours with low RE generation where the lack of active power is imported from the external networks. Accordingly, the operating points on the left side of the vertical green line specify moments that the active power production via RE generators are higher than the total required active load inside the synthetic power network where the excess production is exported to the external networks.

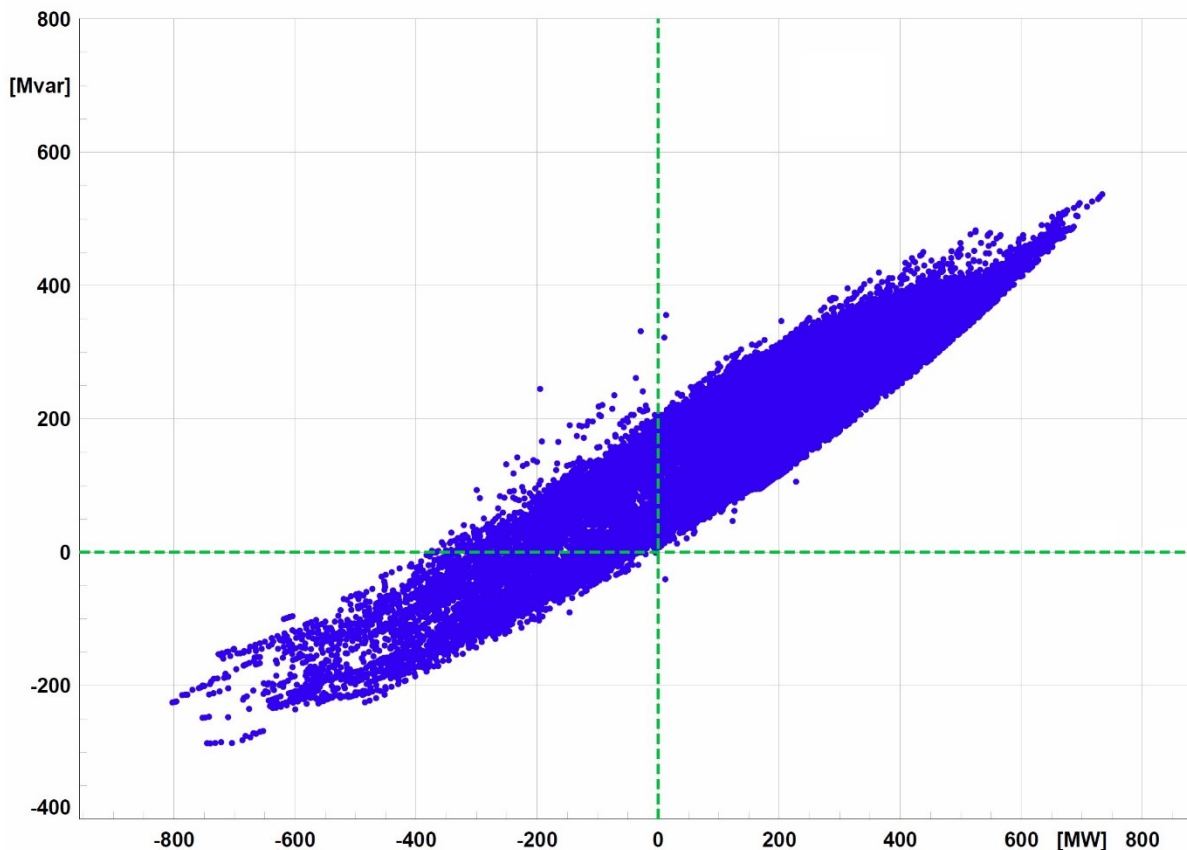


Figure 4-21: PQ operating points of the external networks; QDS with Q(P), 50% DLC

Analyzing the QDS results and considering the presented QP operating diagrams, it is understandable that the best reactive power provision strategy is a strategy that moves the QP operating points of the external networks towards the horizontal green line. In this case the reactive power interactions between the synthetic network and the external networks are at the minimum level. Meaning that the RE parks are almost able to cover the reactive power demand.

It is clear that in time steps where the active power production via RE generators is smaller than 20% of the installed capacity, the RE generators have restricted available potential for provision of reactive power. These time steps correspond to working points on the right side of the QP diagrams in Figure 4-20 and Figure 4-21. Therefore, it is expected that the proper hybrid reactive power strategy has a bigger impact on the operating points on the left side of

the vertical green line where RE generators are in excess production and have less restrictions for providing reactive power.

In the next step, load flow sensitivity analyses deliver valuable results in identifying the cells which encounter mostly voltage problems (because of lack of reactive power) in critical situations with the highest and lowest RE infeed. Sensitivity analyses are based on the LFCs which implement the linearization of the synthetic power network around the chosen operational point. In this method, the sensitivities are calculated by injection of power at the chosen connection points and the changes are documented. Evaluation of the LFCs in different scenarios showed that the operational situation inside the synthetic power network depends highly to the active and reactive power infeed from the RE generators. In this dissertation, the voltage sensitivities for dU/dQ and dU/dP are investigated based on power injections at the chosen connection points.

Figure 4-22 and Figure 4-23 present the results of the sensitivity analyses around two chosen operation points. The operation points are related to the peak load and base load situations of the main double busbar systems inside each cell. Calculations prove that the other connection points inside the cells show a similar sensitivity behavior to the injected power as the chosen double busbar systems.

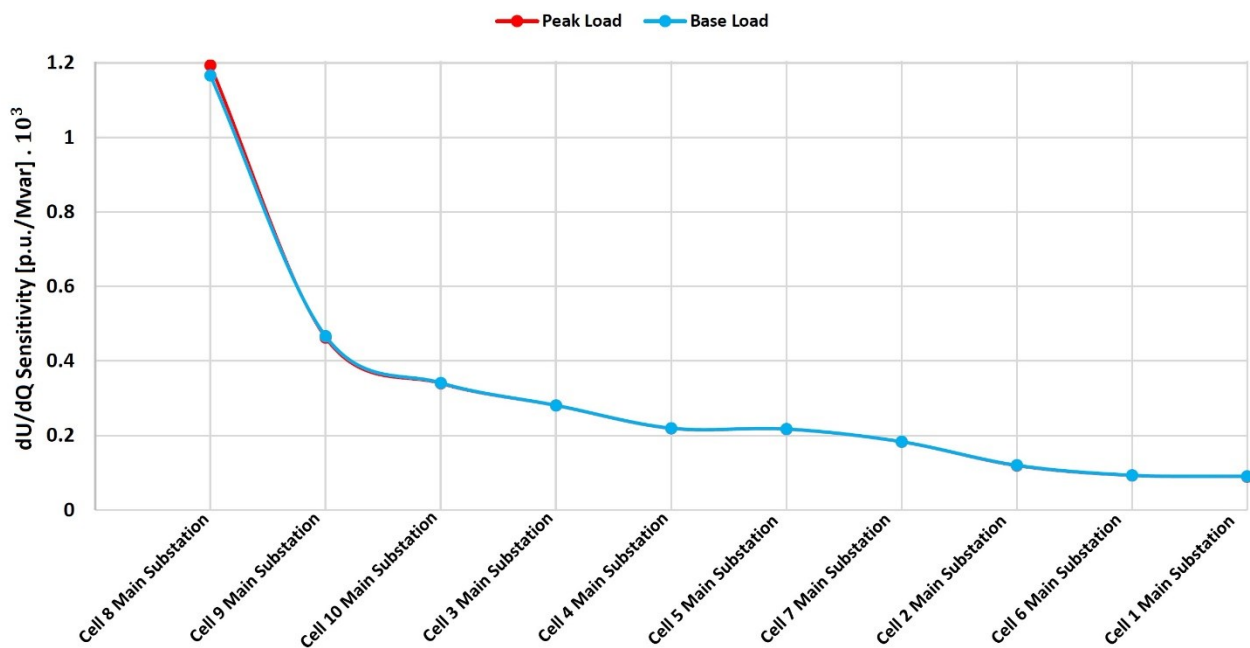


Figure 4-22: dU/dQ sensitivity for main connection points in each cell

It is remarkable that the distance to the external networks plays an important role in voltage stability. It is clear that the cells with longer connection paths to the external networks are the most sensitive cells to changes of RE infeed. As it can be seen from Figure 4-22 and Figure 4-23, cell 8, cell 9, cell 10 and cell 3 with the longest paths to the external networks are up to several times more sensitive to changes in comparison to the cells with a direct connection to the external networks (cells 1, cell 2 and cell 6). The sensitivity analyses

around the two chosen operation points show slight differences in values, but confirm the same pattern of sensitivity to infeed changes.

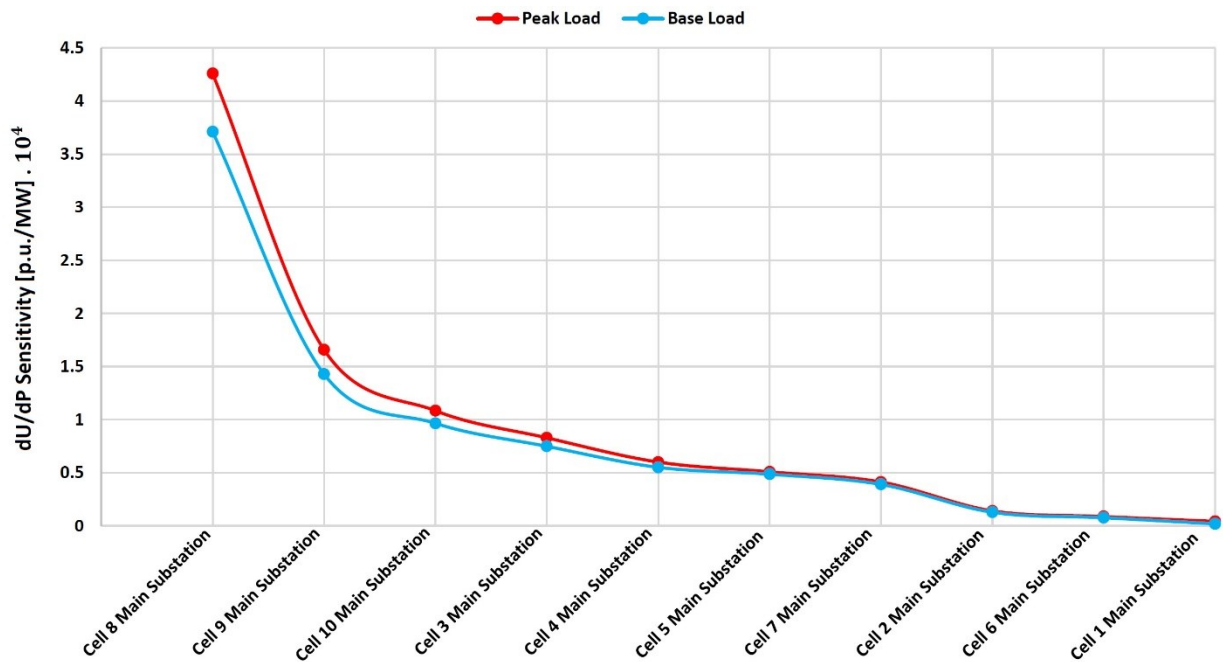


Figure 4-23: dv/dP sensitivity for main connection points in each cell

Based on the sensitivity results, it is reasonable to assign a Q(U) controlling strategy to the cells with higher voltage sensitivity to power infeed as the strategy is aligned with the requirements of the local connection point. Therefore, all the RE generators at cell 8, cell 9, cell 10 and cell 3 are equipped with the Q(U) controllers. For the rest of the cells which have less sensitivities to changes of the infeed power, the proper reactive power controlling strategy is realized by the Q(P) controllers. By means of that, these cells are aligned with the global requirements of the synthetic power network in provision of reactive power.

Figure 4-24 illustrates the results of the above mentioned hybrid controlling strategy in form of the PQ operating points of the external networks. In contrast to the Q(U) and Q(P) controlling strategies, the hybrid controlling strategy delivers much better results with faster convergence rate. It is remarkable that the number the LFC failures is reduced to about 0.5%. Further analysis of the QDS results reveals that the minimal number of appeared LFC failures happen due to divergence in time steps with dramatic changes of RE infeed power. This can be seen as the drawback of the QDS calculation method which is based on the values with 15 minutes time steps. The author believes that with reduction of the calculation time steps, less LFC failures would appear in the calculations.

As expected, the difference between the three controlling strategies manifests itself more in the moments where the RE generation is more than the demand inside the synthetic network (operational points on the left side of the green vertical line). It can be seen clearly from the diagrams that the hybrid controlling strategy reduces immensely the amount of reactive power interactions between the synthetic power network and the external networks.

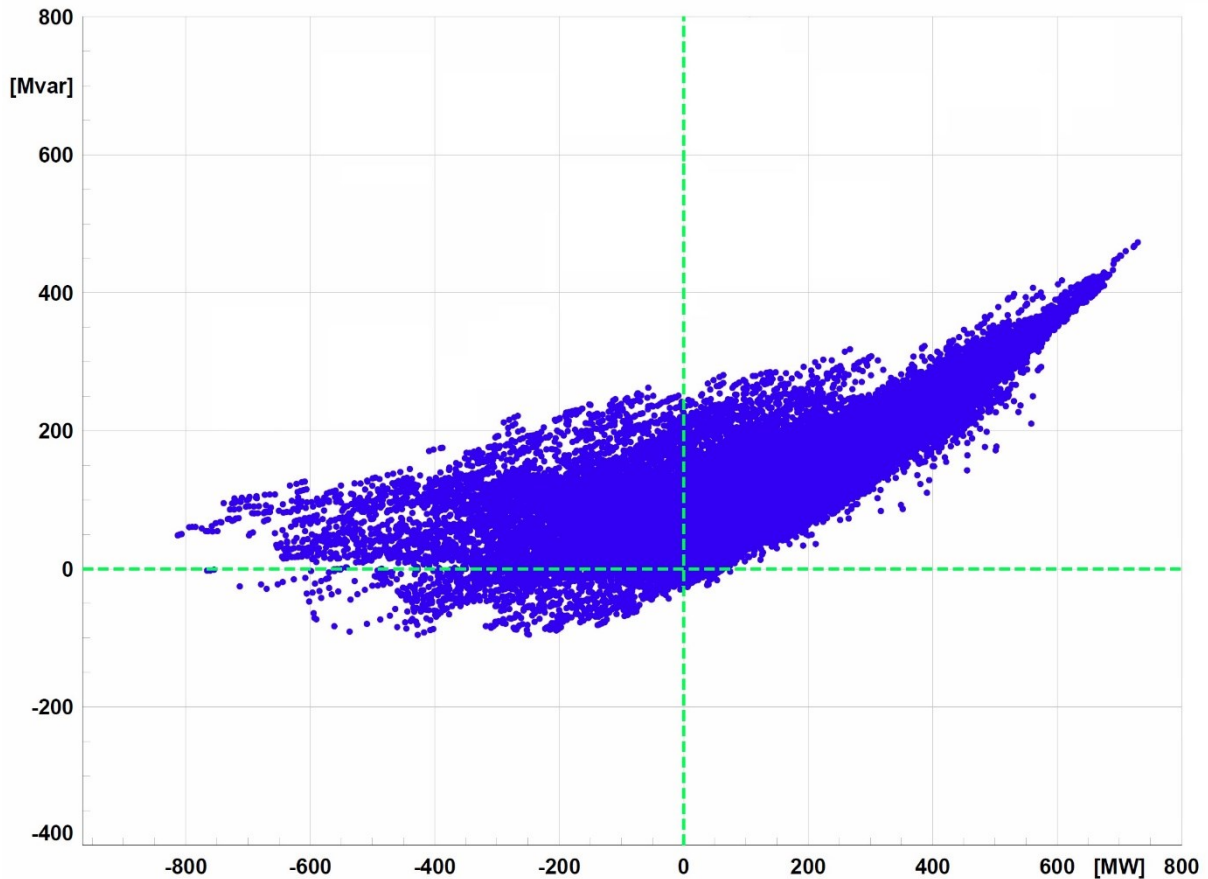


Figure 4-24: PQ operating points of the external networks; QDS with hybrid Q strategy, 50% DLC

Table 4-4 provides the overview of the QDS with hybrid reactive power controlling strategy. It is remarkable that the suggested solutions by MATLAB optimization for DLCs greater than 50% are according to PowerFactory not feasible. The solution with 50% DLC is also on the edge of acceptability as operational hours where the difference between generation and load is greater than 500 MW are challenging situations.

DLC [%]	Percentage of LFC Failures in February	Percentage of LFC Failures in July	Peak Load [MW]	Peak Generation [MW]
20	0%	0%	572	380
30	0%	0%	572	543
40	~0%	~0%	572	725
50	~0.5%	~0.5%	572	971
60	~7%	~7%	572	>1200

Table 4-4: Overview of the QDS results for the first approach with hybrid controlling strategy

4.2.4. Medium Voltage Networks in Simulations

Considering the scenario with hybrid reactive power control and 50% DLC as the solution, the situation inside the MVNs are investigated further. It can be seen that the 20 kV MVNs connected to cell 3, cell 8 and cell 10 face more voltage deeps than other MVNs because of their distance to external networks. The MVN in cell 6 shows different results despite the direct connection to the external network. The 20 kV MVN in this cell face also voltage deeps in the same order as the MVNs connected to cell 3, cell 8 and cell 10. This is due to the fact that this MVN has a much higher circuit length in comparison to other MVNs (about 51 km). It is clear that the circuit length has a direct correlation with the voltage deeps at critical operational situations. Table 4-5 shows a summary of the results in MVNs for the scenario with 50% DLC and hybrid reactive power controlling strategy.

Connection Point	Type of MVN	Peak Active Load [MW]	Peak Reactive Load [Mvar]	Length of Circuit [km]	Range of Voltage Changes [p.u.]
Cell 1	Urban	22	1.3	30	$0.96 < U < 1$
Cell 2	Industrial	40	18	27	$0.92 < U < 1$
Cell 3	Rural	24	2.4	51	$0.91 < U < 1$
Cell 6	Rural	24	2.4	51	$0.91 < U < 1$
Cell 8	Urban	22	1.3	30	$0.95 < U < 1$
Cell 10	Industrial	40	18	27	$0.92 < U < 1$

Table 4-5: Voltage changes inside the MVNs in QDS with 50% DLC and hybrid Q strategy

The above mentioned voltage values with maximum 9% deviation from the operational voltage values are acceptable under normal situations. However, small changes inside the MVNs like connection of new consumers or disconnection of RE generators might deteriorate the voltage values. In this case new measurements are required. Solutions like rising the operational voltage up to 5% or utilization of compensation technologies are in these cases practical.

4.2.5. Contingency Analysis

Considering the solution with 50% DLC with the hybrid reactive power controlling strategy as the chosen solution, contingency analysis is performed as the last step in verification of the results. In this regard, 498 contingency cases are defined for the synthetic power network and iterative AC load flow calculations are executed. By means of the contingency analysis, the power flow through the system, loading of equipments and voltages at connection points are evaluated in fault situations. In this dissertation single contingency cases (N-1 fault analysis) for the transformers, distribution lines and cables are calculated.

In static contingency analysis the system is analyzed at a specific operating point. Therefore, it is better to select the most critical situations for the investigation. In this respect, two cases are selected for investigation. In the first contingency case, the situation with low RE generation and high load demand is investigated where a great amount of the required power is imported from the external networks. In the second investigated case the situation with high RE generation and high load demand inside the synthetic network is investigated.

Figure 4-25 illustrates the results of the contingency analysis for the first investigated case at 110 kV level. As it can be seen, the power flow in lack of RE generation is from the cell 1, cell 2 and cell 6 with external connections in direction of other cells. Due to the well-meshed topology of the synthetic power network and parallel distribution lines, the outage of one distribution line does not have big impacts on the performance of the whole grid as the maximum loading of the distribution lines rises to the maximum amount of 60%. However, the outage of the transformers can raise the loading of the parallel transformers up to the 90%. In this situations the N-1 contingency at 110 kV level is still satisfied. Nevertheless, the situation is considered as threatening where further outages might lead to interruption of supply for some consumers. It is also clear that cell 8, cell 9 and cell 10 encounter the most voltage deficiencies because of the furthest distance from external networks. In these cells, voltage values down to 0.90 p.u. can be observed which are considered as critical.

The situation in the first contingency case inside the MVNs might get more complicated than the 110 kV level. In the MVNs with a ring structure, the outage of one line or transformer changes the shape of the network to a radial structure. It is obvious that in this case the overloading of some elements and voltage drops at the end of the radial network are inevitable. Figure 4-26 illustrates the result of the contingency analysis for the first investigated case inside cell 6 as an example of a MVN. It can be seen that in case of a transformer outage, the loading of the parallel transformer might increase up to 80% and the loading of cables might increase over 100%. The voltage deeps down to 0.80 p.u. are also seen in some connection points which are not within the permissible ranges.

Figure 4-27 illustrates the results of the second investigated contingency case at 110 kV level. In this case the power flow direction is from the cells towards the external networks. Similar to the first investigated case, the well-meshed topology of the synthetic power network and parallel distribution lines, takes out the risks during the outage of one distribution line. In case of the outage of a distribution line, the loading of other distribution lines rise to the values around 60% which is not threatening for the synthetic power network. The outage of one transformer leads still to rise of the loadings for parallel transformers to values around 90%. Unlike the previous contingency case, the combination of high RE generation and the proper reactive power strategy contributes in prevention of the voltage deeps at 110 kV level.

However, the situation at MVNs is completely different in the second investigated contingency case. The outage of one element (transformer or cable) inside the MVNs might directly lead to the voltage drops under der permissible values. The investigations show that the loading of the cables might also rise to amounts above 100% and violate the defined

contingency criteria. Figure 4-28 illustrates the results of the second investigated contingency case inside cell 6 as an example of a MVN.

To summarize the results of the N-1 contingency analyses, it is clear that the outage of one element at 110 kV level does not have a big impact on overall operation of the network as parallel distribution lines and transformers can compensate the outage without extra efforts. The problem of the voltage deeps remains unaffected at 110 kV level in outage situations. According to the calculations, the voltage deep problems are directly correlated with the lack of generation inside the synthetic network and the outage of one element in a well-meshed network does not have extra-ordinary effects on it.

Unfortunately, the N-1 contingency at MVNs is not satisfied. The overloading of cables over 100% and voltage deeps down to 0.80 p.u. are outside the permissible ranges. In order to comply with the given standards, reinforcement measures are necessary. The reinforcement measures include:

- 1) Increasing the transport capacity of cables
- 2) Application of compensation facilities for voltage problems

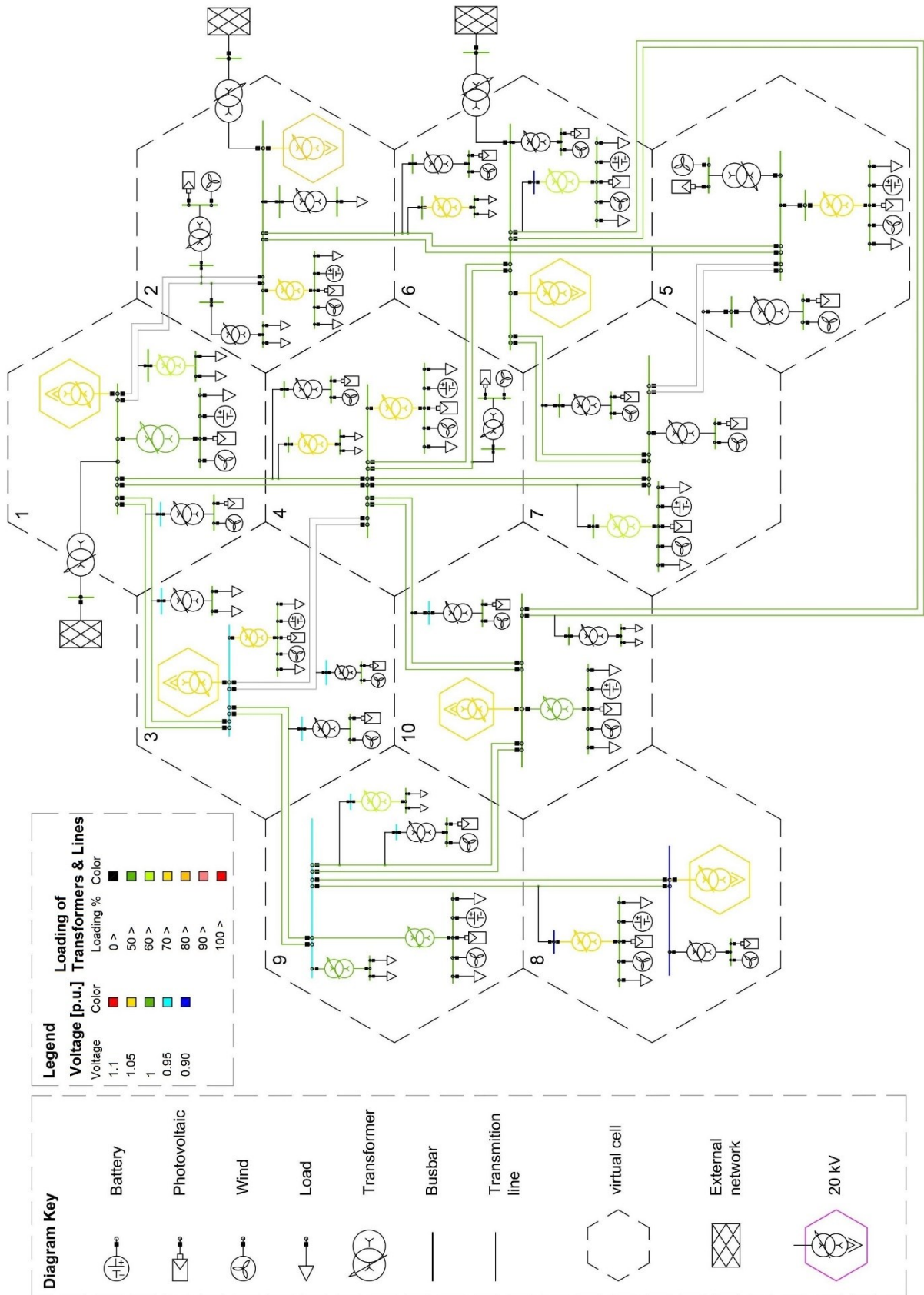


Figure 4-25: Contingency analysis for low RE generation and high load demand at 110 kV level

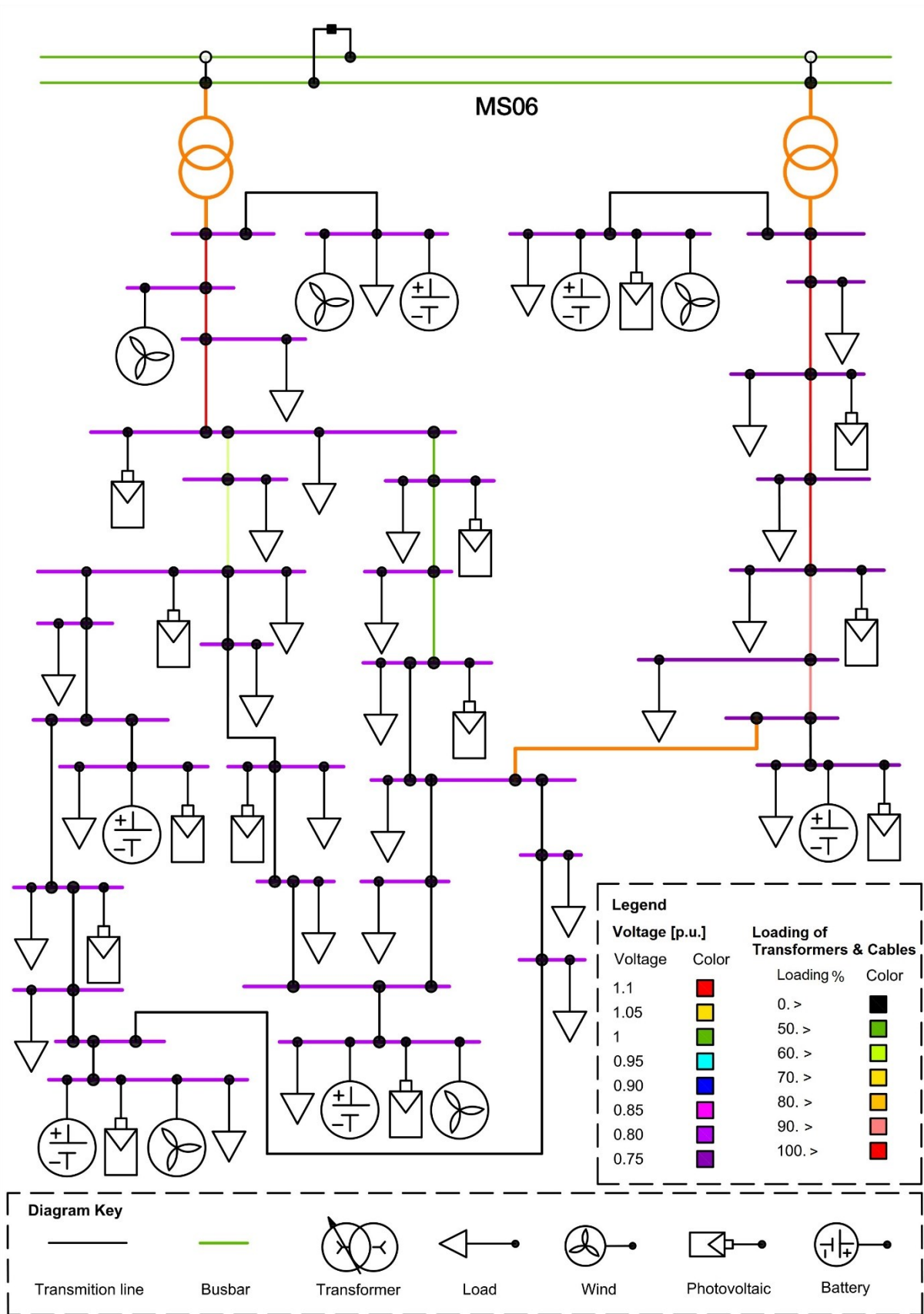


Figure 4-26: Contingency analysis for low RE generation and high load demand at MVN in cell 6

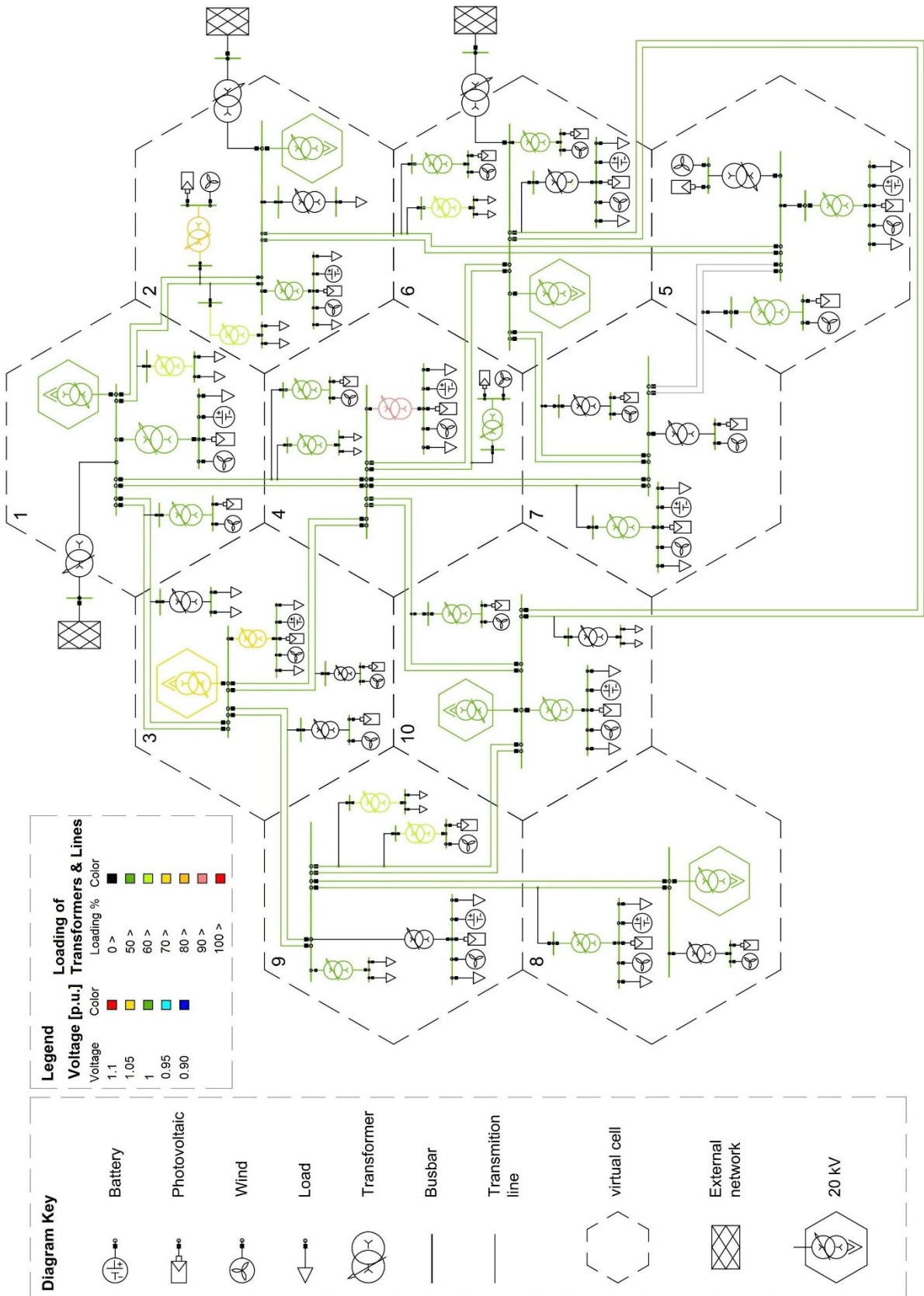


Figure 4-27: Contingency analysis for high RE generation and high load demand at 110 kV level

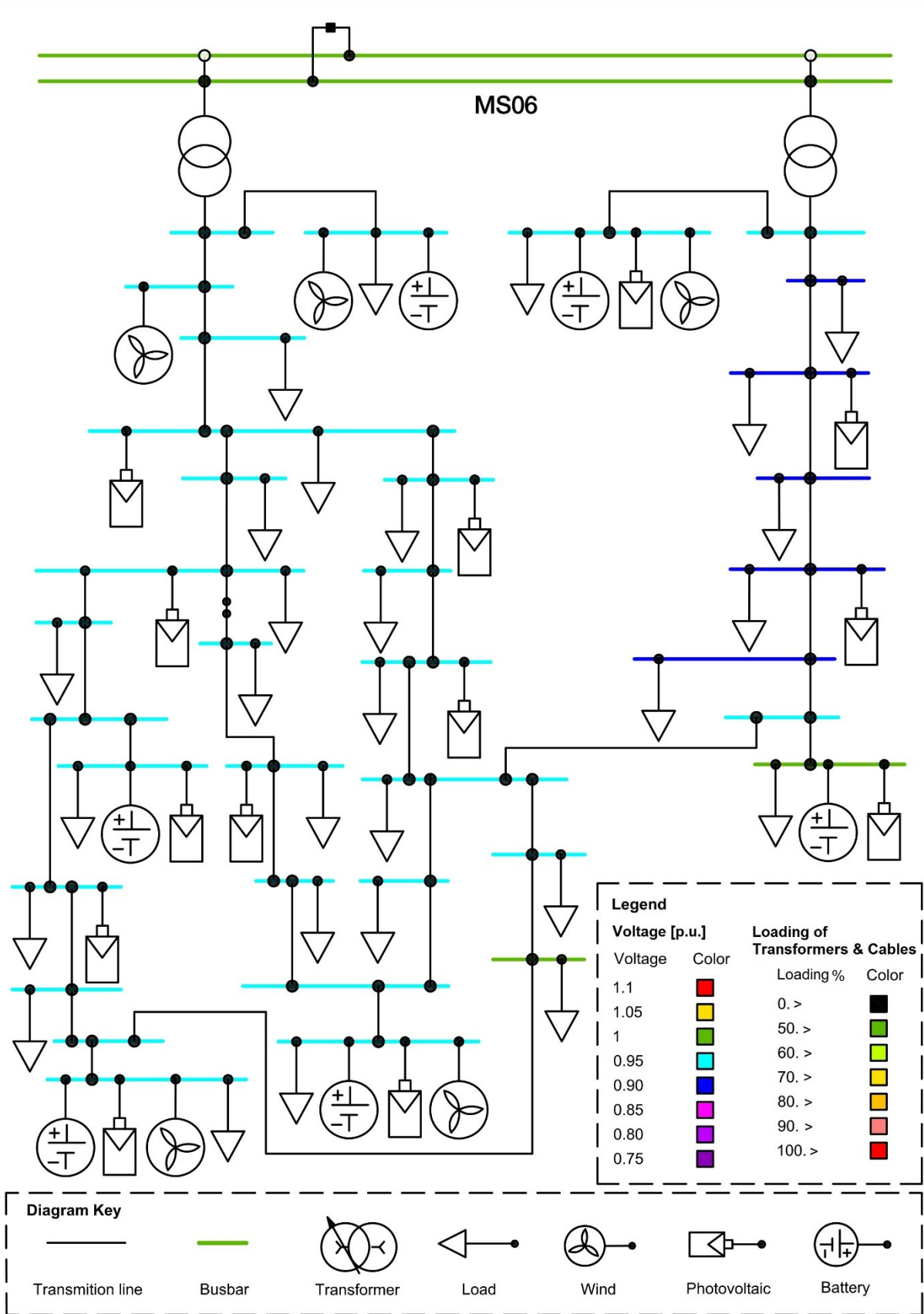


Figure 4-28: Contingency analysis for high RE generation and high load demand at MVN in cell 6

5. Chapter: Summary and Outlook

In this dissertation, the current methodology for expansion of RE technologies and their effects were investigated on the example of a synthetic power network. It was explained that the market-driven approach for expansion of RE technologies can have some drawbacks when the rapid expansion of RE technologies does not match with the pace of network development plans. At the present time, the expansion of the RE technologies is tied with parameters like yearly energy production from renewables and balance sheet autarky as goals of decarbonization process. Unfortunately, projection of the goals based on these parameters does not consider the technical restrictions of the power systems. Therefore, serious concerns about the reliability of power supply, the increasing need for ancillary services and the raising costs of the transition process are raised.

In this dissertation, the author suggested a new methodology that is based on the cellular approach. The suggested methodology ties the expansion of RE technologies to parameters like DLC, PUF and NPC in an optimized manner. The suggested methodology considers the current available potentials and limitations of the electricity network. It highlights the optimal technology-based expansion plan and recommends the best integration strategy for the RE technologies. The presented methodology was investigated on a synthetic power network. The investigations showed that the integration of the RE technologies into the synthetic power network can be realized up to the DLC value of 50% without extensive network expansions. Table 5-1 represents a short summary of the results for the solution with 50% DLC value which highlights a technical border for the solutions that are technically feasible without extensive network expansions.

NPC of the Suggested Solution (50% DLC)		€3.6 bn	
Installed Wind	Installed PV		Installed Battery
840 MW	1273 MW		467 MWh
Active Power Load of the Network		Reactive Power Load of the Network	
150 MW < P _{Load} < 750 MW		7 Mvar capacitive < Q _{Load} < 296 Mvar	
Active Power from Generators	Yearly Energy Yield	Yearly Energy Demand of Network	
0 MW < P _{Generation} < 875 MW	2.37 TWh	3.03 TWh	
DLC	PUF	Autarky of Balance Sheet	
50%	84%	78%	

Table 5-1: Summary of the results for the suggested solution with DLC value of 50%

The main outcomes of the dissertation can be summarized under the following points:

- In this dissertation two different optimization approaches were introduced and investigated. In the first optimization approach, minimizing the NPC value over 25 years was defined as the objective function while achieving a certain DLC value as the boundary condition. In the second optimization approach, maximizing the PUF value was defined as the objective function while achieving a certain DLC value as the boundary condition. The comparison of the both optimization approaches shows that the first optimization approach delivers better results in the sense of economic feasibility and practicability of the suggested solutions. The reason for that is the fact that in the second optimization approach, maximizing the PUF value is realized by utilization of enormous amount of battery modules to store the surplus RE generation inside the virtual cells that increased the NPC values drastically. Therefore, the results of the first optimization approach were considered as more realistic and were investigated further.
- The results of the second optimization approach for the synthetic network highlighted the DLC value of 50% as a border between two categories of solutions. For the first category of solutions with DLC values less than 50%, the optimization algorithm proceeds much faster and suggests solutions with reasonable increase of NPC values related to the increasing DLC values. For the second category of solutions with DLC values more than 50%, the optimization algorithm proceeds slower and it experiences difficulties in convergence to solutions. The suggested solutions for the second category showed much higher increases in NPC values by increasing DLC values, as more installation of RE generators and battery modules were required to satisfy the boundary conditions.
- The results of the QDS highlighted the 50% DLC value again as the technical border for the synthetic power network. Integration of more RE generators beyond this border led to overloading of the operational equipments. Accordingly, the author would like to point out that the current sketches for an autarkic renewable-based power system are not based on facts. It must be mentioned that utilization of storage technologies supports the integration of more RE generators into the power systems, however they are not a replacement for the secured power from conventional plants.
- In the course of the simulations, it was observed that there is a direct correlation between the rising number of the RE generators and the number of failed LFCs. Investigation of the failed LFCs reveals strong changes in direction of power flow within the neighboring time intervals. The permanent changes of the power flow direction can be considered as signs for the complexity of the operation. In such a power system, topics like feed-in management and redispatching will gain more weight which shall be investigated further by means of dynamic simulations.
- Based on the results of the QDS, planning of the suitable reactive power strategy for the RE generators within the availability time of the renewables has a significant importance. Results of the QDS proved that there is a direct correlation between the proper reactive power strategy and the reduced number of failed LFCs. The failed LFCs can be interpreted as critical operational situations which mostly happen due to overloading of the equipments. The author proposed a method based on sensitivity analysis for

assigning the proper reactive power strategy to each virtual cell. This method helped to reduce the power flow and accordingly the number of failed LFCs drastically.

- In addition to the problems from volatile renewable generation, provision of reactive power in power systems with high share of wind and photovoltaic plants is also a serious matter of concern. According to the calculations, in more than 70% of the entire period of a year the generation from photovoltaic parks is less than 10% of their installed capacity. The generation from wind parks are also less than 10% of their installed capacity in more than 55% of the entire period within one year. Considering the mentioned numbers and the technical frameworks for operation of the generators, it is clear that the RE generators have restricted potentials for provision of reactive power. As countermeasures for the mentioned restrictions, compensation facilities can be considered as possible solutions.
- The suggested methodology in this dissertation proposed the installation of 840 MW of wind, 1273 MW of photovoltaic and 467 MWh of battery storage for the synthetic power network by the DLC value of 50%. Considering the synthetic network with the peak active power demand of almost 750 MW and the reactive power demand that varies between 7 Mvar capacitive to 296 Mvar inductive. The ratio of the installed active power of the RE generators to the peak active load demand of the synthetic network is almost 2.8. This number is astonishing in comparison to power systems that rely mostly on conventional power plants with the secured power of about 90%. However, the ratio is understandable for a power system with RE technologies with less than 2% secured power supply.
- Regardless of the integration of RE technologies, voltage deeps in times with no generation remain as the permanent feature of the investigated synthetic power network. Therefore, raising the operational voltage of the slack busbars to higher voltages (like 1.05 p.u.) or utilization of compensation technologies for reactive power provision as countermeasures for strong voltage deeps at both 110 kV and 20 kV levels would be necessary. New interconnection between 110 kV and 380 kV levels and provision of reactive power from external connections can also help to avoid the extreme voltage deeps. However, construction of the interconnection between the voltage levels might correspond to higher costs in comparison to application of compensation technologies.

Coming back to the central question of this dissertation, the questions and the proposed answers by the author can be formulated as:

- 1) Is the current strategy helpful in reaching the defined goals for a sustainable, reliable and affordable power supply? Or is it gambling on the security of power supply to a very high price?

A methodology was developed and investigated in this dissertation for better integration of RE technologies into the distribution networks without extra need for extensive grid expansions. For the investigated synthetic power network, it can be seen that the DLC value of 50% (corresponding to 78% autarky of balance sheet) defines a kind of technical boarder. By integrating more RE generators beyond the detected technical boarder, expansion of the electricity network will be inevitable because of the overloading of the distribution lines. Based on the GWO results, it can be claimed that from this special point

integration of more RE generators does not bring remarkable additional benefits for the power system as for solutions beyond the 50% DLC values, the NPC of the solutions will rise dramatically (without consideration of the required network expansions). In other words, it might be possible to integrate more RE generators into the electricity network with extra costs and efforts, but the PUF will be decreased accordingly. Which states that a portion of the integrated potential cannot be used and must be ramped down or transported out of the system.

The results of the GWO show that for smaller DLC values, integration of RE generators have a good contribution in moving towards the defined sustainability goals. However, the results of the QDS proved that RE generators cannot be counted as reliable power sources even with the support of battery storage. Interactions of the synthetic network with the external networks are good evidences that the synthetic power network cannot be operated in an autarkic manner. Therefore, the security of the power supply is only ensured by having reliable sources which can be the conventional power plants.

The author believes that the proposed methodology in this dissertation helps to find out the above-described technical boarder of a power system. Integration of RE generators up to this special point, would have a good contribution to the sustainability goals with acceptable NPC values. However, integration of more RE generators beyond the found special point would have relatively small contribution to sustainability goals with relatively high NPC values. The investigations of the synthetic power network also showed that with increasing number of RE generators, topics like expansion of the electricity network, extra ancillary services and reserve power will definitely gain more weight. The author believes that the security of power supply without conventional power plants is an illusion and a gamble at a high price.

- 2) The current RE development strategies have caused operational complexities for power networks. How can we improve the strategies to facilitate the transition process by using the current available potentials?

Based on the results of the QDS for the synthetic power network, it could be seen that by moving towards higher DLC values (integration of more RE generators into the system), higher volatility of the feed-in power from the decentral generators would dramatically affect the power flow inside the system and cause operational complexities. The operational complexities within the QDS manifest themselves in form of convergence problems or failed load flow calculations. The author believes that the suggested methodology in this dissertation can reduce the operational complexities in two different ways which are very supportive to facilitate the transition process.

To justify this claim, the following aspects must be considered: 1- by using the methodology with the cellular approach, it is possible to integrate the right number of decentral RE generators at the right places inside the network (generation near load) and reduce the unnecessary transport of energy within the system and between the virtual cells. In other words, the active power flow within the system will be reduced drastically. 2- based on the proposed methodology, by assigning the right reactive power provision strategy to the decentral RE generators, the reactive power flow inside the system can

also be reduced accordingly. Considering the both mentioned aspects, the proposed methodology in this dissertation provided a way to reduce the power flow inside the synthetic power network that played a crucial role in better convergence of the load flow calculations (having less operational complexities).

It is clear that the high volatility of the production from wind and photovoltaic parks and the high costs of the storage technologies could cause some obstacles for a smooth transition process. However, the proposed methodology in this dissertation helped to find out the strengths and weaknesses of the synthetic power network at the cellular level, find out the available transport potentials of the synthetic power network and tie the expansion of RE generators to the specification of the local network. By means of that, it is also possible to find out which combination of technologies would have the most added value to help the system to have less operational complexities and move towards the defined goals.

At the present time, the proposed methodology is not used in practice for planning of the wind and photovoltaic parks as according to the directives, construction of the RE plants is only regulated by the availability of land.

- 3) How the development strategies can be improved to reduce the rising demand for specific ancillary services and grid stability measures?

In operation of the power systems, different types of ancillary services are required. In this dissertation, it was focused on reactive power provision and voltage stability as two important types of the required ancillary services. The QDS showed that the presented strategy in this dissertation has an important contribution in stability of the operation of the synthetic power network. By means of that, the right amount of reactive power can be provided from the decentral RE generators when they are available. The importance of the right reactive power provision strategy was also signified in the course of QDS by increasing DLC values. As due to higher volatilities from renewables in higher DLC values, the right reactive power provision strategy gains more weight because decreasing the load flow in these situations has a huge contribution in stability of the network operation. It is clear that with raising number of RE generators inside the synthetic power network, the need for extra ancillary services requires more attention.

The QDS showed that these services are required at local levels and at specific spatial areas. The simulations proved also that the RE generators have a very restricted potential for provision of reactive power. Nevertheless, simulations showed that by assigning the proper reactive power provision strategy at the cellular level to the RE generators for the periods of availability, a portion of the required services can be fulfilled. The author would like to mention that the methodology of assigning the right reactive power provision strategy to the RE generators might reduce the demand for specific types of required ancillary services and increase the grid stability at specific periods, however it is highly restricted to the availability of the generators. In other words, it is as trustable as the reliability of power supply from RE generators.

It is clear that the other aspects of the required ancillary services like short circuit power, system inertia, operating reserves and grid restoration issues could not be investigated by means of QDS and requires further investigations.

- 4) The raising costs of the transition process is a matter of serious concern. What kind of new integration strategies can help to optimally align the future development plans in a beneficial way?

The optimization and simulation results of the synthetic power network show that the raising costs of the transition process will stay as a matter of serious concern. Considering the optimization results of the synthetic power network, it can be seen clearly that the NPC values are increased drastically for higher DLC values. Thinking about the defined technical boarder of the synthetic power network which is reached by DLC value of 50%, it is clear that the costs of the system will increase further by going beyond this solution. In this case the required network expansion and the need for extra ancillary services must be considered for further investigations. It was mentioned before that the autarkic operation of the synthetic power network based on RE generators and battery storage is not possible. It can be stated that the larger the power system, the more challenging the transition process will be.

The results of this dissertation prove that with the proposed methodology a portion of the unnecessary costs can be prevented or postponed to the future with the optimal integration of the RE technologies. In the viewpoint of the author, the approach for reducing the unnecessary costs in the way of transition process in a power system can be boosted by performing the following three steps: 1- defining RE expansion goals based on parameters like DLC and PUF, 2- tying up the RE expansion goals to the available potentials of the electricity network considering the optimal technology-based expansion plan and 3- continuous evaluation of the results and correction of the RE and network expansion plans.

Considering the recent developments in German power system and based on the results of this dissertation, it can be stated without doubts that following the current strategies draws the electrical network towards its physical limitations. The raising number of the congestion problems and demand for extra ancillary services are the first warning signals of this transformation. Due to the existing frameworks and regulations of NDPs in Germany, it is clear that the pace of the network expansions cannot easily get aligned with the RE expansions. That means the mentioned concerns will remain for a while. The discussions about the reliability of power supply from RE generators and storage technologies do not match with the reality of power systems and are economically not feasible at the moment. The results of this dissertation also prove that upholding the power system without conventional plants (coal, nuclear or gas) is an illusion. Further integration of RE technologies into German power system leads to raising operational costs and further shutdowns of conventional plants results in more complexity of network operation and more dependency to the neighboring countries at high costs for covering the own demand.

The suggested methodology in this dissertation has the advantage that helps to reduce a portion of unnecessary costs or postpone the dispensable network expansion plans, but it

does not offer a solution for the whole problem. The proposed methodology in this dissertation is based on a two-step plan with optimization as the first step and QDS as the second step. The drawback of this method is in the simplifications for the optimization models. It could be seen that due to the simplifications, the found solutions after the technical borders of the power system can only be realized by network expansions. This matter provides the starting point for future research activities to improve the optimization model with less simplifications. Further developments of the mathematical methods for multi-objective optimizations, for instance minimizing the NPC while maximizing the PUF simultaneously, are also valuable activities for future works. Considering the operational challenges of the power systems with increasing RE technologies, dynamic simulation of critical situations will definitely reveal new valuable findings.

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6. Annex

6.1. Annex 1: Technical Frameworks

VDE-AR-N 4110 – related regulations for Medium Voltage Networks (MVN): [49]

Principally the operational voltage in MVN lies between 90% and 110% of the supply voltage. This regulation is very important when new elements are supposed to be connected to the MVN and depending on the situation, the voltage of the connection bus can change accordingly. In MVNs provision of reactive power from generation units plays an important role for static voltage stability. In this regard, generating units must meet the requirements at grid connection point according to Figure 6-1 if the infeed power is equal to the installed capacity. According to this diagram, reduction of active power infeed in support of reactive power provision is permitted. However, this action is not related to feed-in management as a security measure for network operators. If the infeed power is less than the installed capacity, the operational limits of the generators can be presented as in Figure 6-2. These operational limits are integrated into MVN part of the simulation models (refer to chapter 3).

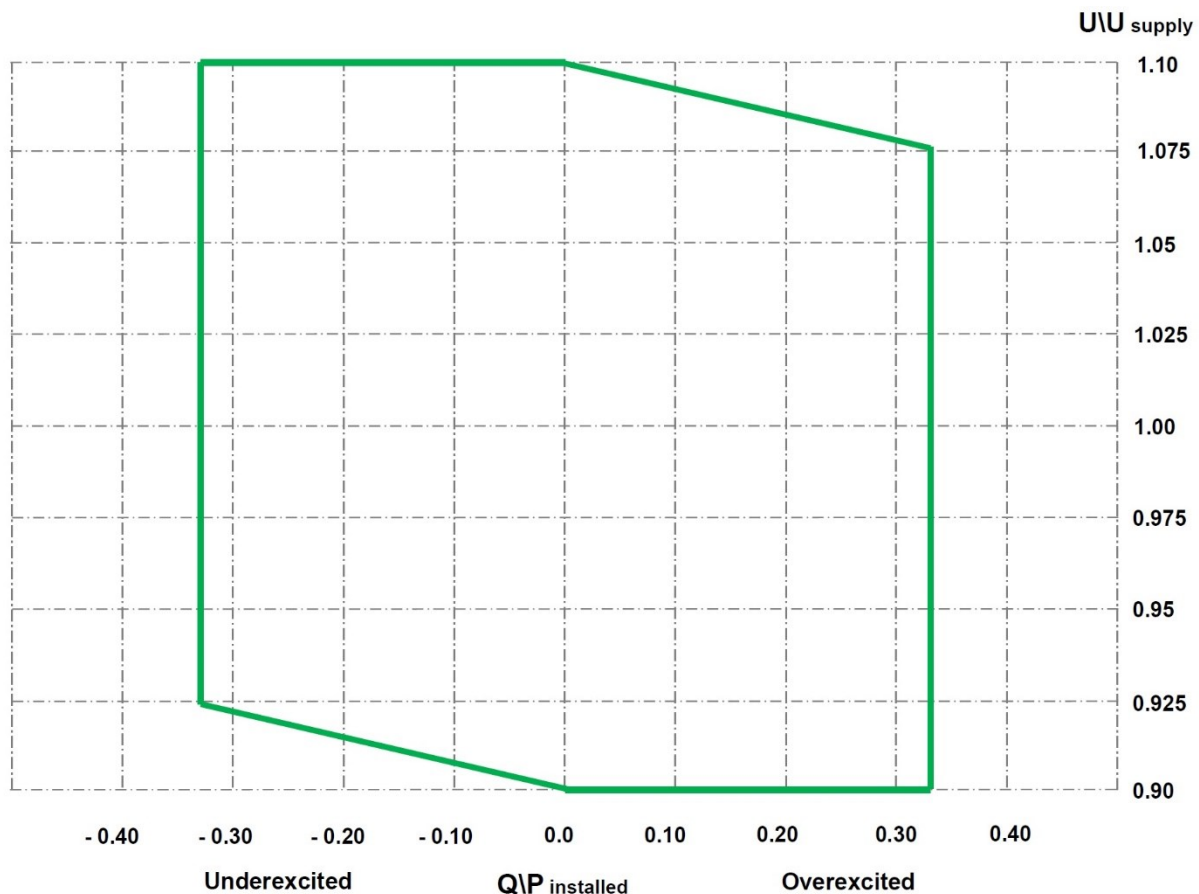


Figure 6-1: Requirements for provision of Q via generators at grid connection point in generator-reference arrow system (data based on: [48])

With the defined operational limits, grid operators can choose between the four available procedures for provision of reactive power according to the requirements of the network at the connection point. These procedures are:

- 1) Reactive power as a function of voltage ($Q(U)$ characteristic curve)

- 2) Reactive power as a function of active power (Q(P) characteristic curve)
- 3) Constant reactive power ($Q = \text{const.}$)
- 4) Constant power factor ($\cos \varphi = \text{const.}$)

In Q(U) procedures generators provide reactive power depending on the operational voltage of the connection point and based on the defined characteristic curve of the grid operator. An example of the Q(U) characteristic curve is illustrated in Figure 6-3. Voltage dead band is normally chosen between 0% to 1.5% of the reference voltage.

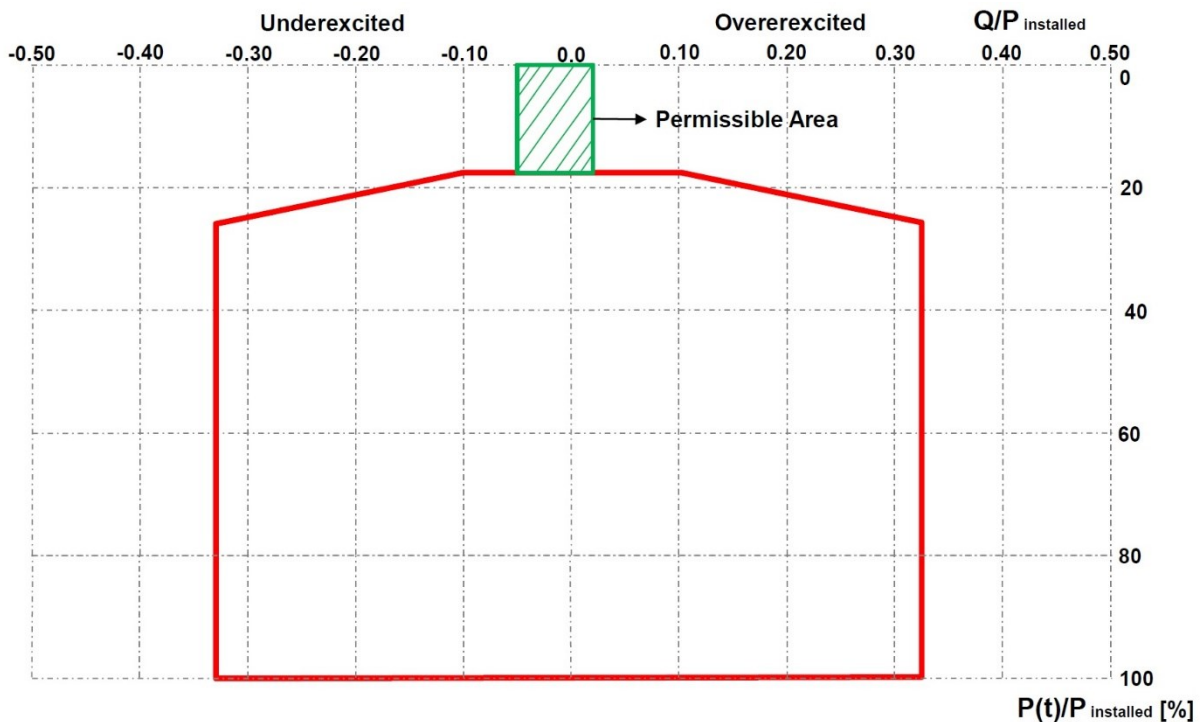


Figure 6-2: PQ diagram for provision of Q via generators at grid connection point in generator-reference arrow system (data based on: [48])

Sometimes it is better to define Q provision subjected to P generation. In this case Q(P) characteristic curve can be defined with maximum 10 supporting points by grid operators. Figure 6-4 illustrates an example of Q(P) characteristic curve. It is good to notice that Q(P) characteristic curve can also be converted into other forms. For instance, it can also be indicated as $\cos \varphi$ (P) characteristic curve.

It is clear that the grid operators have also the opportunity to prescribe constant reactive power ($\cos \varphi = \text{const.}$) or constant power factor ($\cos \varphi$). However, the defined values will have to stay in the operational limits.

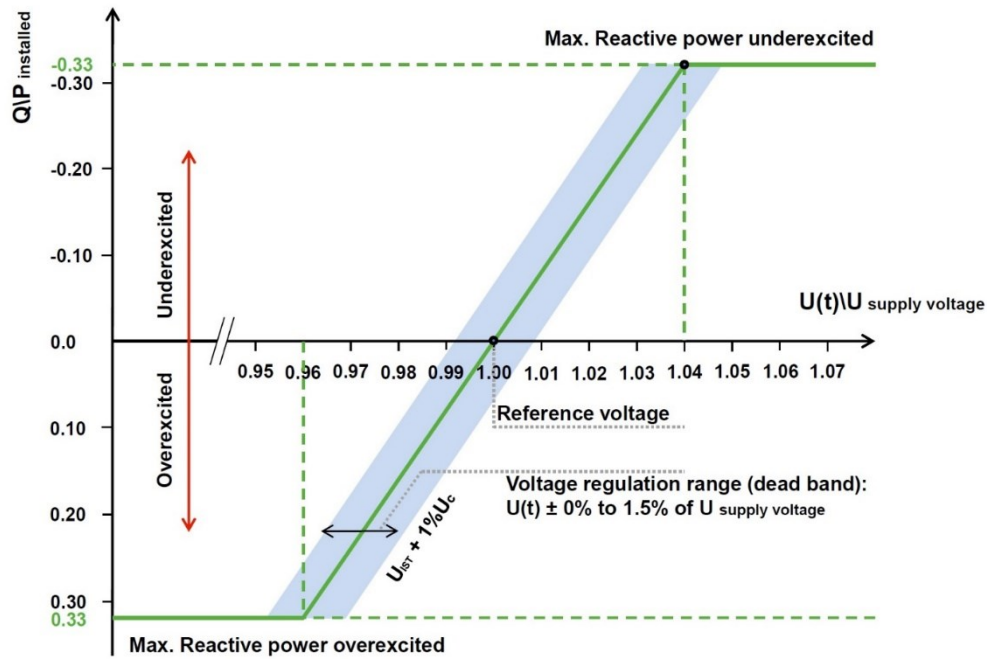


Figure 6-3: Example of a standard Q(U) characteristic curve for a generator in MVN in generator-reference arrow system (data based on: [48])

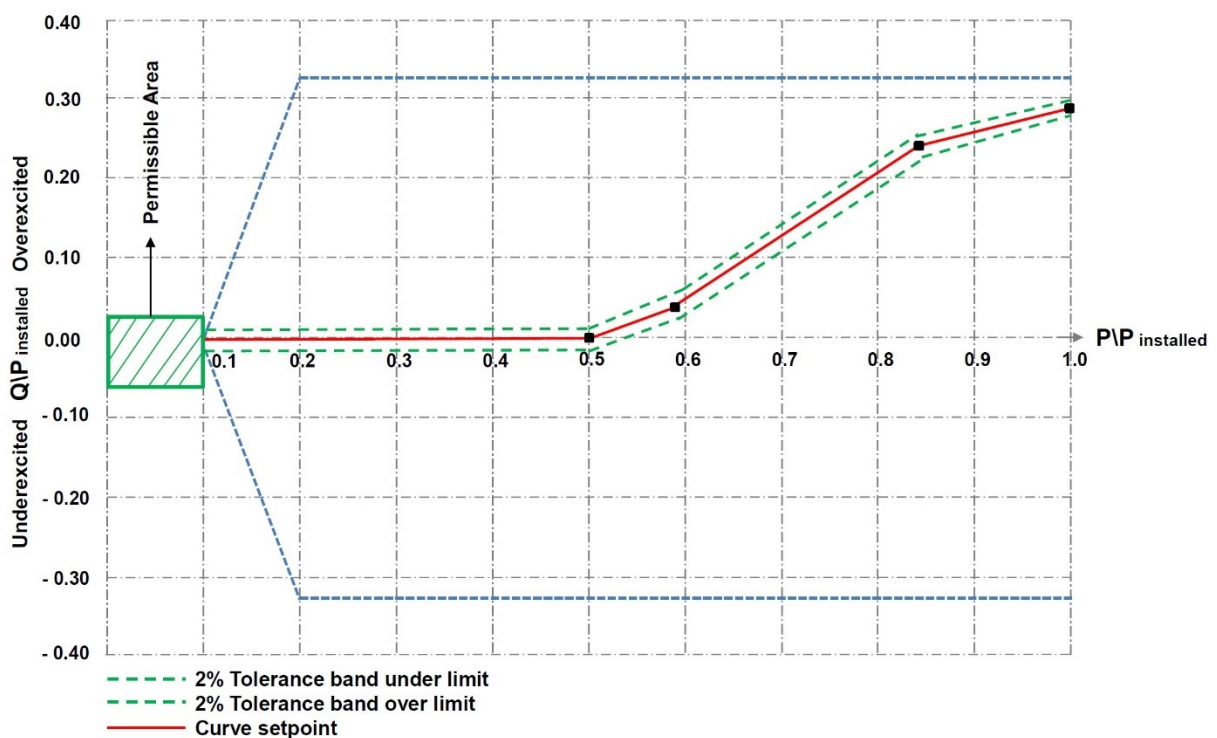


Figure 6-4: Example of a standard Q(P) characteristic curve for a generator in MVN in generator-reference arrow system (data based on: [48])

VDE-AR-N 4120 – related regulations for High Voltage Network (HVN) [49]

Operational voltage at grid connection point in HVN is defined to be between 96 kV to 127 kV. Similar to MVN, reactive power provision through generators is an essential foundation for static voltage stability in HVN. Figure 6-5 specifies different variants of

requirements for provision of reactive power via generators at grid connection point. For the fulfillment of requirements, grid operators are entitled to choose a specific variant according to their network condition at the planning phases of grid connection. The specification of generators for provision of reactive power can also be illustrated in form of PQ diagram as shown in Figure 6-6. This diagram visualizes the reactive power demand in accordance with the installed active power and instantaneous active power.

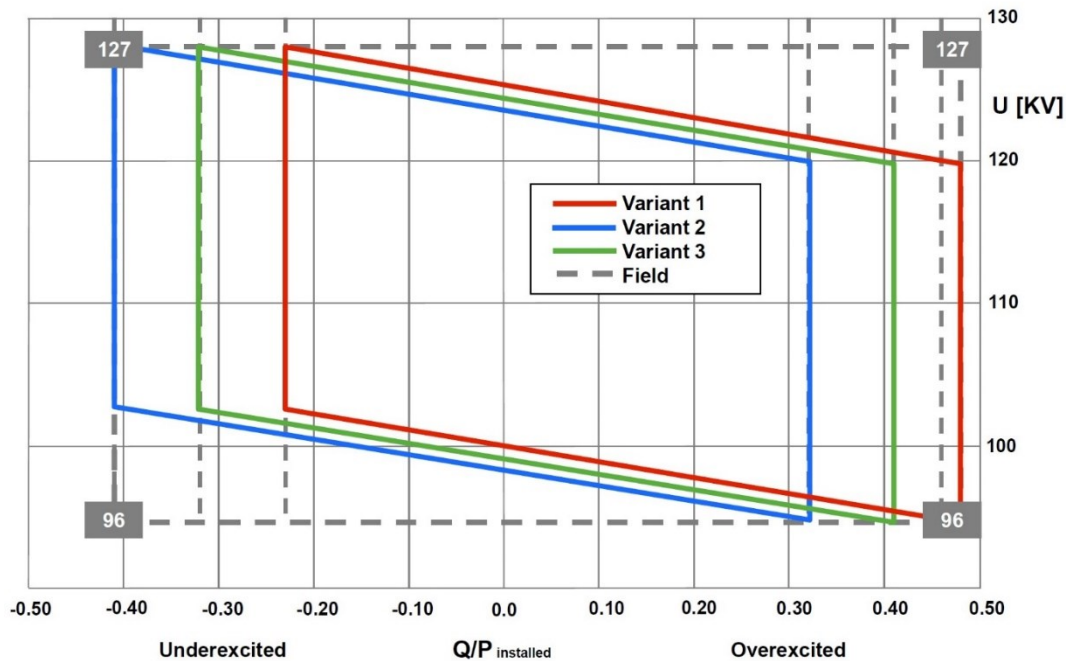


Figure 6-5: Possible variants for provision of Q via generators at grid connection point in HVN in generator-reference arrow system (data based on: [49])

Similar to MVN, the same four procedures are defined for provision of reactive power in HVN (Q(U), Q(P), Q = const. and $\cos \varphi = \text{const.}$). In this regard, the network operator specifies one of this procedures for the plant owner in planning phase of grid connection.

In Q(U) procedure, the grid operator defines a specific characteristic curve with fixed values for gradient, dead band and reactive power provision. The reference voltage will then be communicated via telecontrol technologies. Similar to Figure 6-3, a Q(U) characteristic curve for HVN can be defined. The voltage dead band for Q(U) characteristic is adjustable between 0% to ± 5 % of the defined reference voltage. Gradient m is also an adjustable parameter which has to be specified by network operator and lies normally between 3% to 12%. Network operators have also the possibility to define a Q(P) characteristic curve.

Grid operators have also the opportunity to decide on choosing other strategies like constant reactive power (Q = const.) or constant power factor ($\cos \varphi$). However, the defined values must be defined inside the operational limits as introduced in Figure 6-6.

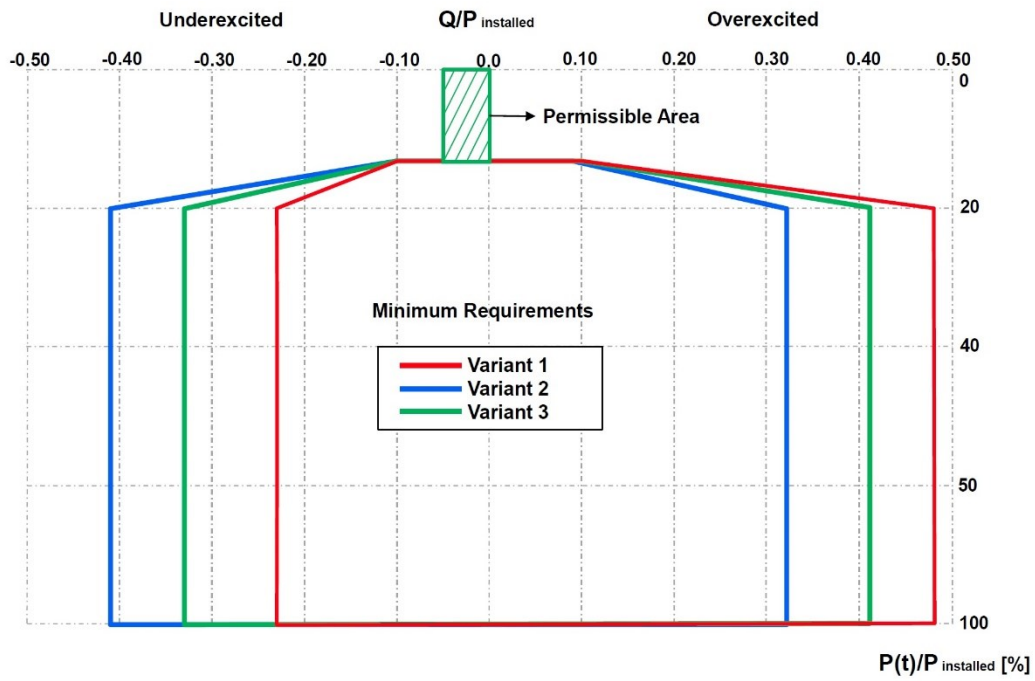


Figure 6-6: PQ diagram of variants for provision of Q at grid connection point in generator-reference arrow system (data based on: [49])

6.2. Annex 2: Topology and Detailed Structure of Synthetic Power Network

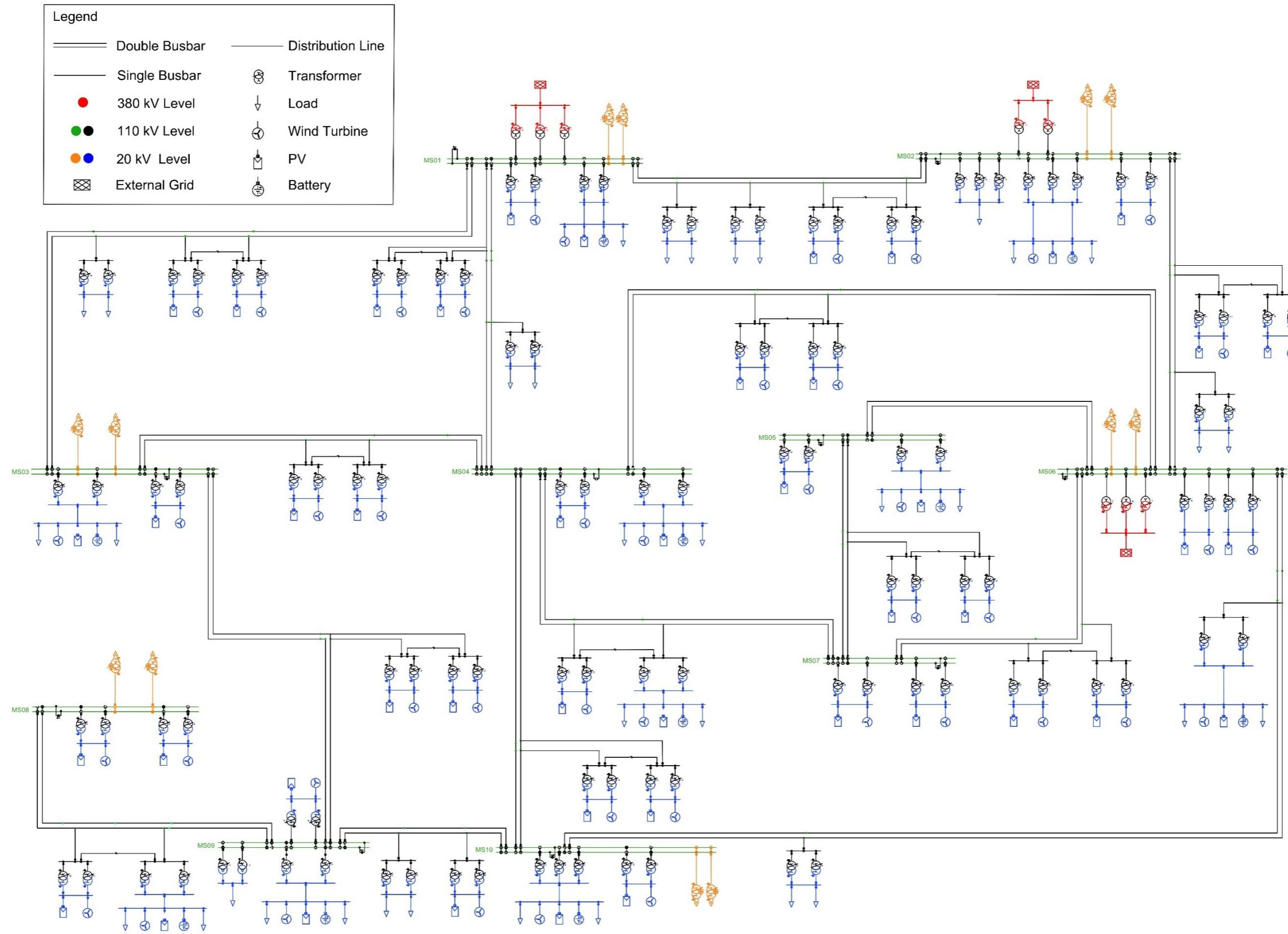


Figure 6-7: Global view of the synthetic power network

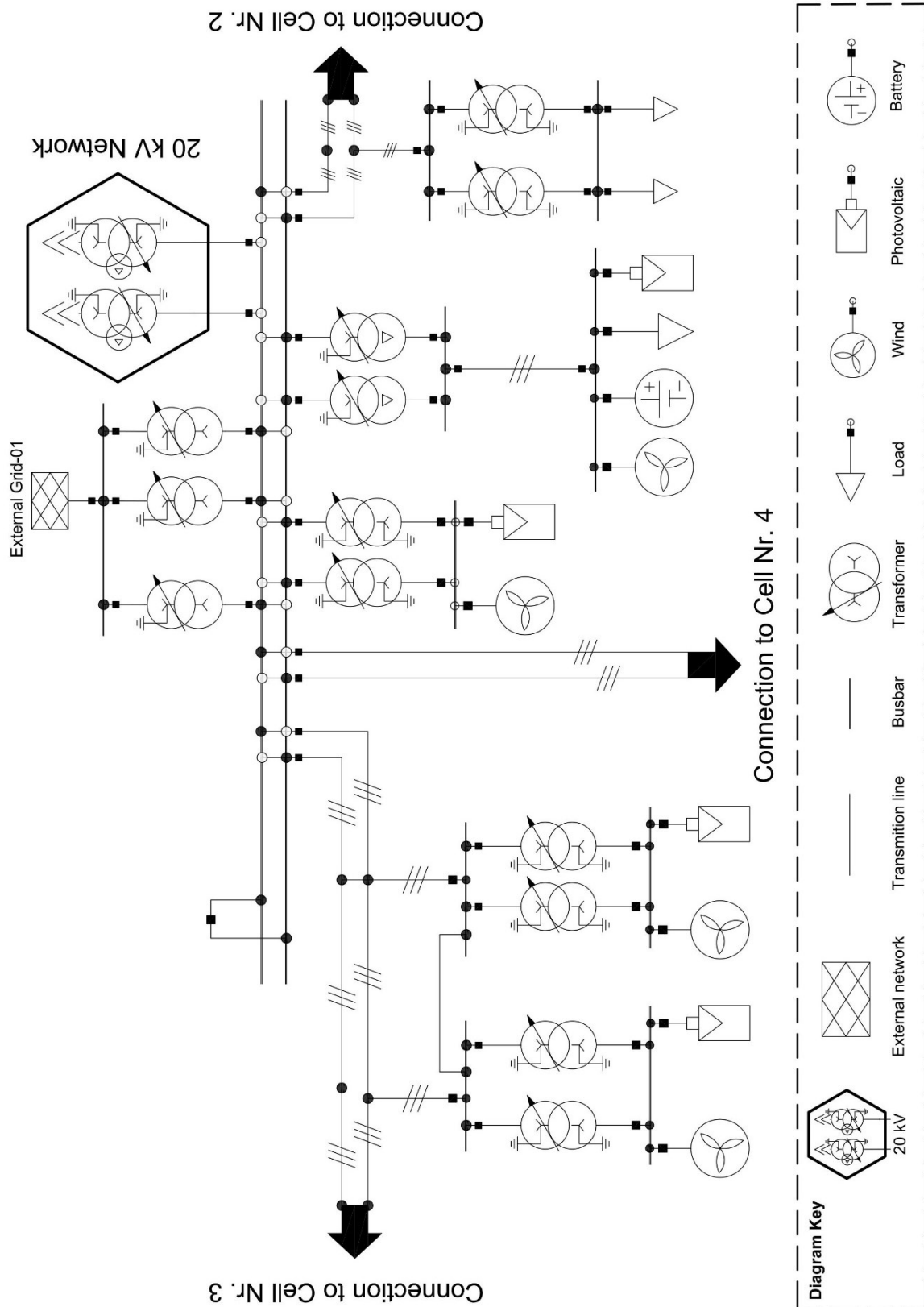


Figure 6-8: Structure of virtual cell number 1

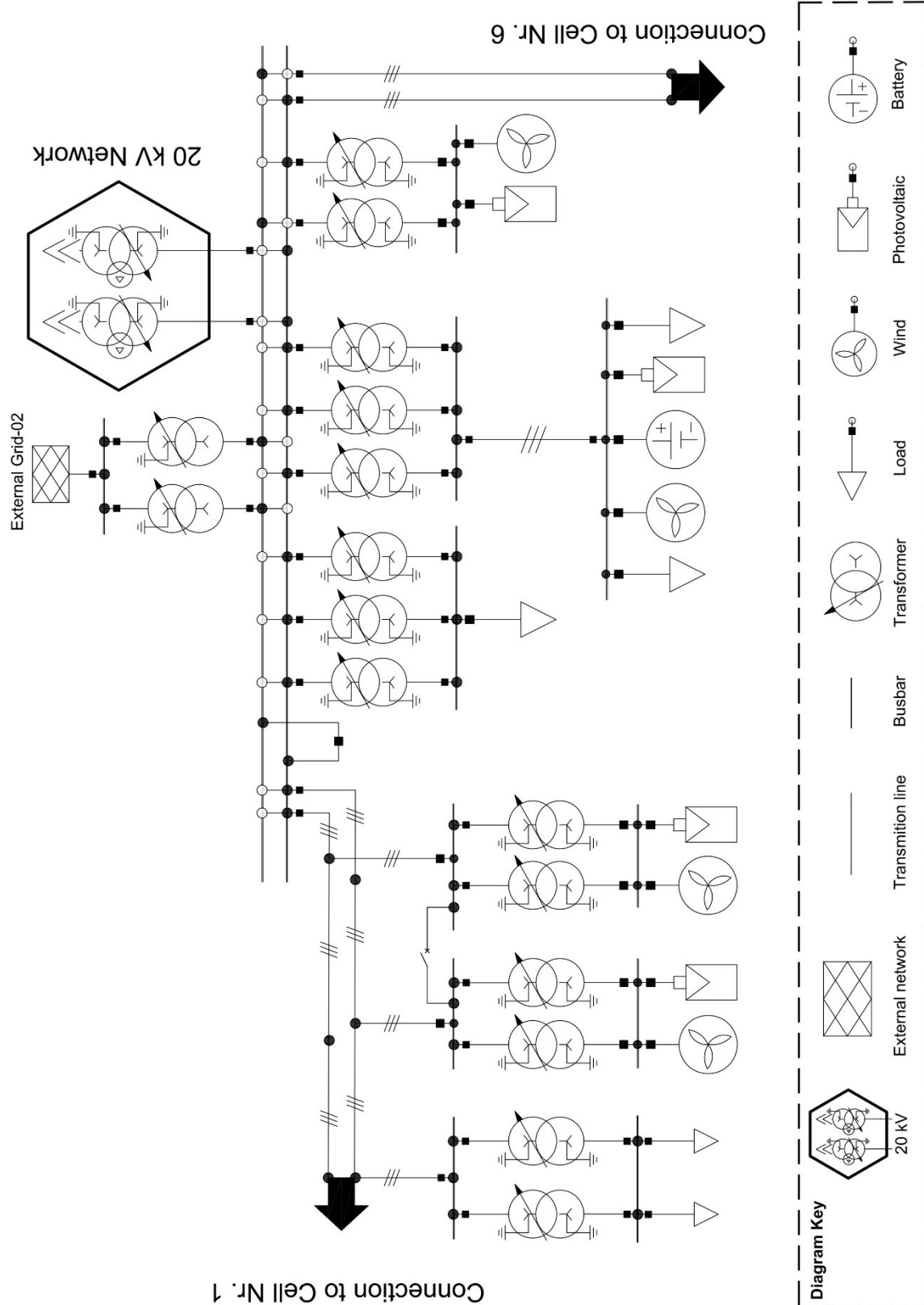


Figure 6-9: Structure of virtual cell number 2

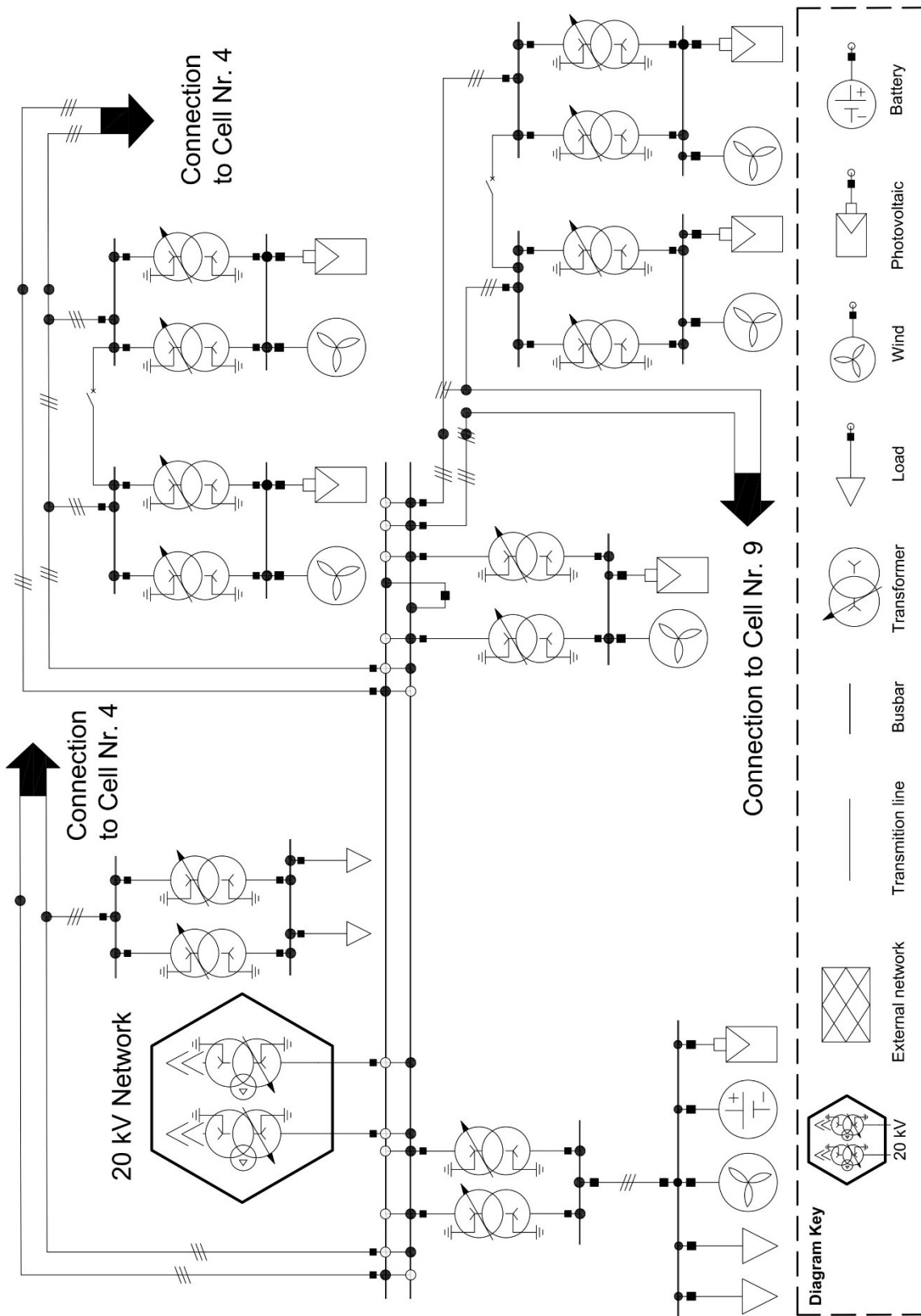


Figure 6-10: Structure of virtual cell number 3

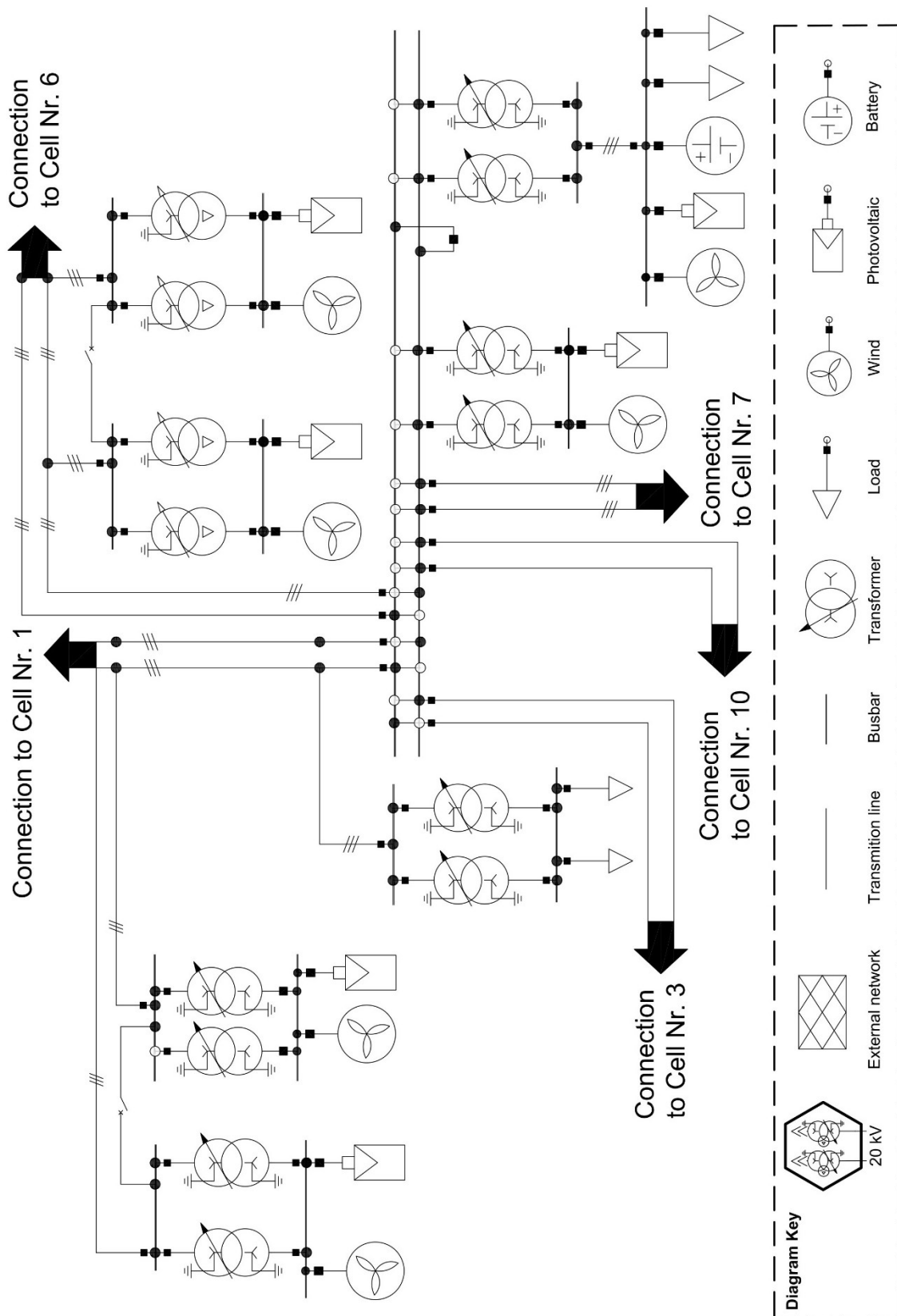


Figure 6-11: Structure of virtual cell number 4

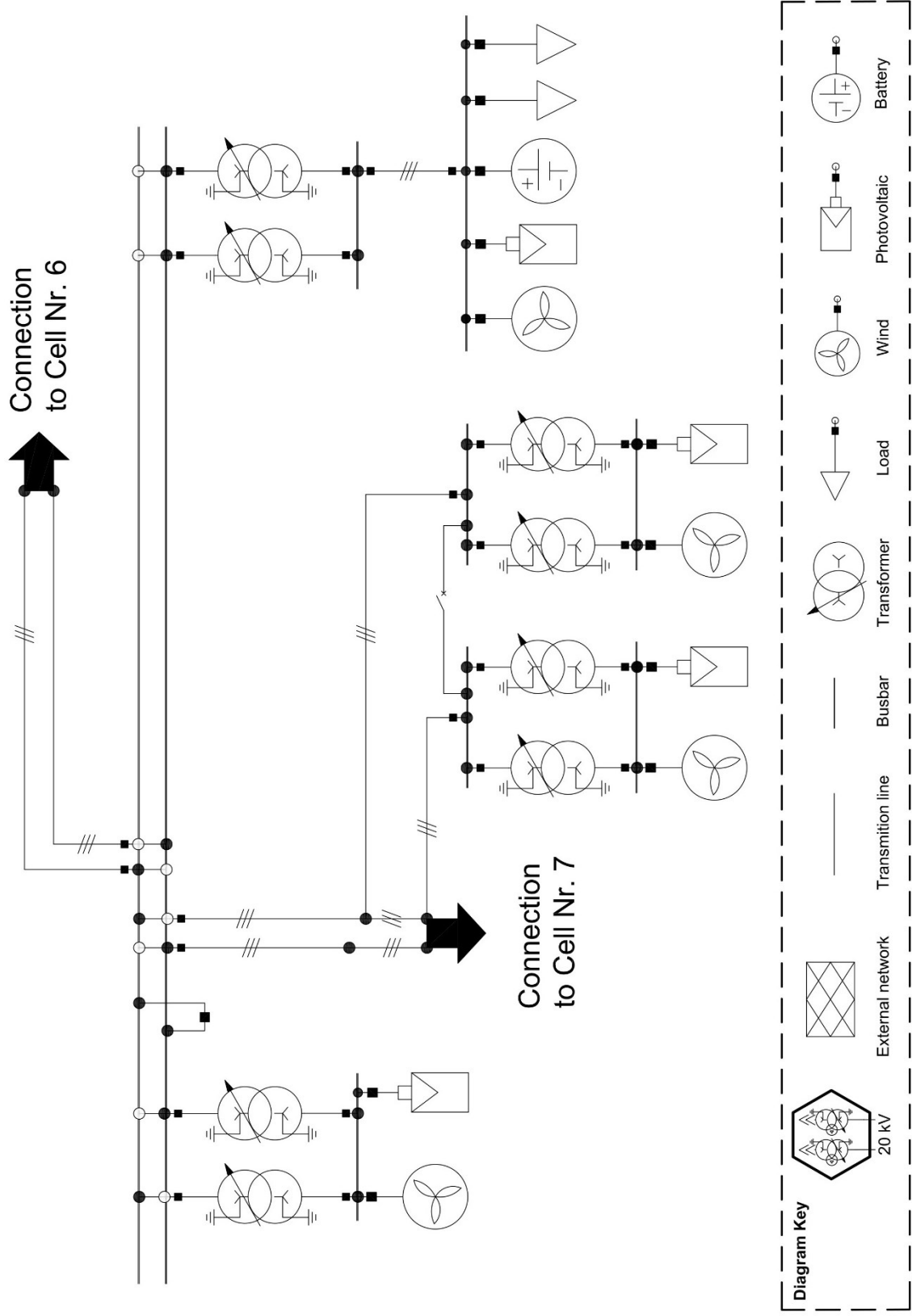


Figure 6-12: Structure of virtual cell number 5

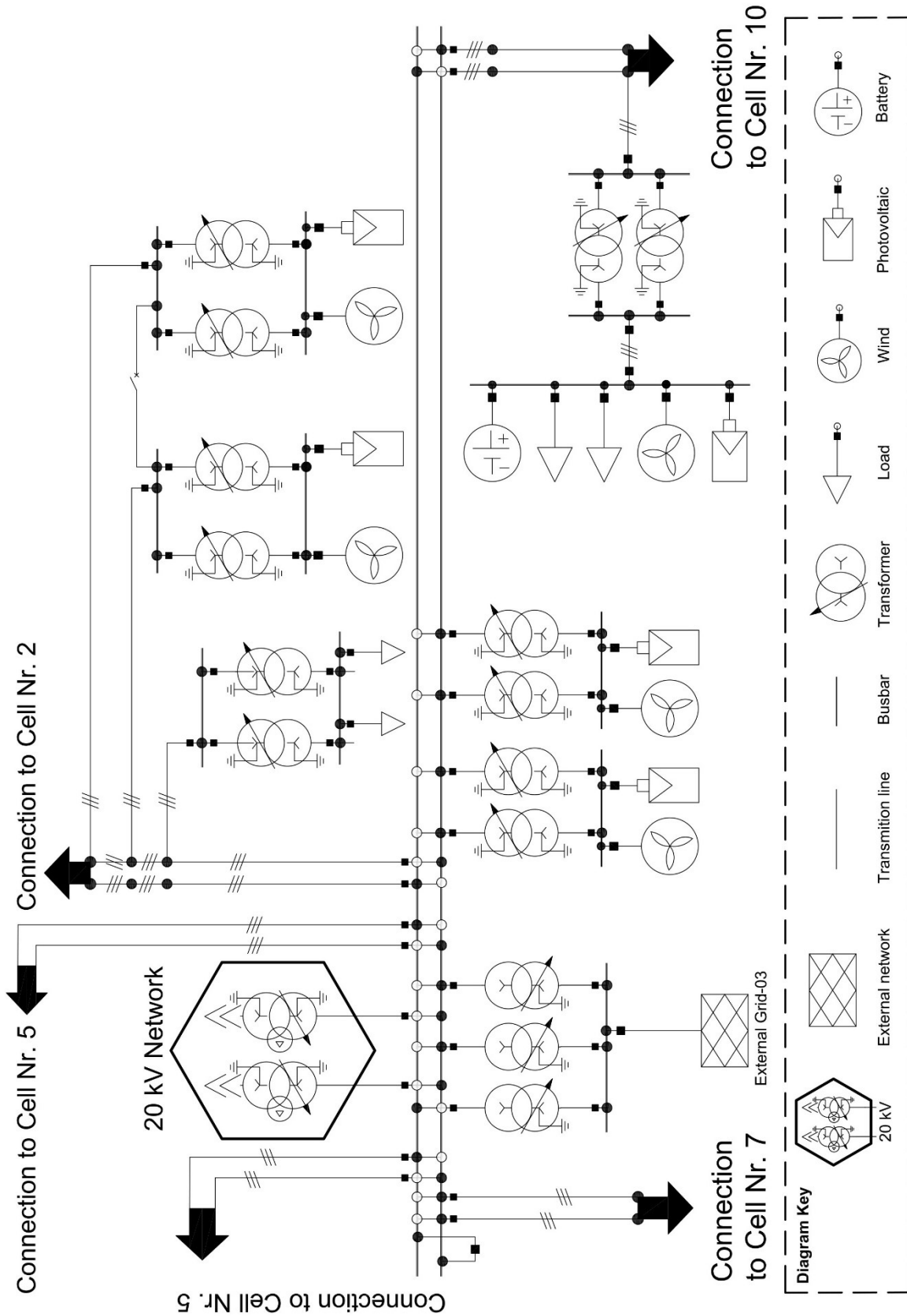


Figure 6-13: Structure of virtual cell number 6

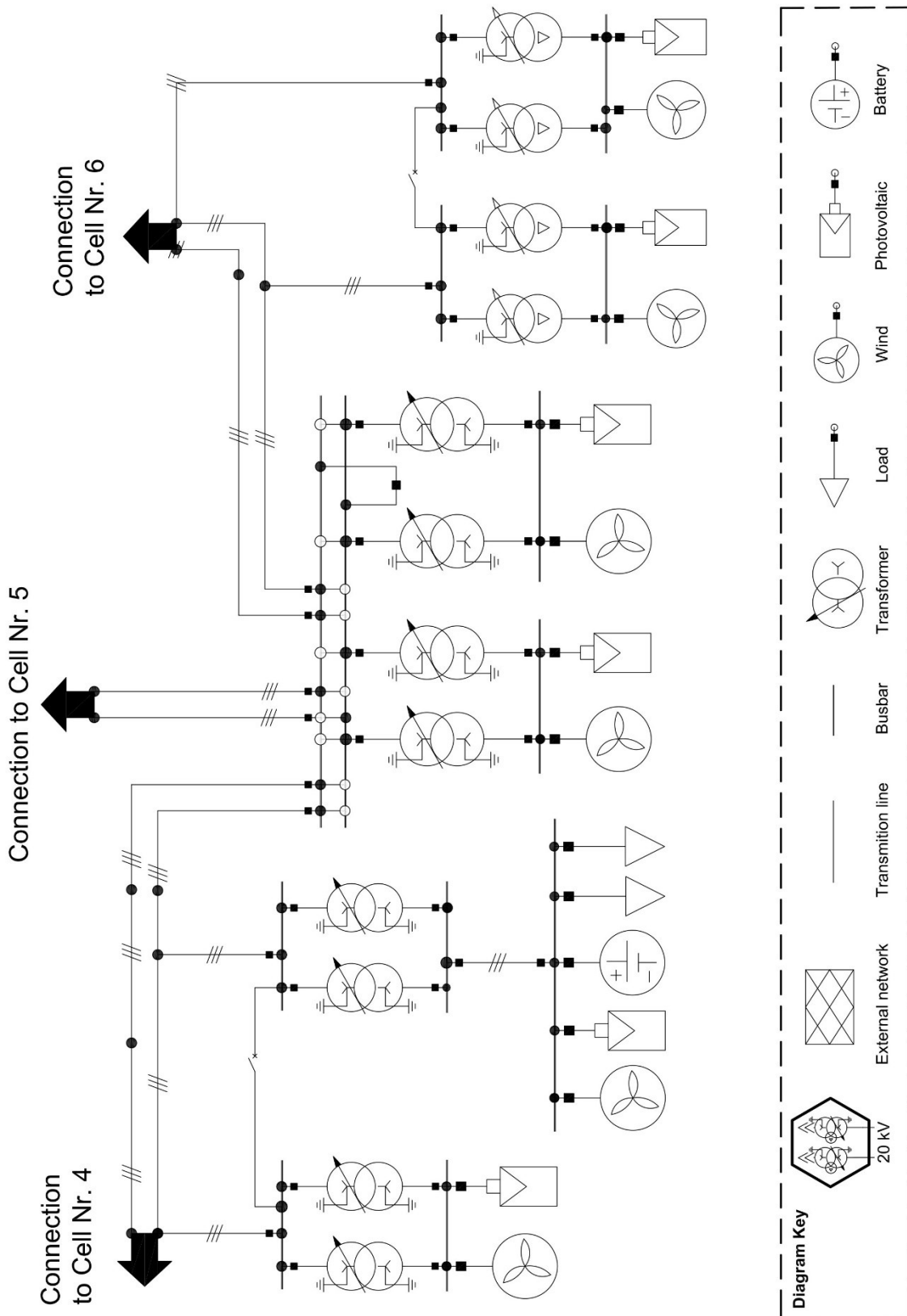


Figure 6-14: Structure of virtual cell number 7

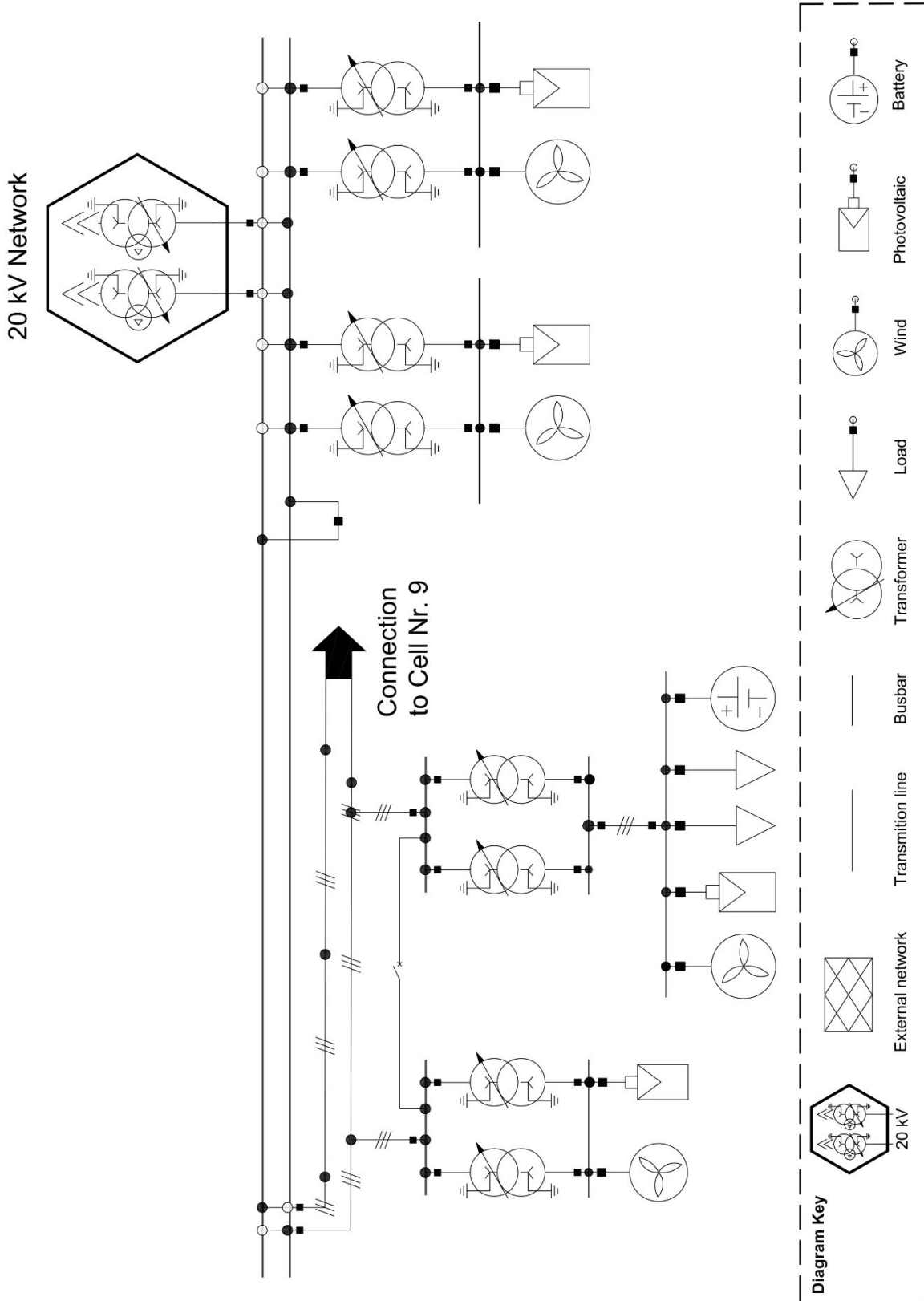


Figure 6-15: Structure of virtual cell number 8

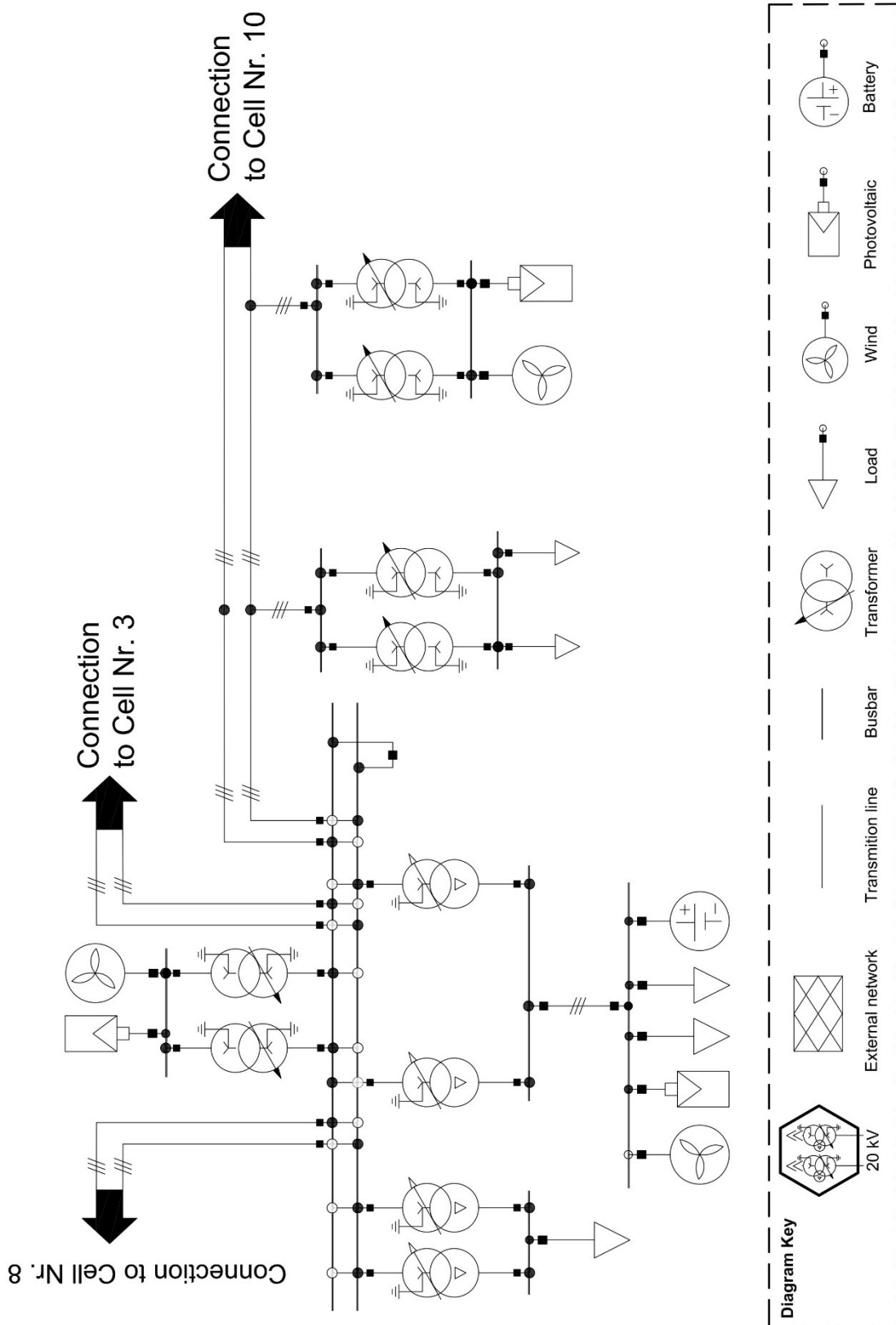


Figure 6-16: Structure of virtual cell number 9

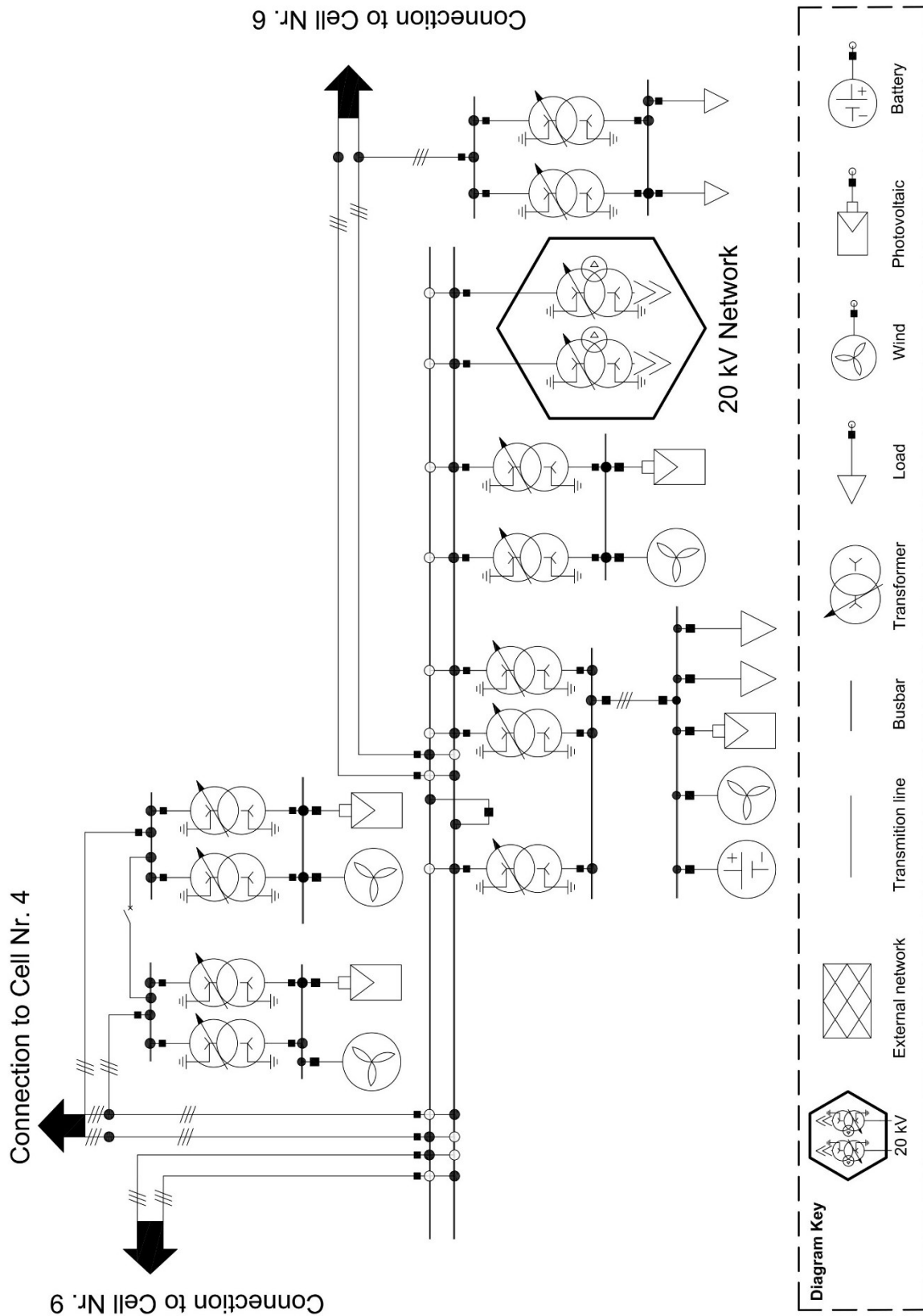


Figure 6-17: Structure of virtual cell number 10

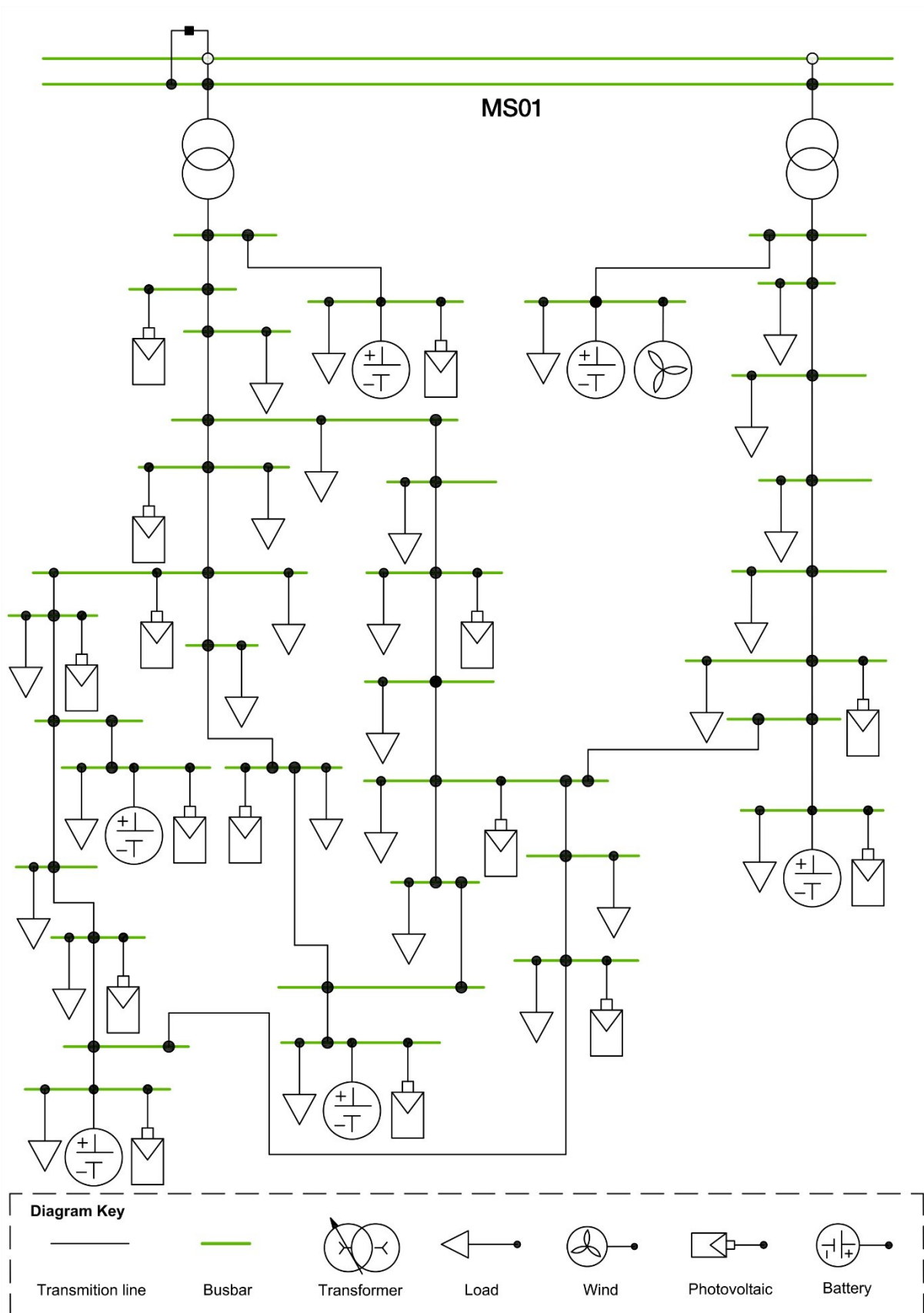


Figure 6-18: Connected 20 kV network to cell 1

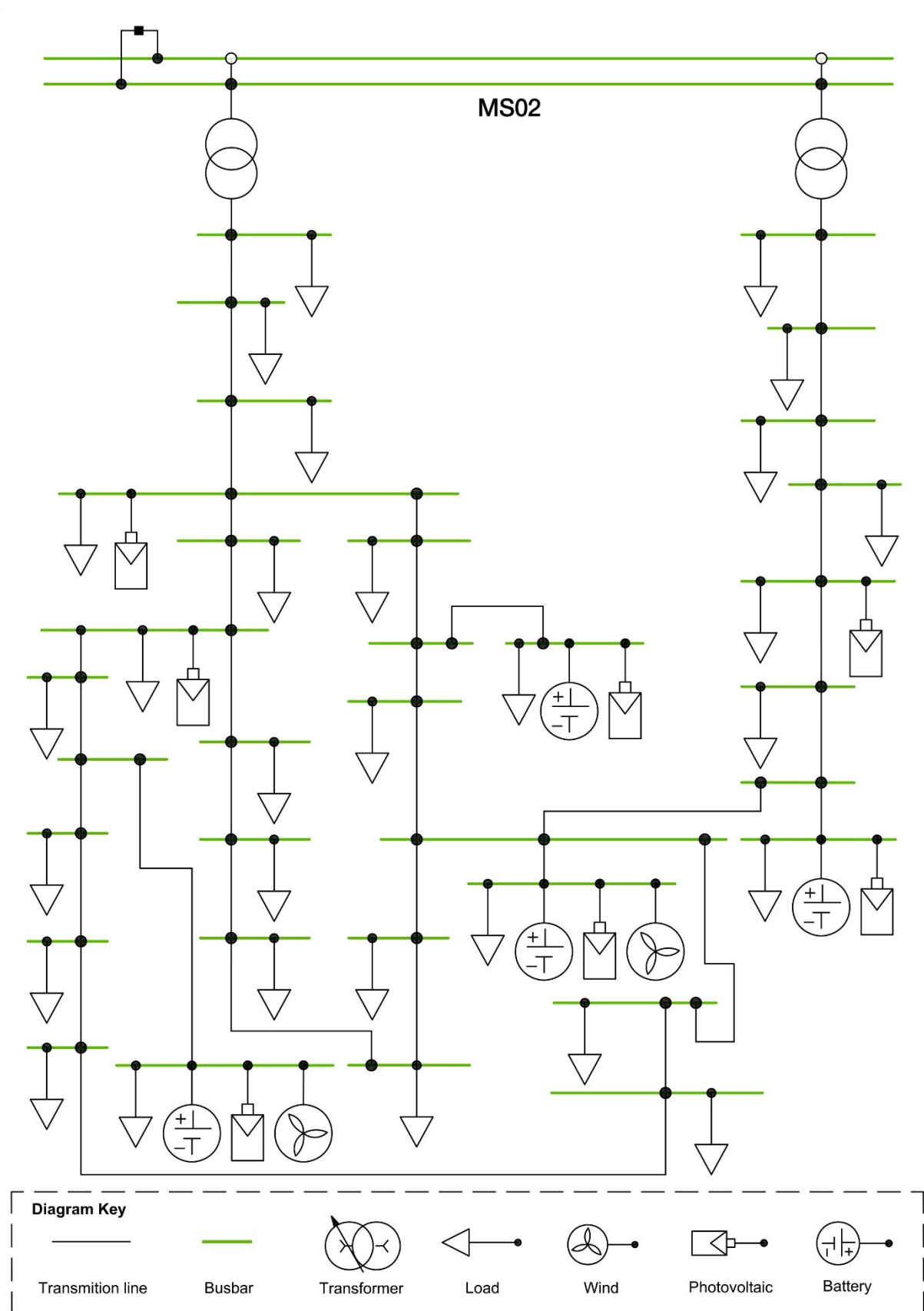


Figure 6-19: Connected 20 kV network to cell 2

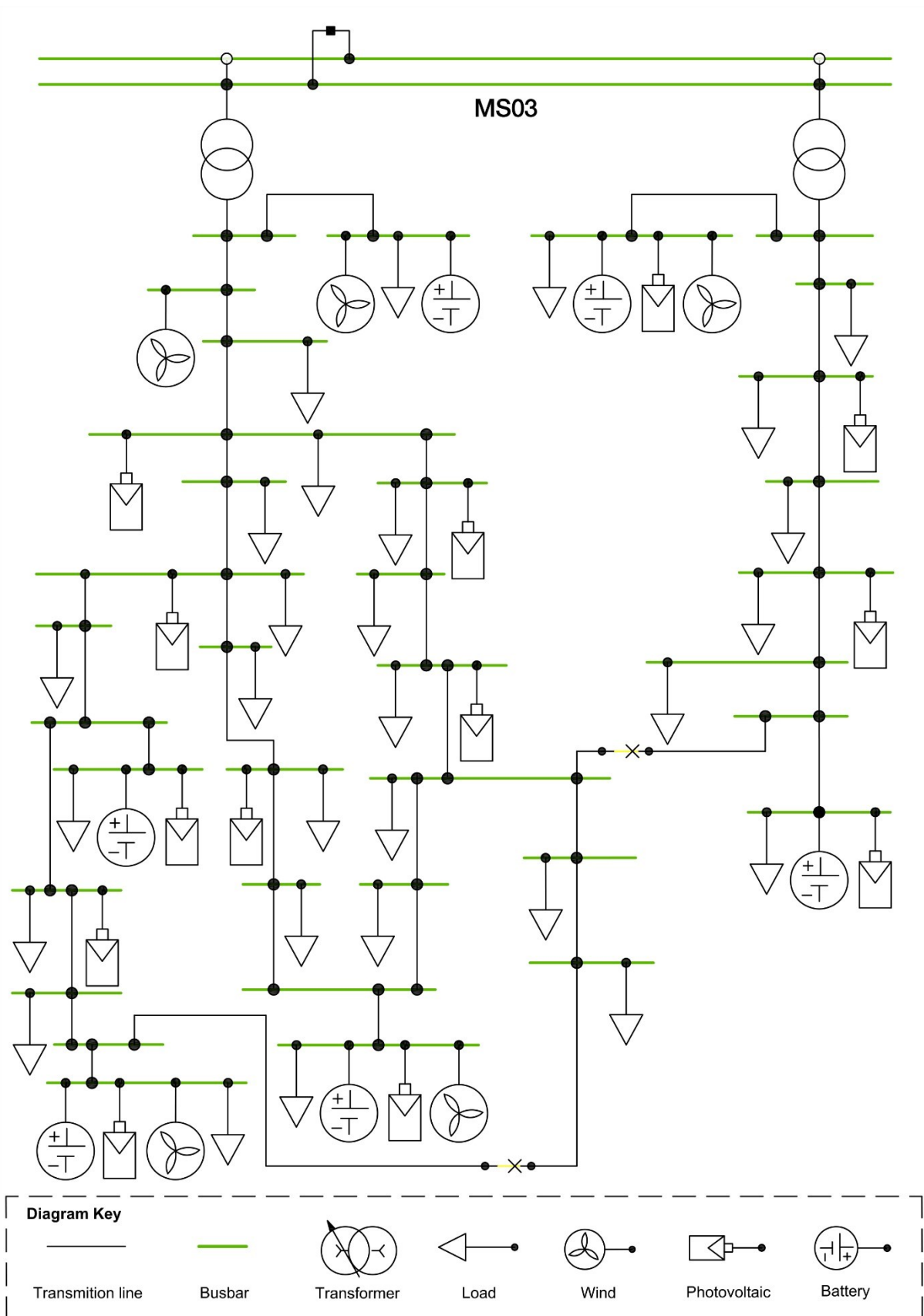


Figure 6-20: Connected 20 kV network to cell 3

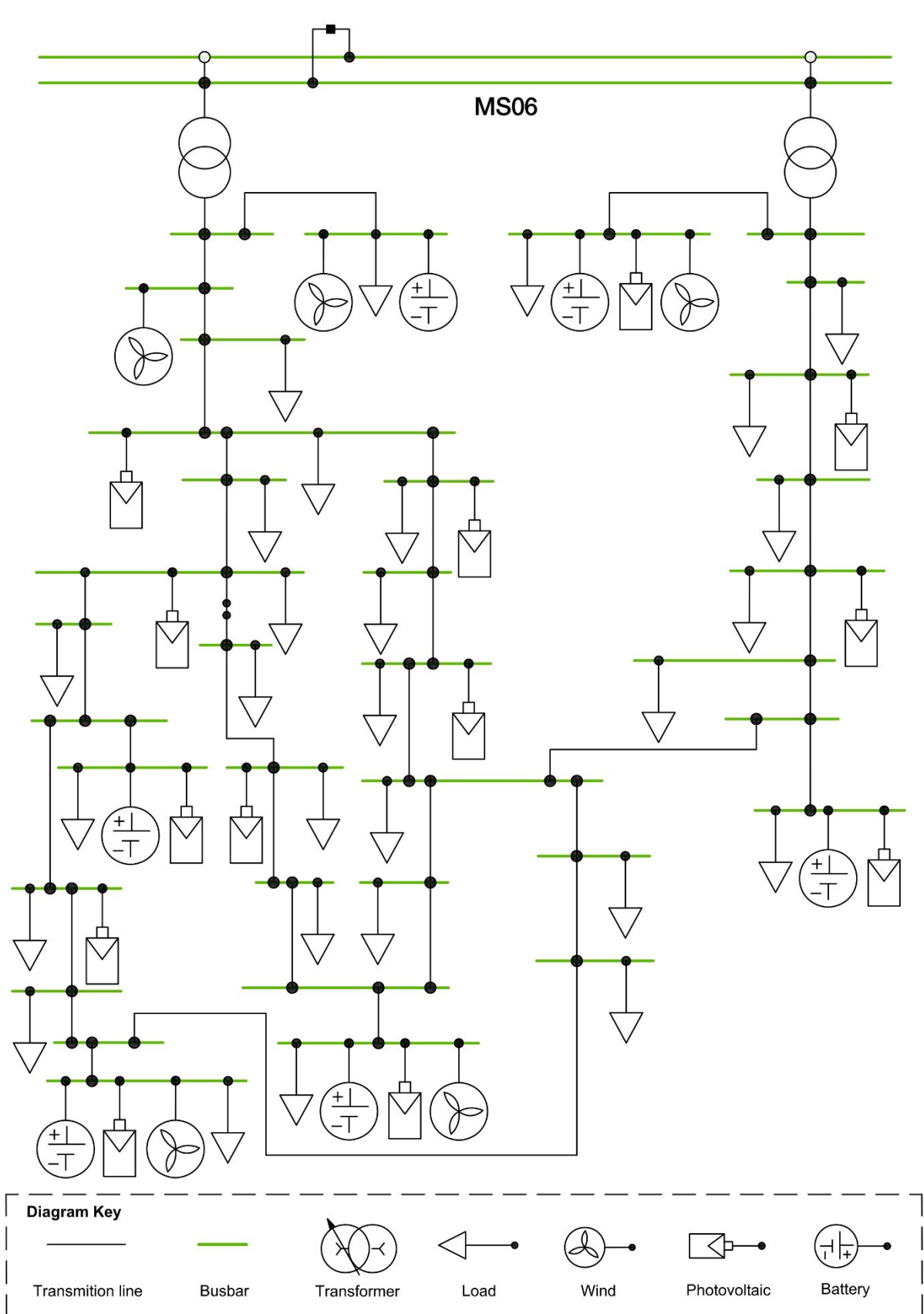


Figure 6-21: Connected 20 kV network to cell 6

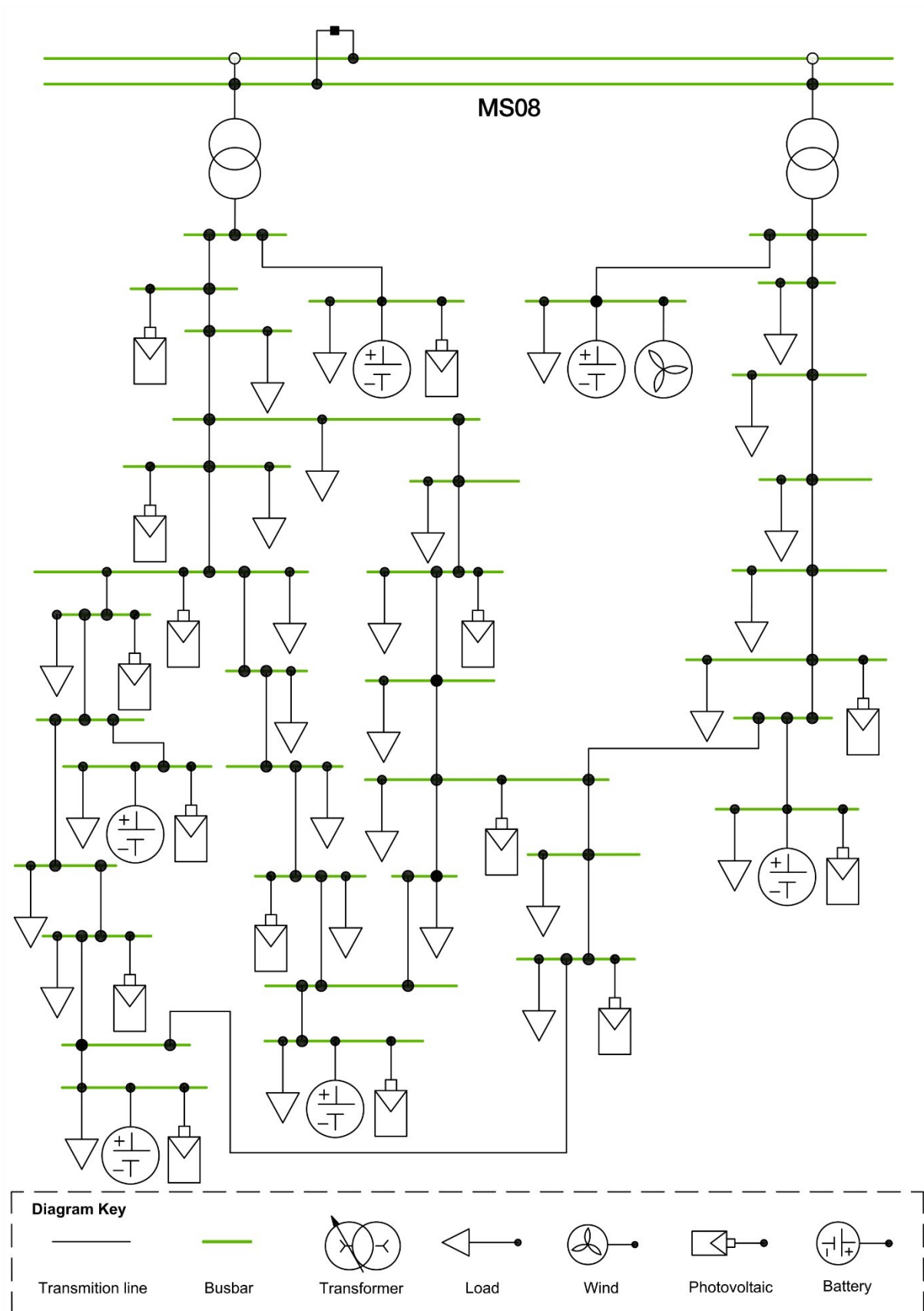


Figure 6-22: Connected 20 kV network to cell 8

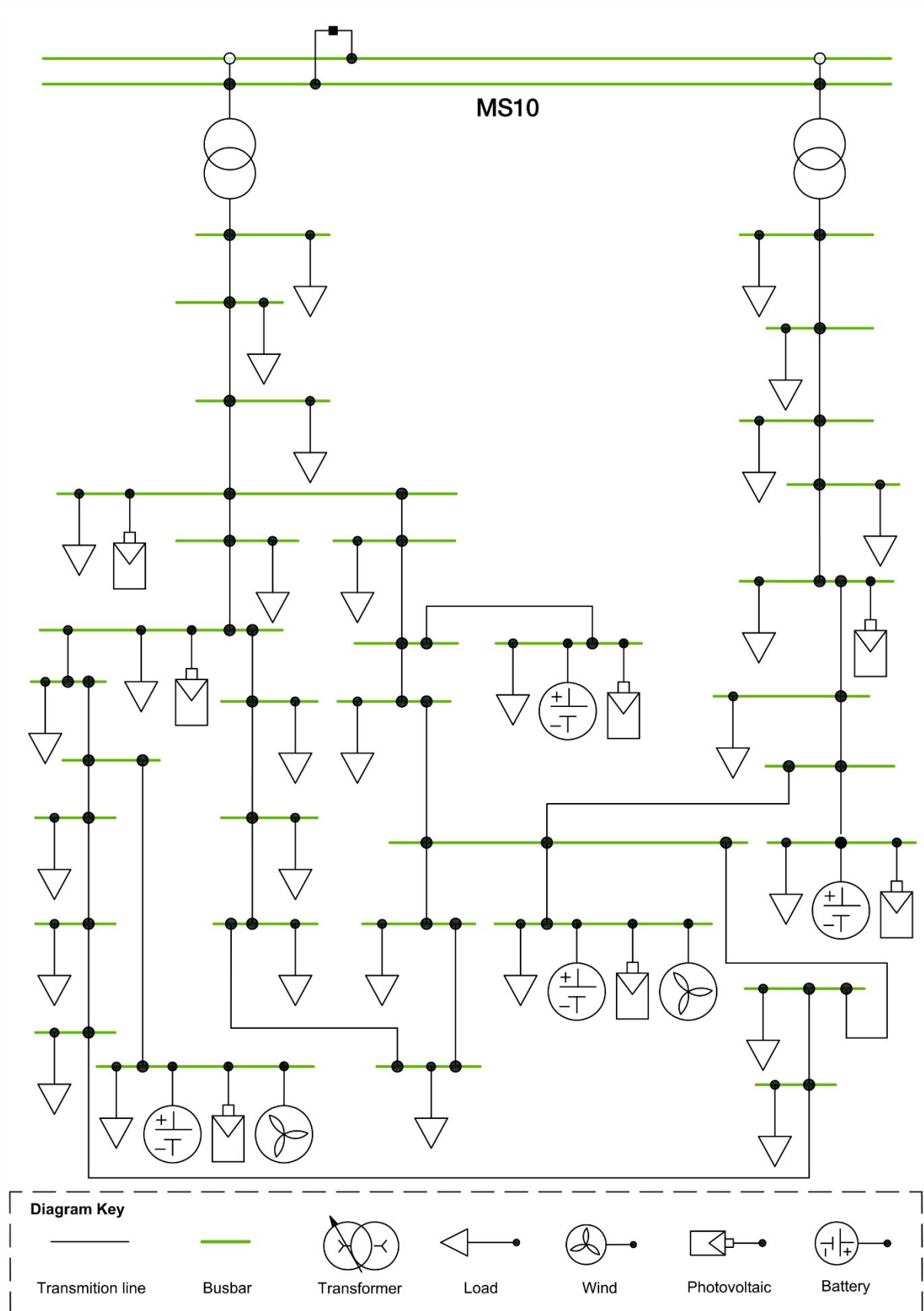


Figure 6-23: Connected 20 kV network to cell 10

6.3. Annex 3: Calculation of Wind and Photovoltaic Power

In order to calculate the output power of wind and photovoltaic generators, recorded hourly historical data of 2018 from Germany's national meteorological service were utilized [50]. Based on the presented methodology below, five different generation characteristic curves for a standard wind turbine with the peak capacity of 3.15 MW and a standard photovoltaic unit with the peak capacity of 1 MW are calculated for a duration of one year. Each of the five characteristic curves represent the output of a wind generator that is installed in different regions. As in reality it is usual that neighboring regions receive almost the same solar radiation or similar wind speed, five groups of twin cells were considered and each generation characteristic curves was assigned to a group of twin cells. The groups of twin cells are: cells 1 and 2, cells 3 and 10, cells 4 and 7, cells 5 and 6, cells 8 and 9.

Wind Power:

The rough data from the meteorological service is then corrected to project the wind speed velocity at the height of the wind turbine. The hourly wind speed data are chosen from the following wind stations in East Germany: Potsdam, Neuruppin, Baruth, Marienberg, Carlsfeld.

The recorded rough data at these stations are based on measurements near the surface of the ground. Therefore, measurements are highly affected by roughness and frictional stress. The corrected wind speed at the height of a wind turbine can be calculated by the following correlation [55]:

$$V_h = V_{ref} \frac{\ln\left(\frac{Z_h}{Z_0}\right)}{\ln\left(\frac{Z_{ref}}{Z_0}\right)} \quad (7-1)$$

Where the parameters are defined as:

V_h :	wind speed at the height of h above the ground m/s
V_{ref} :	recorded wind speed at the weather station in m/s
Z_h :	height of the wind turbine in m
Z_{ref} :	reference height where the wind data are recorded in m
Z_0 :	roughness length in m

Having equation 7-1 in mind and considering following assumptions, corrected wind speed can be calculated based on the following steps: firstly, the reference values for equation 7-1 are considered as stated in Table 7-1. Then based on the assumptions from Table 7-1 corrected wind speed is calculated and presented in Figure 6-24. At last based on the corrected wind speed, output power of a standardized wind turbine with a generating capacity of 3.5 MVA (3.15 MW) and the height of 165 m is calculated. The standard power curve of the turbine is assumed to be as illustrated in Figure 6-25.

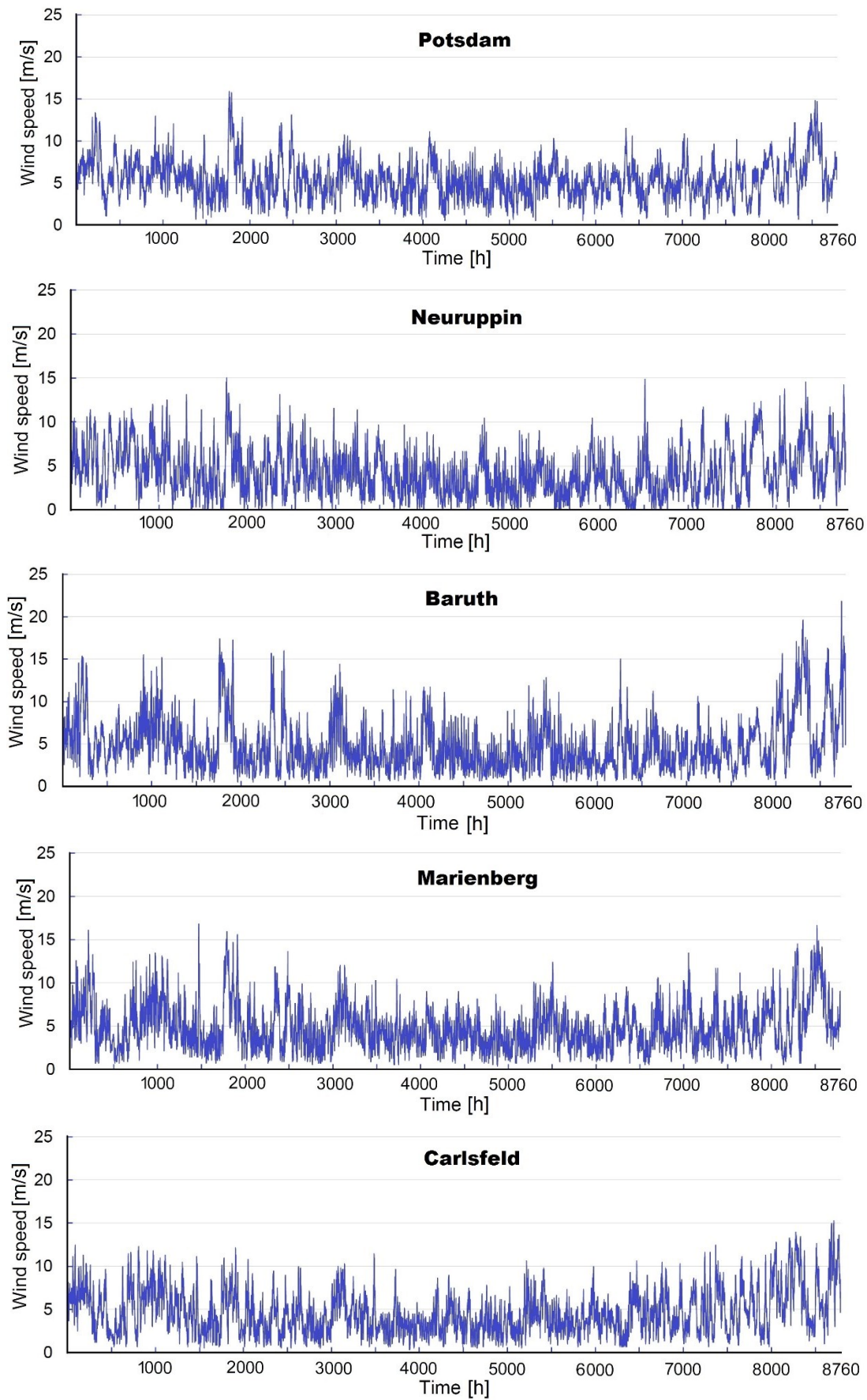


Figure 6-24: Corrected wind speed

Weather station	Potsdam	Neuruppin	Baruth	Marienberg	Carlsfeld
Z_{ref} [m]	37.7	18	18	12	15
Roughness class	3	3	3	3	3
Z_0 [m]	0.4	0.4	0.4	0.4	0.4
Land type	Related to villages or small towns with rough and uneven surface				

Table 6-1: Assumptions for calculating free stream wind speed (data based on: [50] and [55])

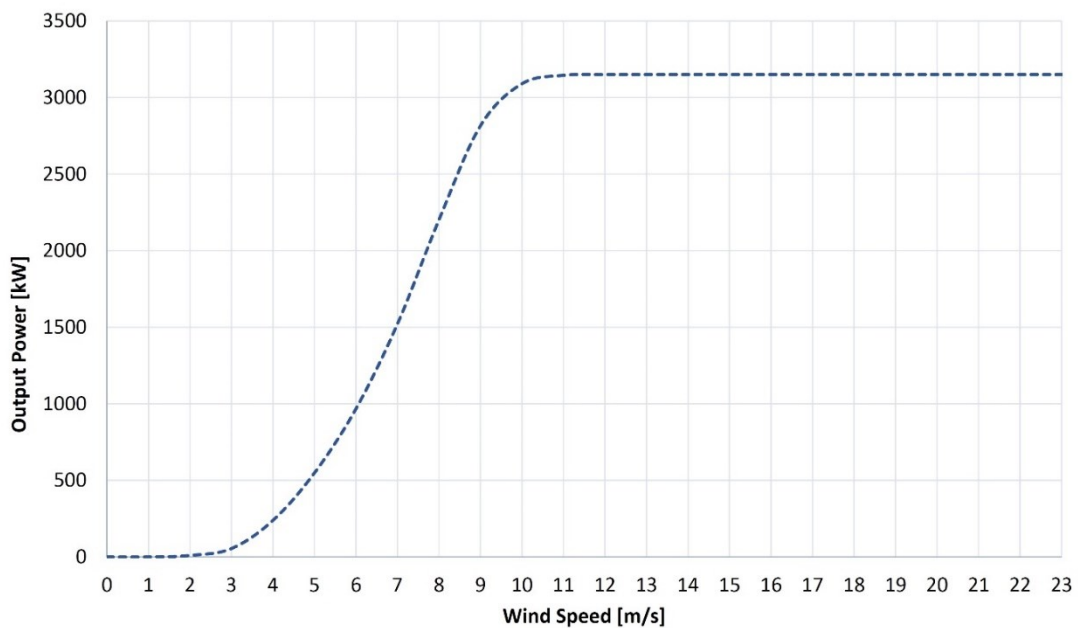


Figure 6-25: Assumed power curve of the standardized wind turbine

Based on the corrected wind speed and the assumed power curve, generated power for a standard 3.5 MVA wind turbine over the period of one year for each site is calculated. The characteristic curves are then used in MATLAB and PowerFactory models. Calculated power duration curves of these regions are illustrated in Figure 6-26.

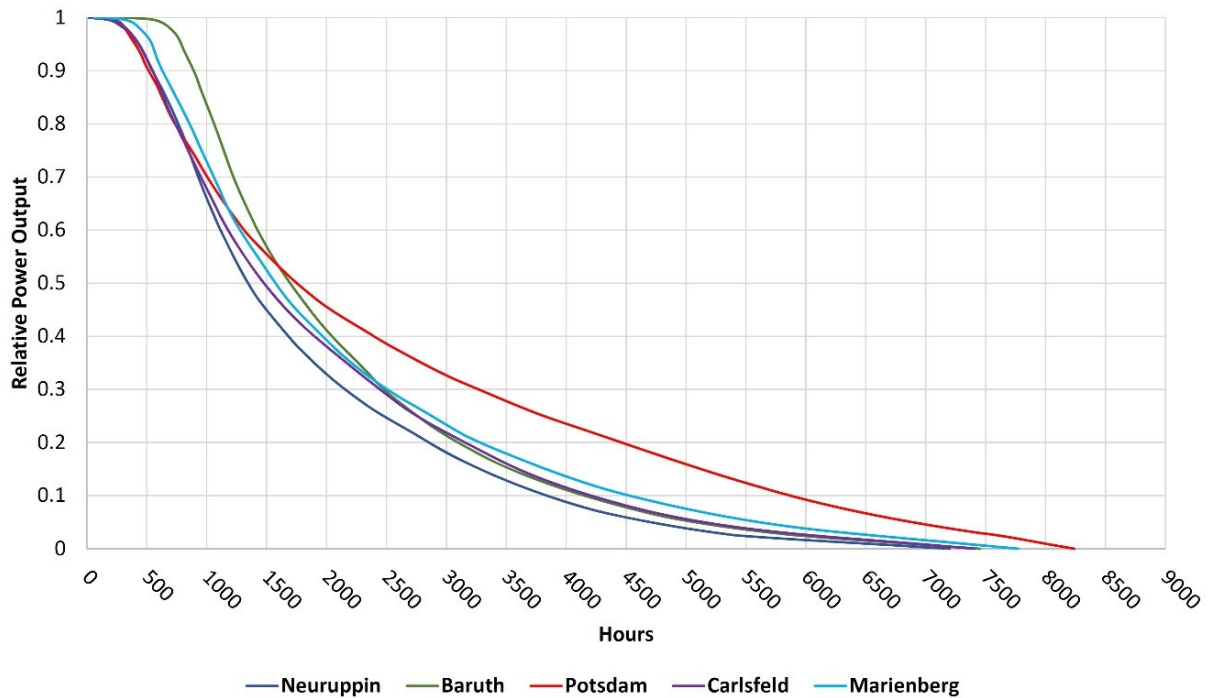


Figure 6-26: Calculated power duration curves for each wind park site

Photovoltaic Power:

With a similar concept, hourly measured solar irradiation data of five weather stations are used to calculate output power curves of a standardized 1 MW-peak photovoltaic park for each region. Diagram of solar irradiance of the stations are illustrated in Figure 6-27. Having the measured solar irradiation, the output power can be determined by equation 7-2 [56]:

$$P_{PV} = \frac{E}{T} = \frac{A \cdot \eta \cdot I_{ir} \cdot PR}{T} \quad (7-2)$$

Where the parameters are defined as:

- E : produced energy in kWh
- T : time in hours
- A : area in m^2
- η : efficiency in %
- I_{ir} : solar irradiation in kWh/m^2
- PR : performance ratio of solar modules in %

The assumptions for calculation of the output power are presented in Table 7-2.

Nominal Power P [W]	Panel area A [m^2]	Efficiency η [%]	Performance Ratio PR [%]
220	1.46	13	83

Table 6-2: Assumptions for calculating output power of photovoltaic panels

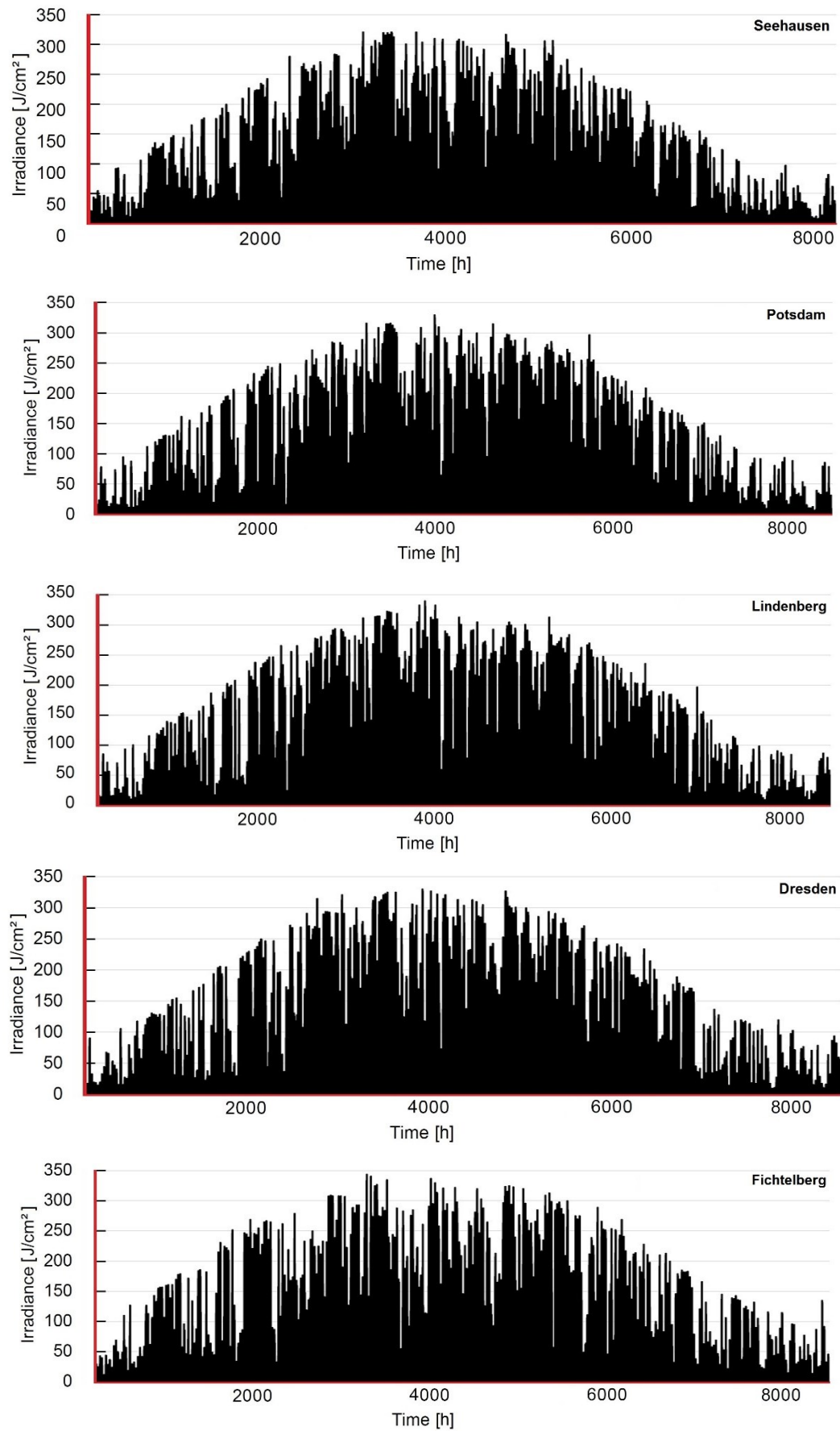


Figure 6-27: Solar irradiance for chosen weather stations

Based on equation 7-2 and assumptions from Table 7-2, the output power for a standardized photovoltaic park with the rated power of 1 MW can be calculated easily. Power duration curves for the chosen regions are illustrated in Figure 6-28.

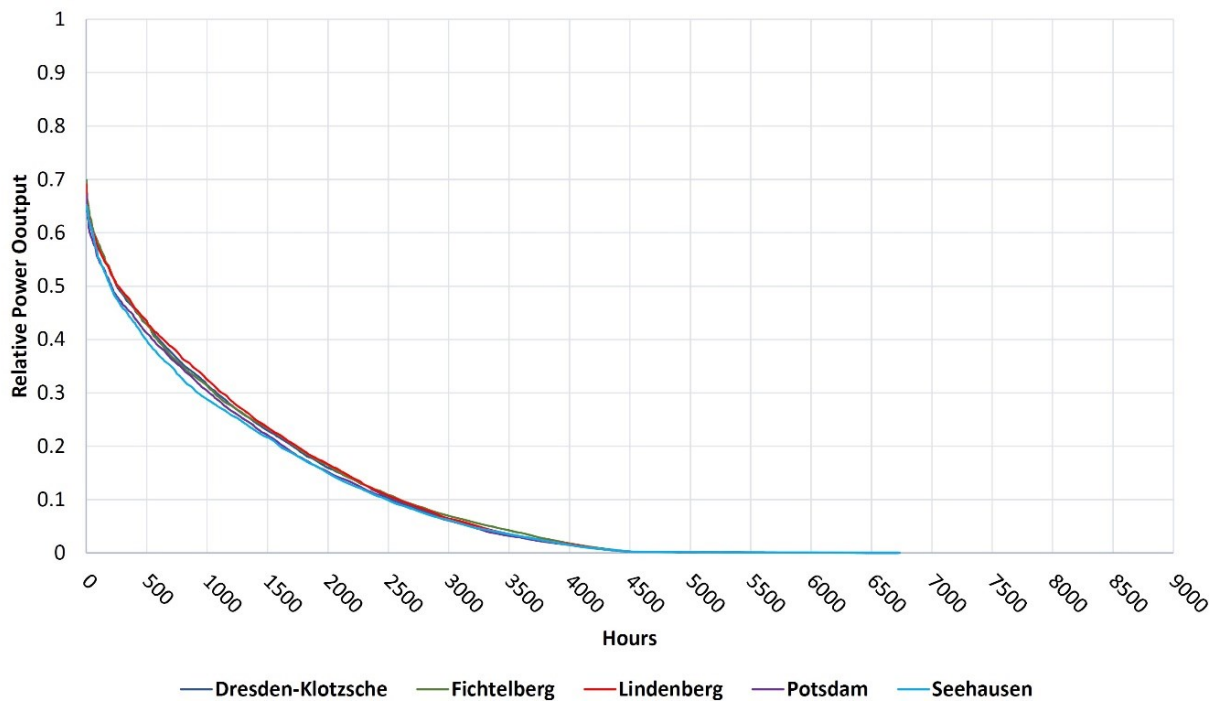


Figure 6-28: Calculated power duration curves for the chosen photovoltaic stations

6.4. Annex 4: Load Models

Principally, five different load characteristic curves are integrated into MATLAB optimization and PowerFactory simulation models. These profiles are based on standard load profiles from German Association of Energy and Water Industries¹⁵ for the following categories [51]: The standard load profiles are presented in Figure 6-29 to Figure 6-38.

- 1) Household in general (H0)
- 2) Industry in general (G0)
- 3) Business on workdays from 08:00 to 18:00 (G1)
- 4) Bakeries with bakehouse (G5)
- 5) Agricultural enterprises (L0)

Note: there are eleven different standard load profile types defined by German Association of Energy and Water Industries. For the purpose of this dissertation, only five types were chosen for diversification of load characters.

The above mentioned load characteristic curves vary not only during the hours of a day, but also have seasonal changes. Principally three types of seasons are considered for four different periods of the year:

- 6) Winter, starting from 01.11. and ending at 20.03.
- 7) First transitional period, starting from 21.03. and ending at 14.05.
- 8) Summer, starting from 15.05. and ending at 14.09.
- 9) Second transitional period, starting from 15.09. and ending at 31.10.

Differences between types of seasons, are also illustrated in the following figures.

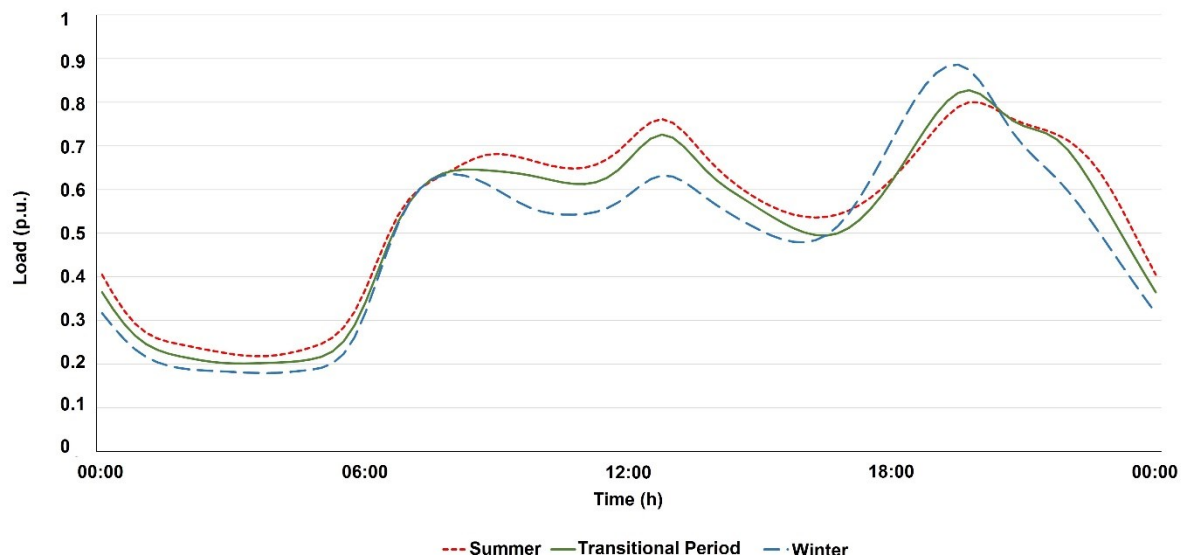


Figure 6-29: Load profile of household in general - working days (data based on: [51])

¹⁵ Bundesverband der Energie- und Wasserwirtschaft (BDEW) e.V.

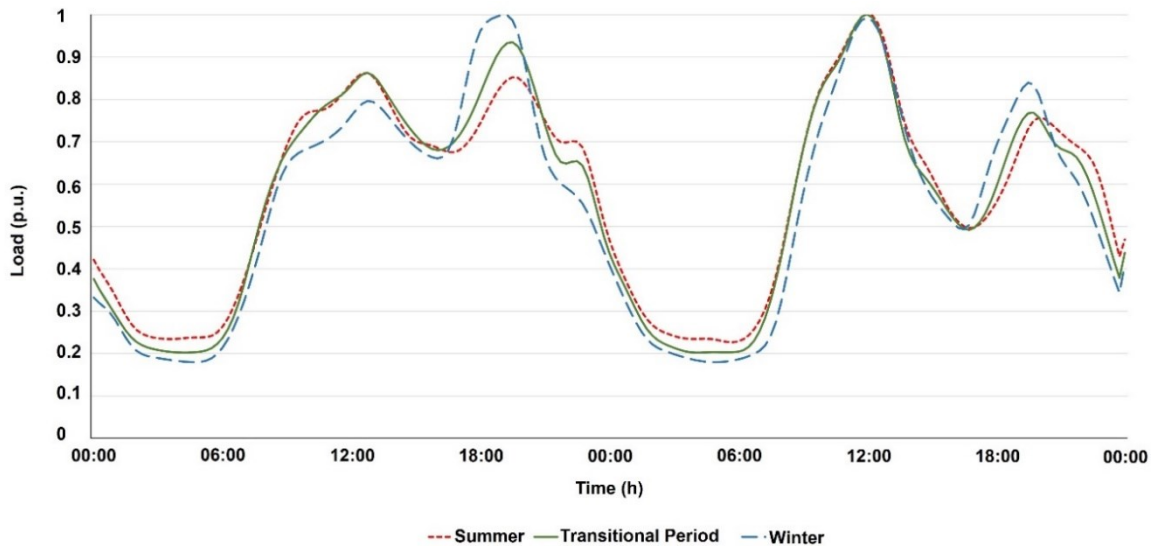


Figure 6-30: Load profile of household in general - Saturday and Sunday (data based on: [61])

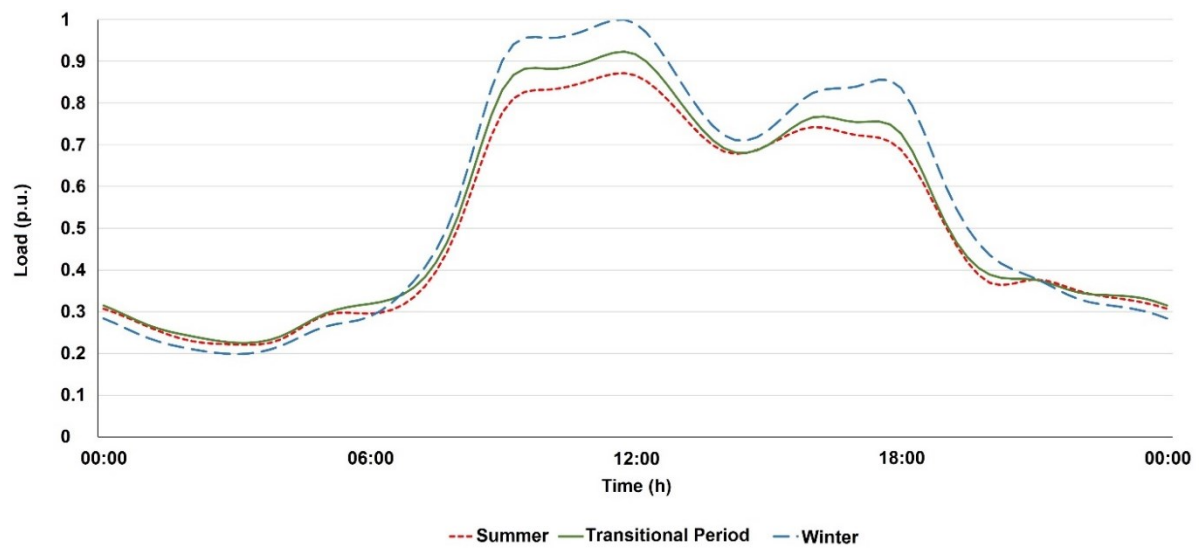


Figure 6-31: Load profile of industry in general - working days (data based on: [61])

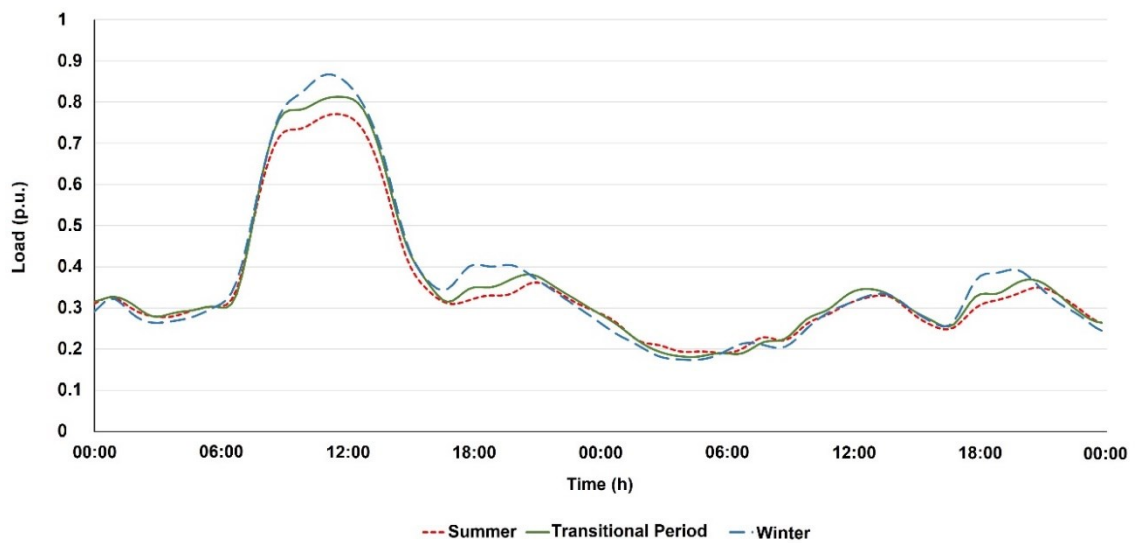
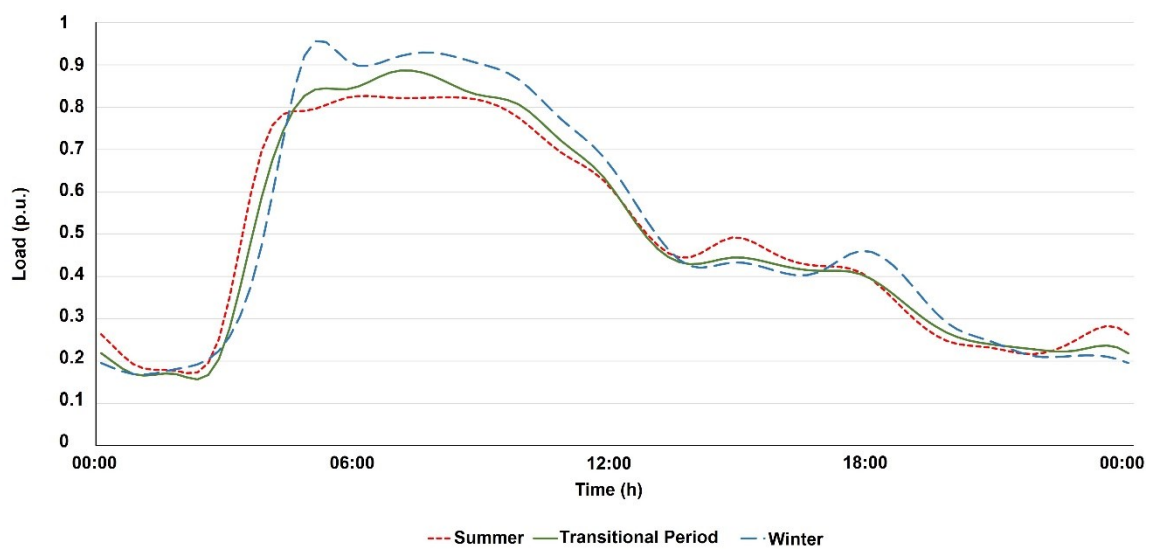
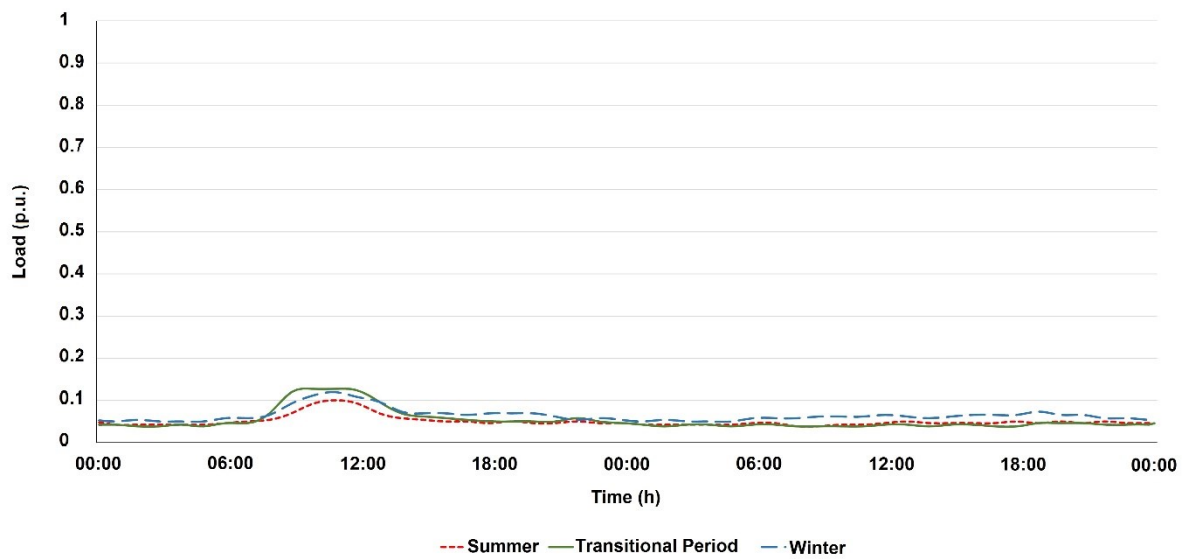
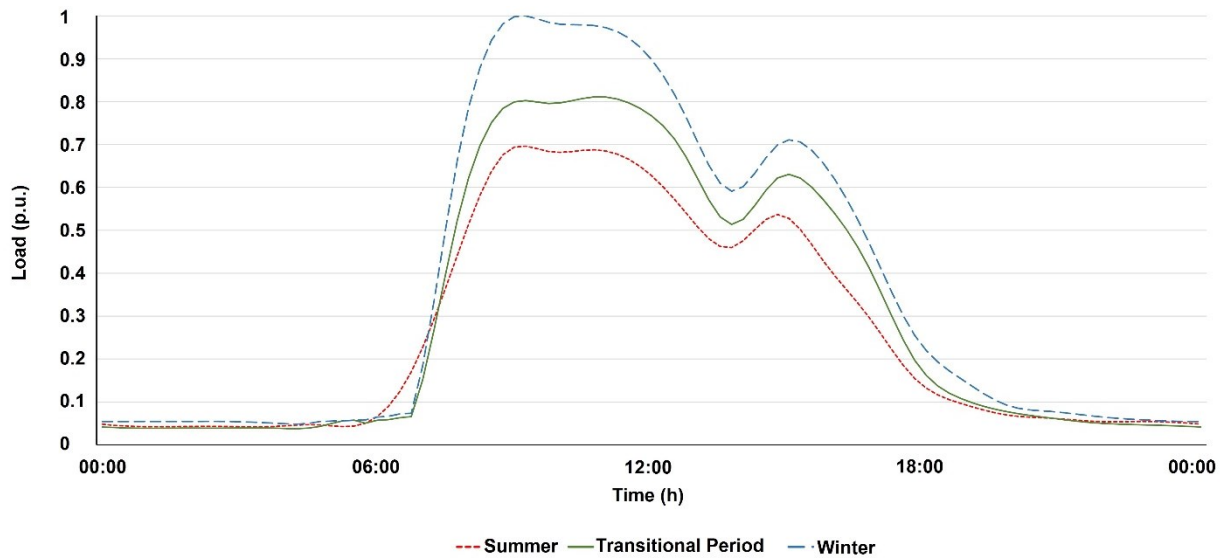


Figure 6-32: Load profile of industry in general - Saturday and Sunday (data based on: [61])



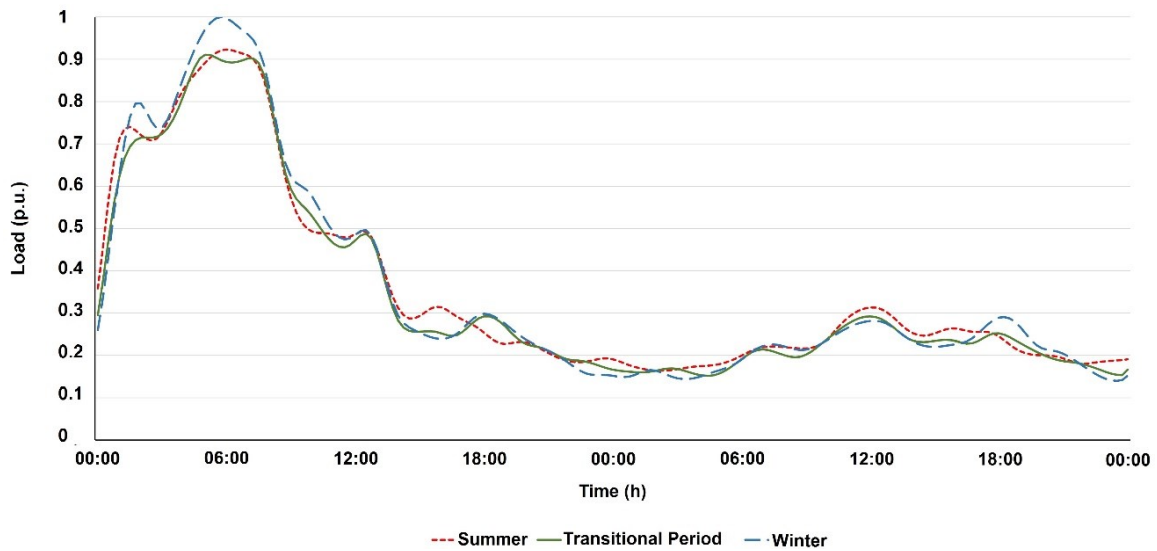


Figure 6-36: Load profile of bakeries with bakehouse - Saturday and Sunday (data based on: [61])

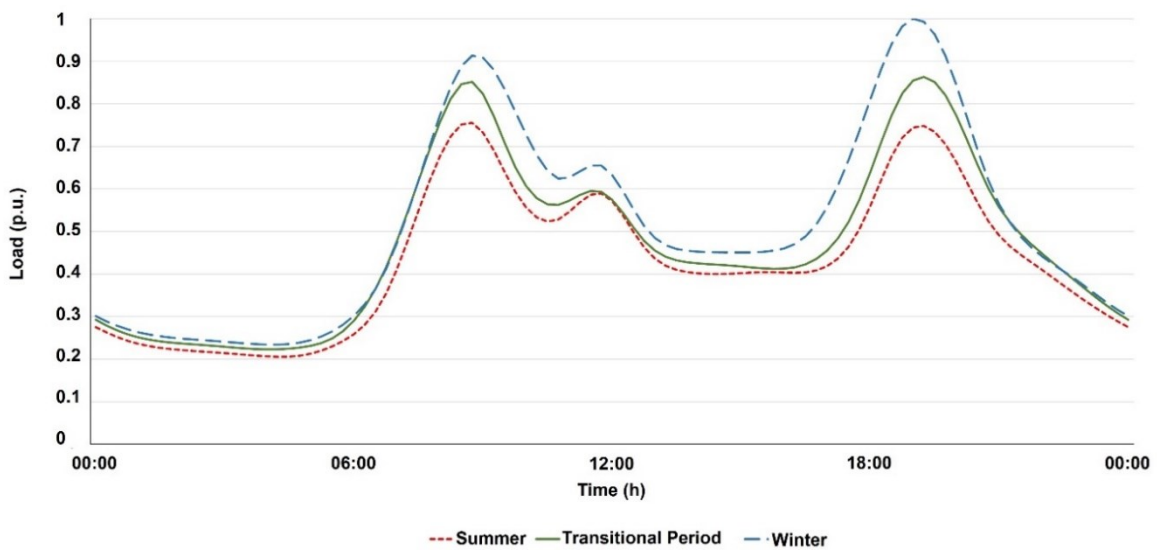


Figure 6-37: Load profile of agricultural enterprises - working days (data based on: [61])

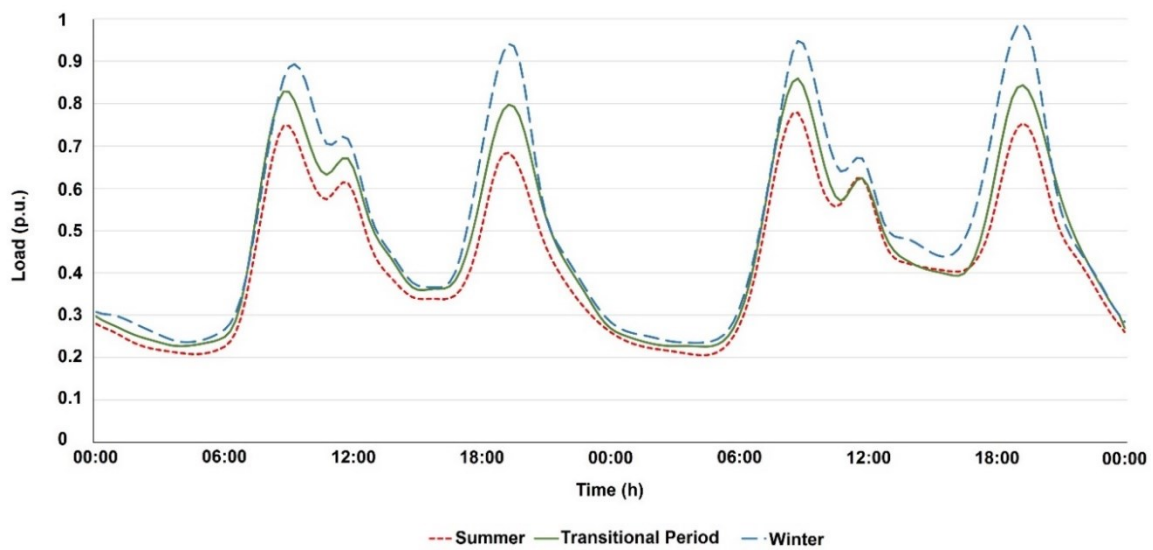


Figure 6-38: Load profile of agricultural enterprises - Saturday and Sunday (data based on: [61])

6.5. Annex 5: Parameters of Transformers and Cables

Principally six different types of transformer models were defined and used by the author for PowerFactory simulations. The defined parameters of the transformers are summarized in Table 7-6.

Parameter		Transformer					
		Type 1: 30 MVA 110/20 kV	Type 2: 40 MVA 110/20 kV	Type 3: 31.5 MVA 110/20 kV	Type 4: 40 MVA 110/20 kV	Type 5: 500 MVA 380/110 kV	Type 6: 80 MVA 110/20 kV
Rated Power [MVA]		30	40	31.5	40	500	80
Nominal Frequency [Hz]		50	50	50	50	50	50
Rated Voltage	HV [kV]	115	115	110	110	380	110
	LV [kV]	20	20	20	20	110	20
Positive Sequence Impedance	Short-Circuit Voltage u_k [%]	14.1	14.1	12.8	12.8	18.638	13.18
	Copper Losses [kW]	125.1	125.1	120.9	120.9	771.3	249.876
Vector Group		YNyn0	YNyn0	YNyn0	YNyn0	YNy0	YNd1
Magnetizing Impedance	No Load Current [%]	0.038	0.038	0.13	0.13	0.043	0.068
	No Load Losses [kW]	14.1	14.1	12.5	12.5	108.9	44.907
Tap Changer	at Side	HV	HV	HV	HV	HV	HV
	Additional Voltage per Tap [%]	1.77	1.77	1.78	1.78	1.23	1.67
	Phase angle [deg]	0	0	0	0	0	0
	Neutral Position	10	10	10	10	0	0
	Minimum Position	1	1	1	1	-13	-9
	Maximum Position	19	19	19	19	13	6

Table 6-3: Parameters of transformer models

Parameter	110 kV Conductor	20 kV Cable
Rated Voltage [kV]	110	20
Rated Current [kA]	0.645	0.286
Resistance of Positive Sequence [Ω /km]	0.0601	0.1803
Impedance of Positive Sequence [Ω /km]	0.2021	0.2592
Reactance of Positive Sequence [Ω /km]	0.1930	0.1862

Table 6-4: Parameters of the overhead conductors and cables (data based on [57])

6.6. Annex 6: GWO Results

In following figures, the blue color shade is a representative of simplicity of convergence and the red color shade is a representative of difficulty of convergence for GWO algorithm in finding solutions for a certain DLC. The yellow circles in the first optimization approach and the green circles in the second optimization approach represent the best results.

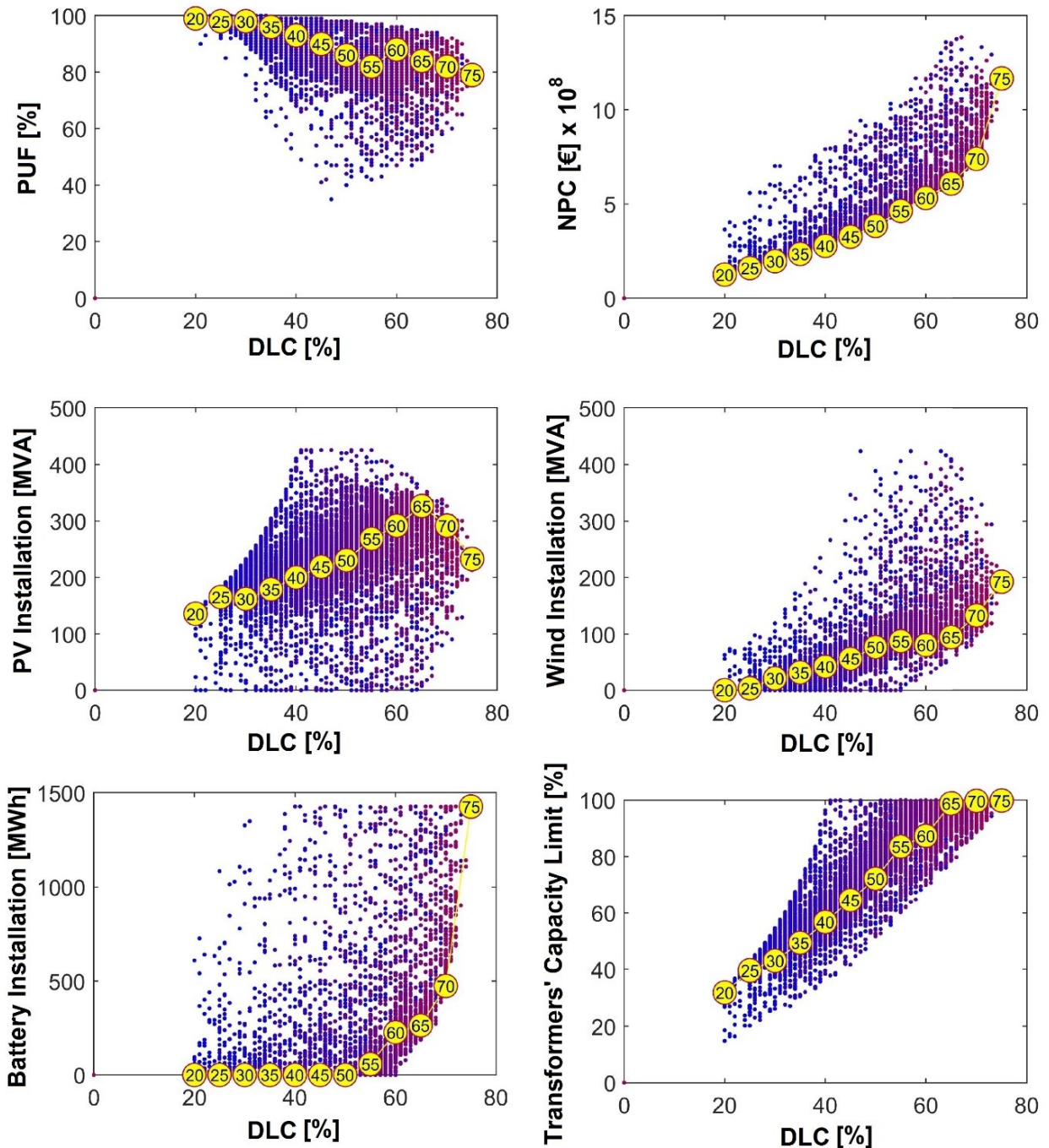


Figure 6-39: Results of the first optimization approach in cell 1

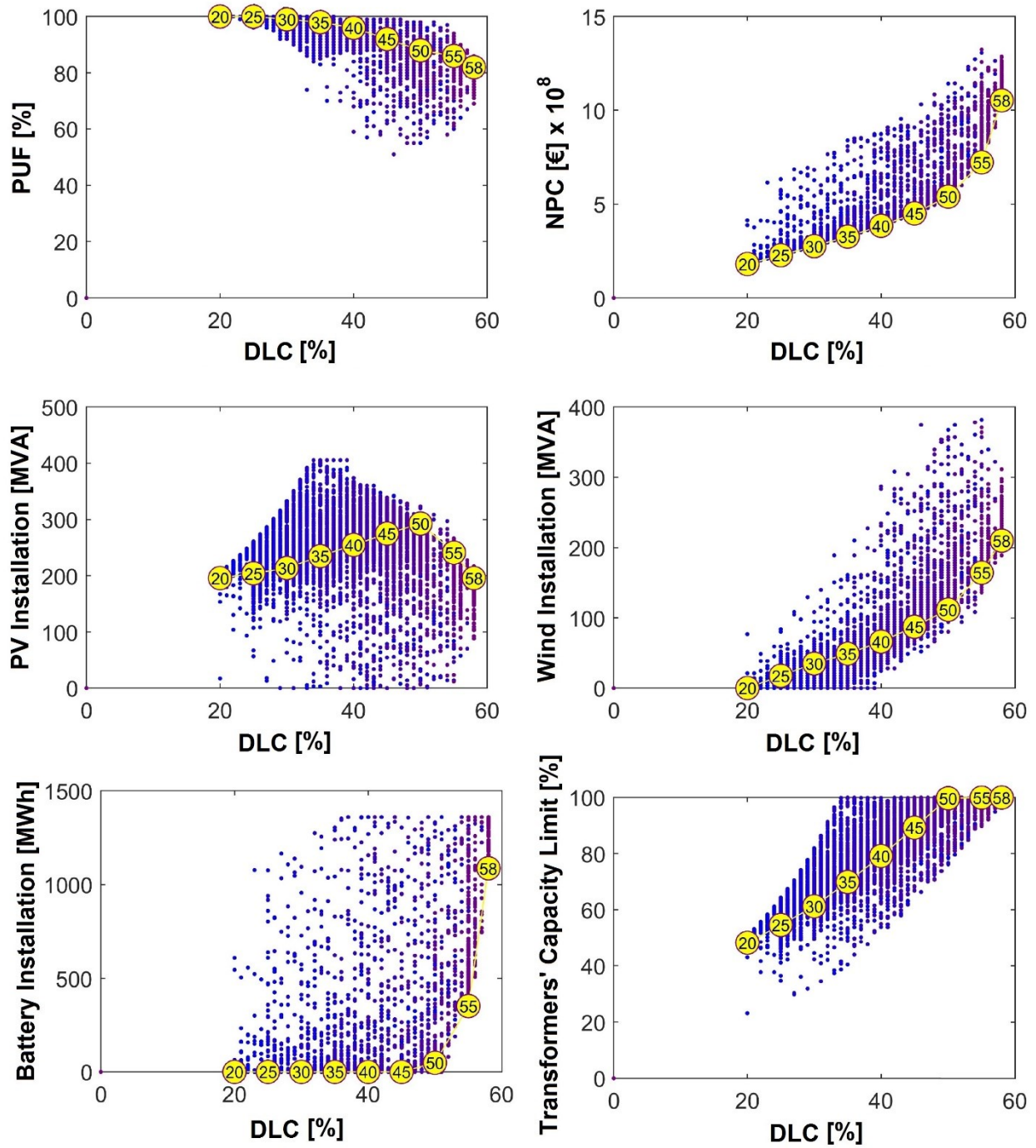


Figure 6-40: Results of the first optimization approach in cell 2

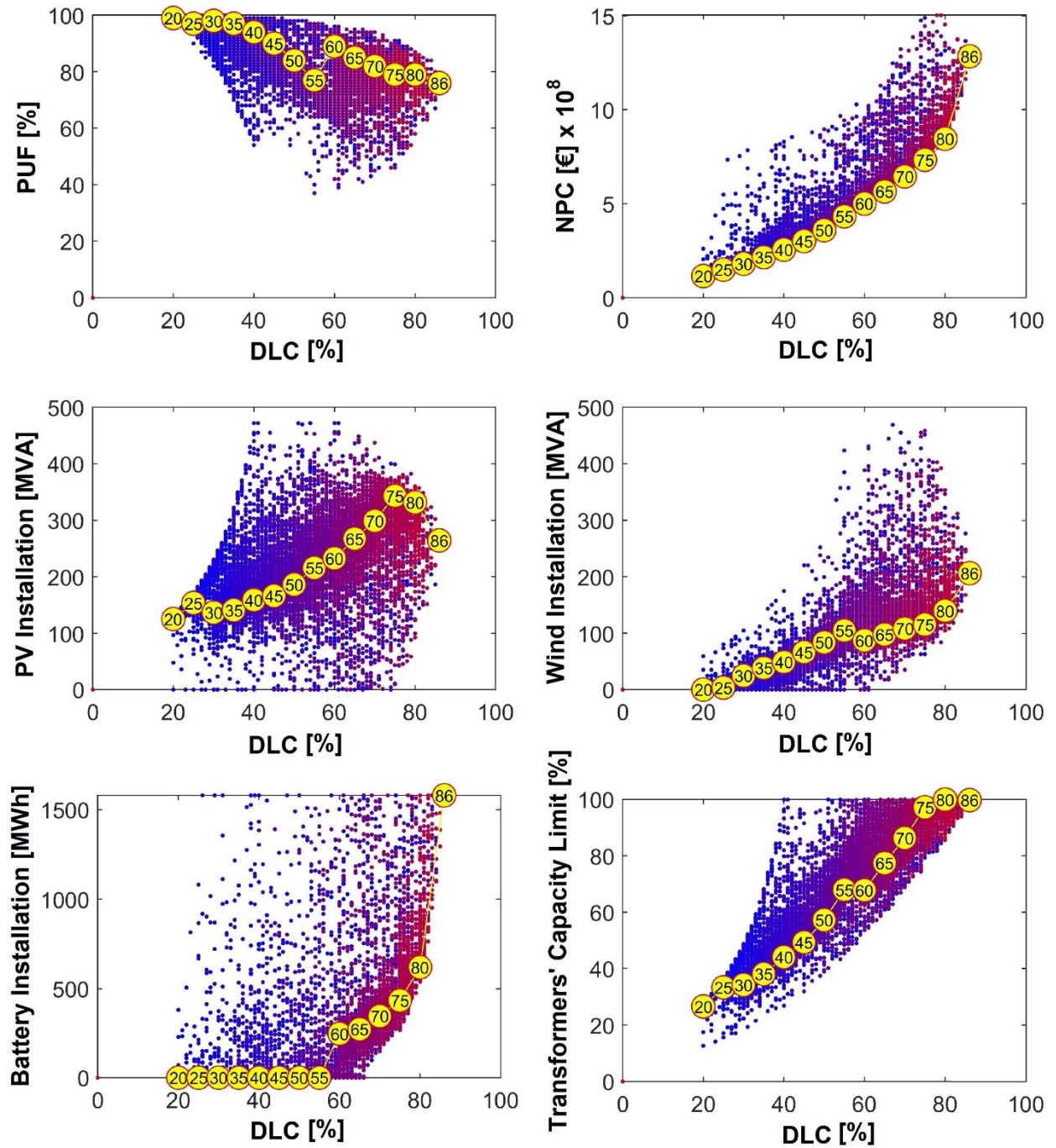


Figure 6-41: Results of the first optimization approach in cell 3

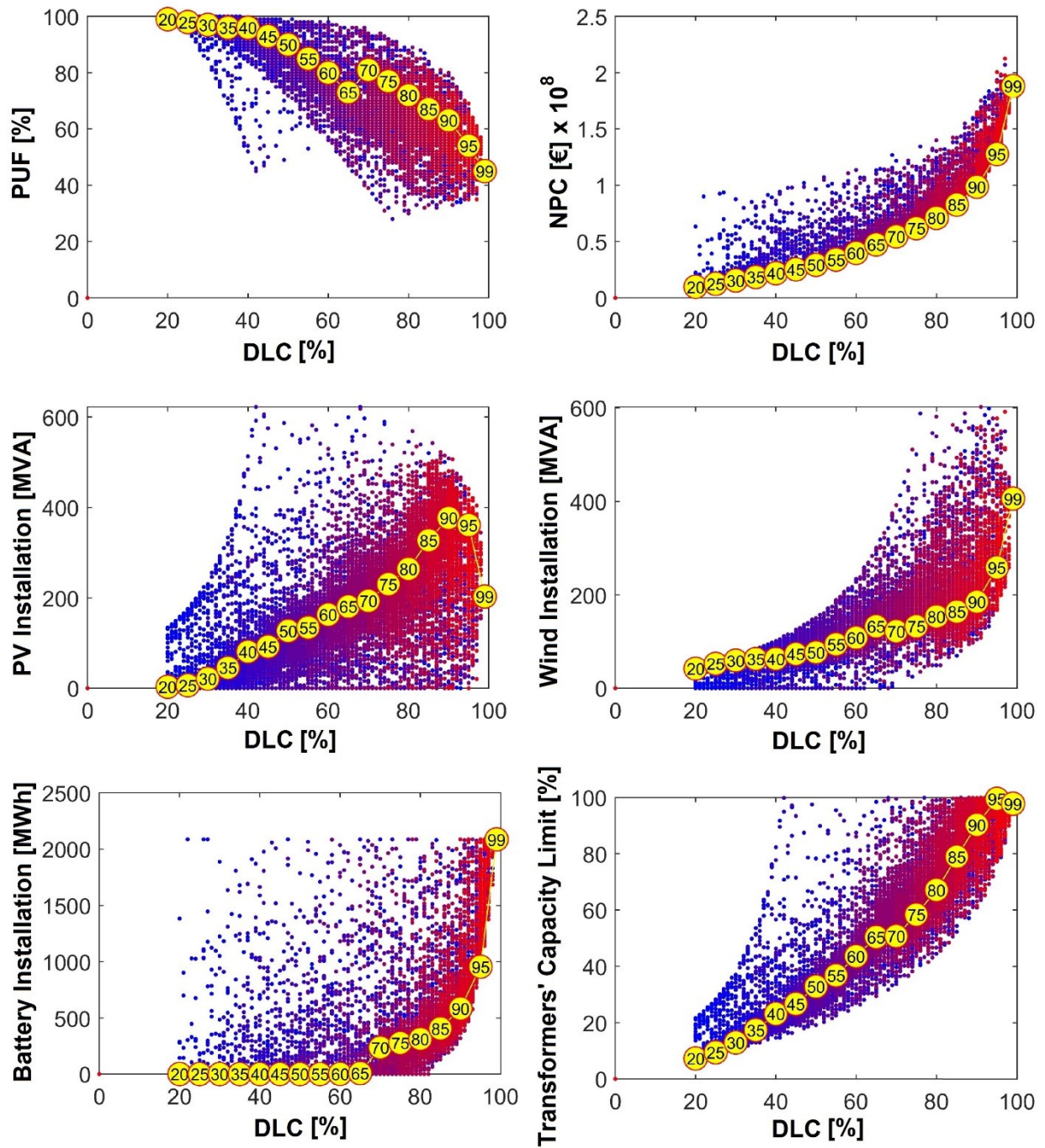


Figure 6-42: Results of the first optimization approach in cell 4

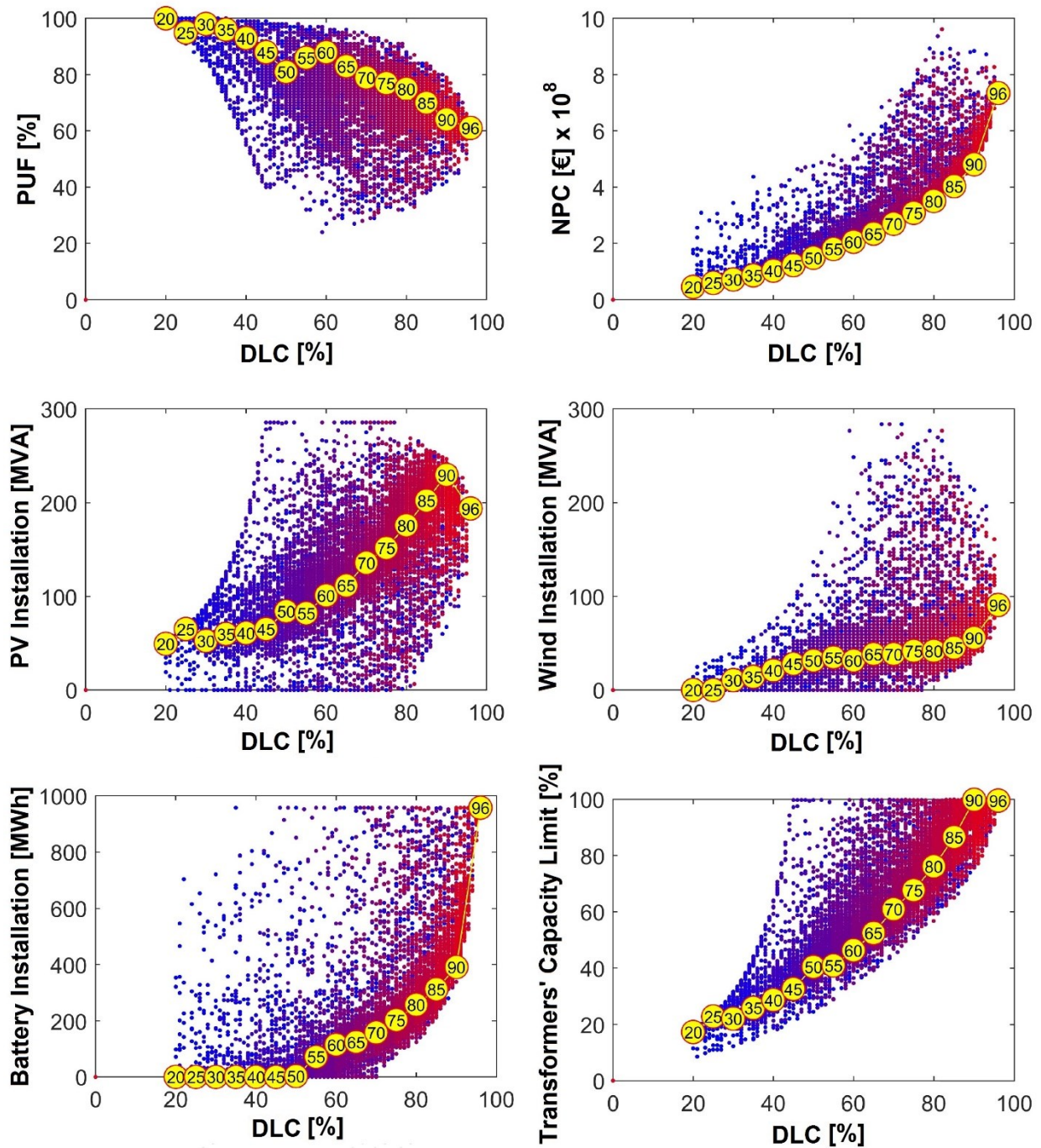


Figure 6-43: Results of the first optimization approach in cell 5

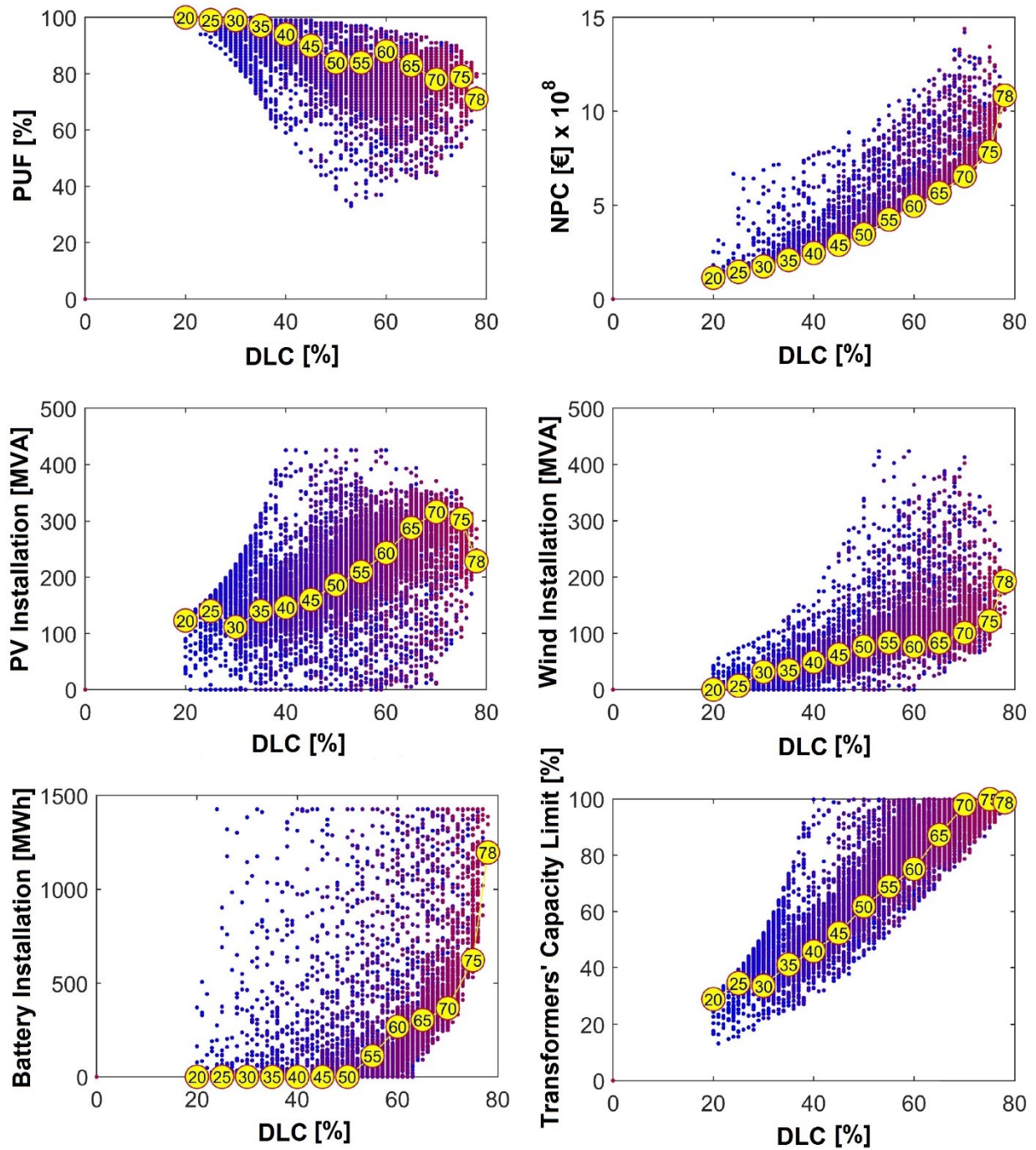


Figure 6-44: Results of the first optimization approach in cell 6

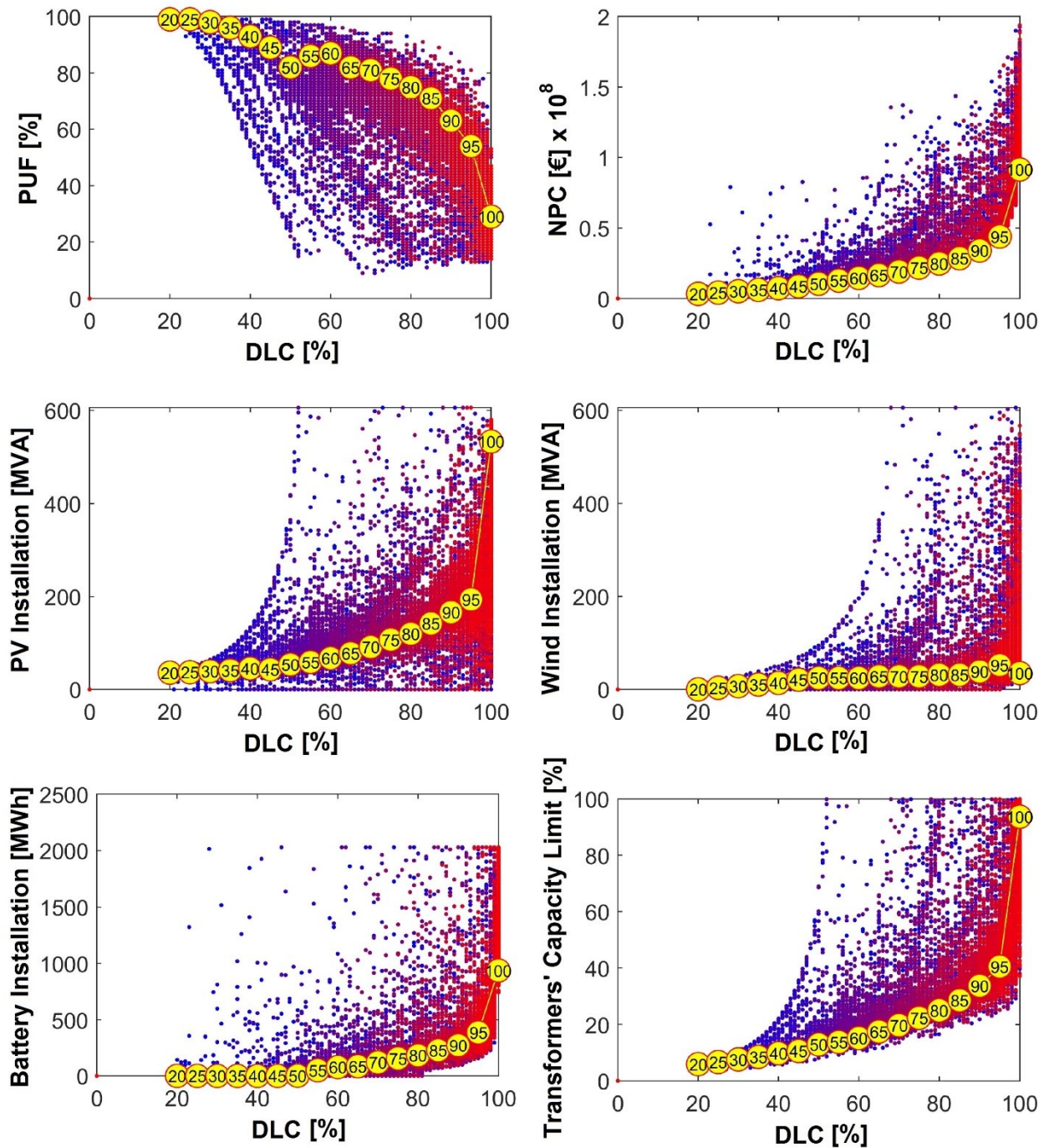


Figure 6-45: Results of the first optimization approach in cell 7

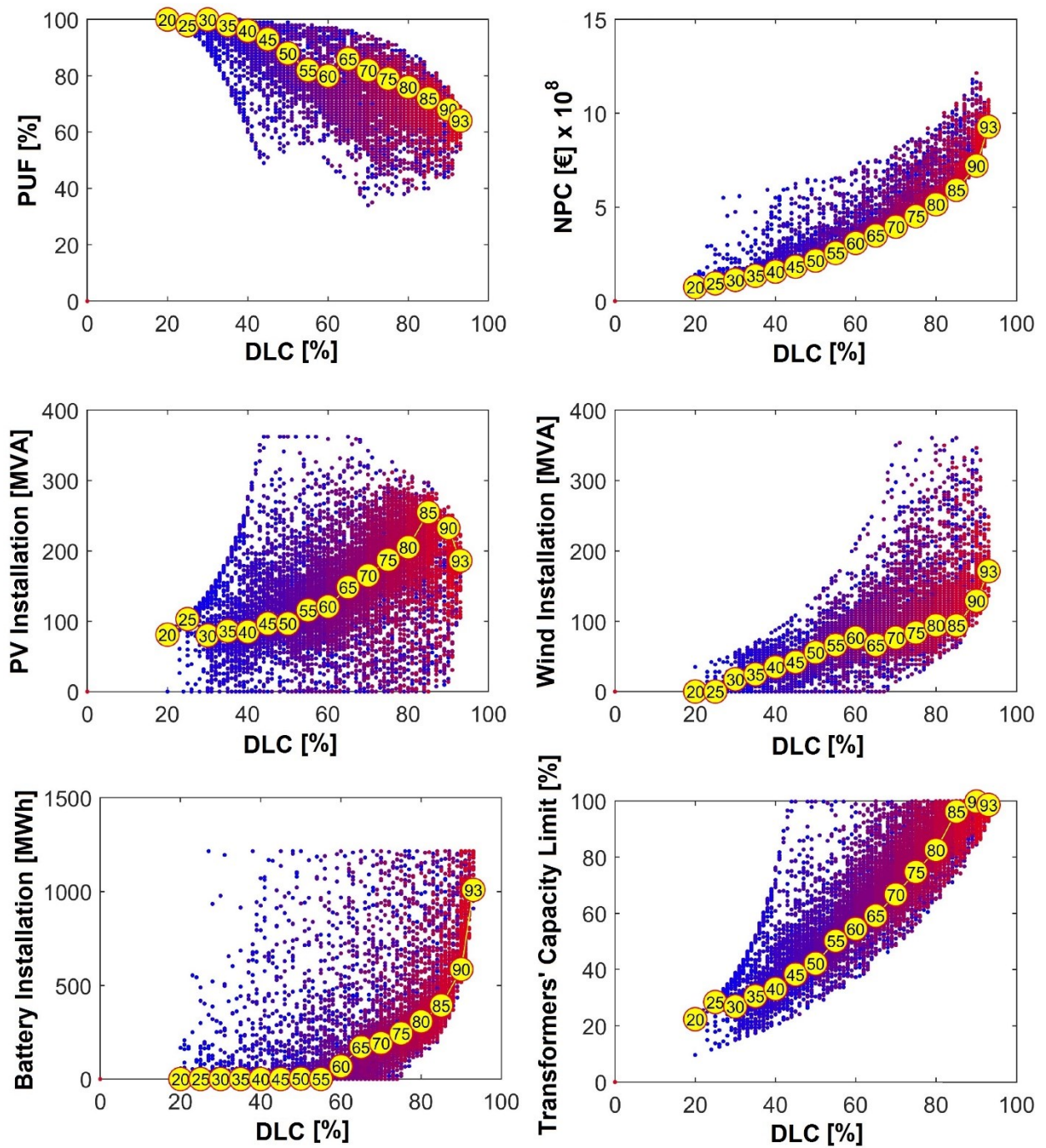


Figure 6-46: Results of the first optimization approach in cell 8

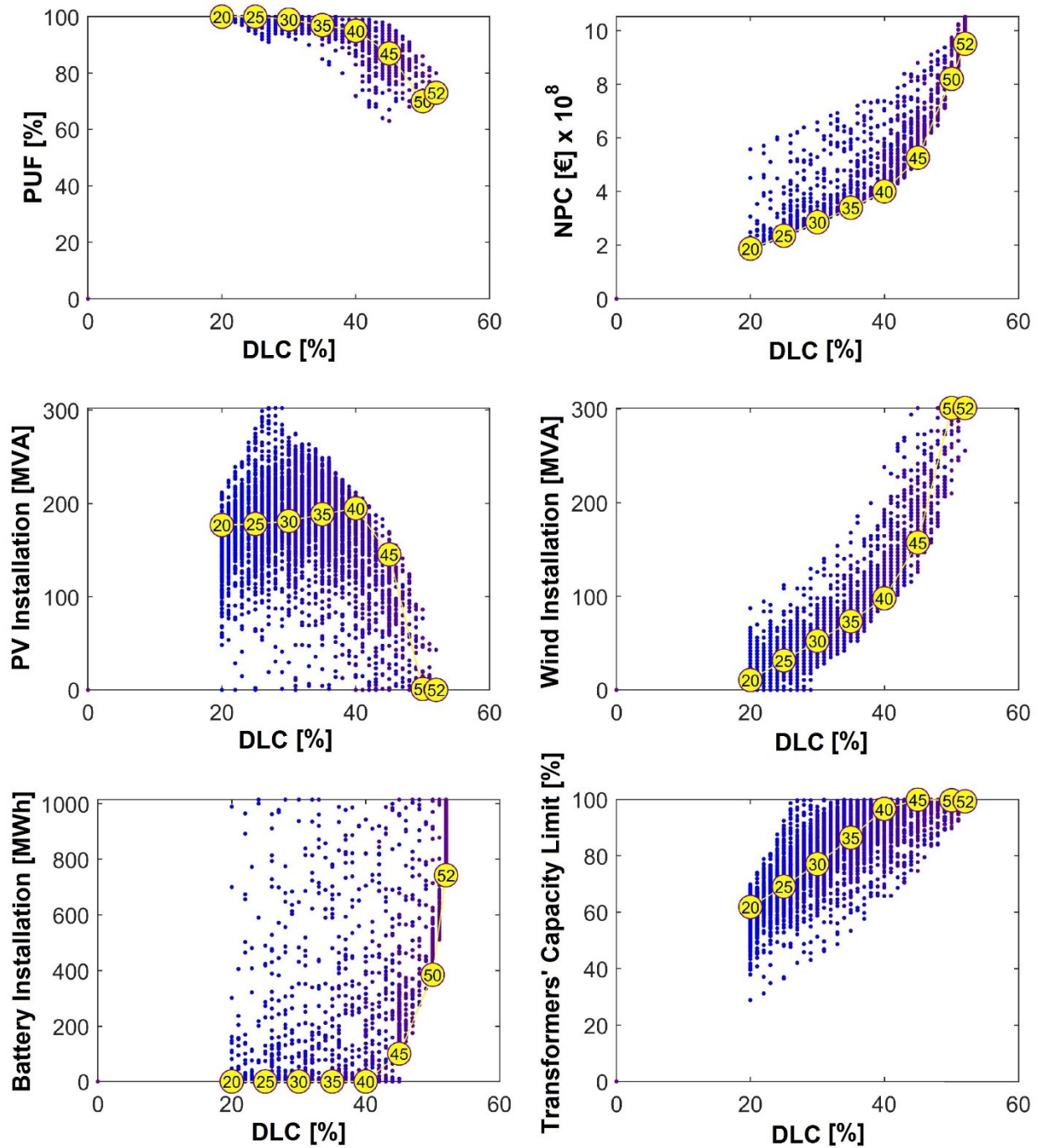


Figure 6-47: Results of the first optimization approach in cell 9

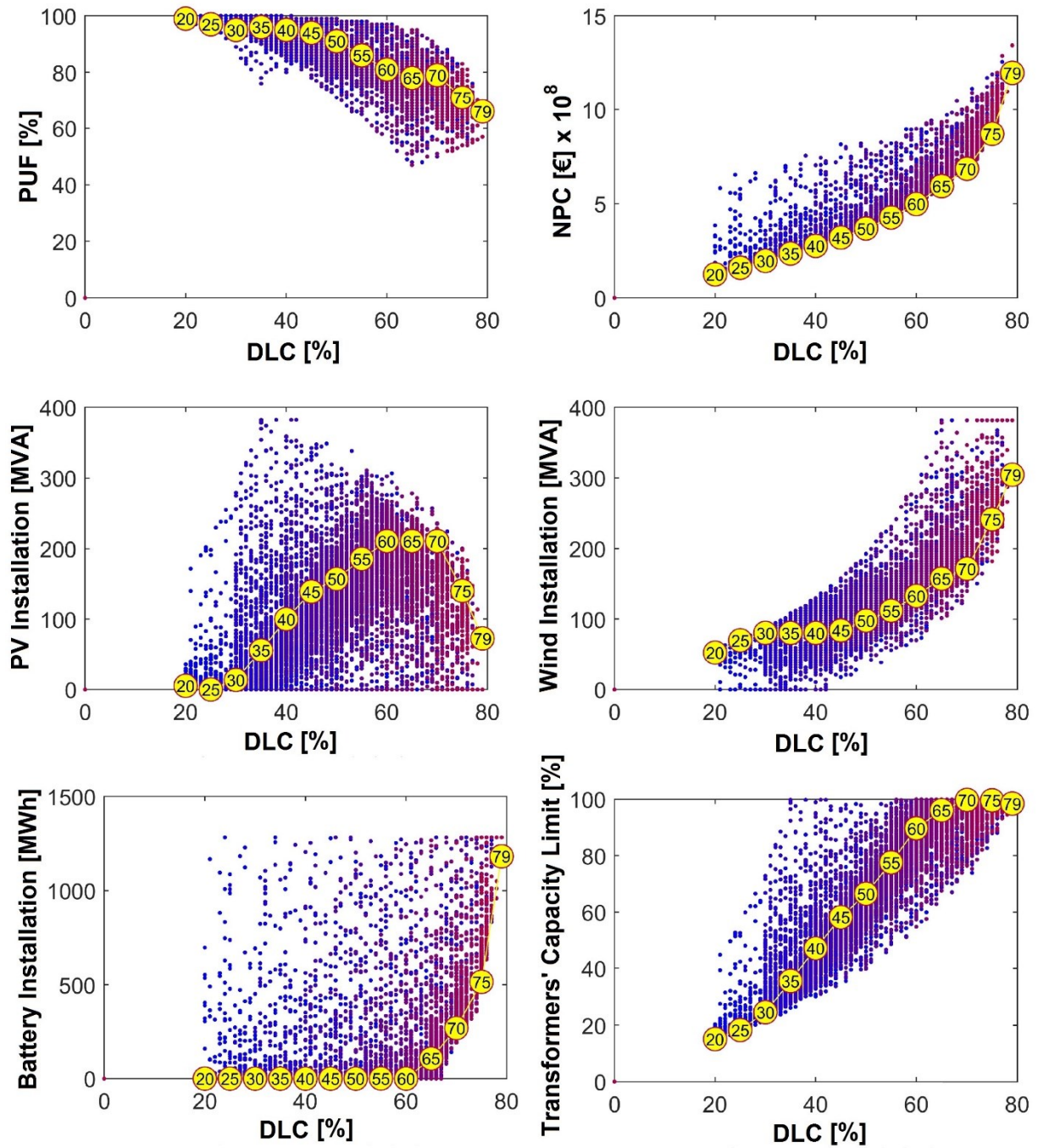


Figure 6-48: Results of the first optimization approach in cell 10

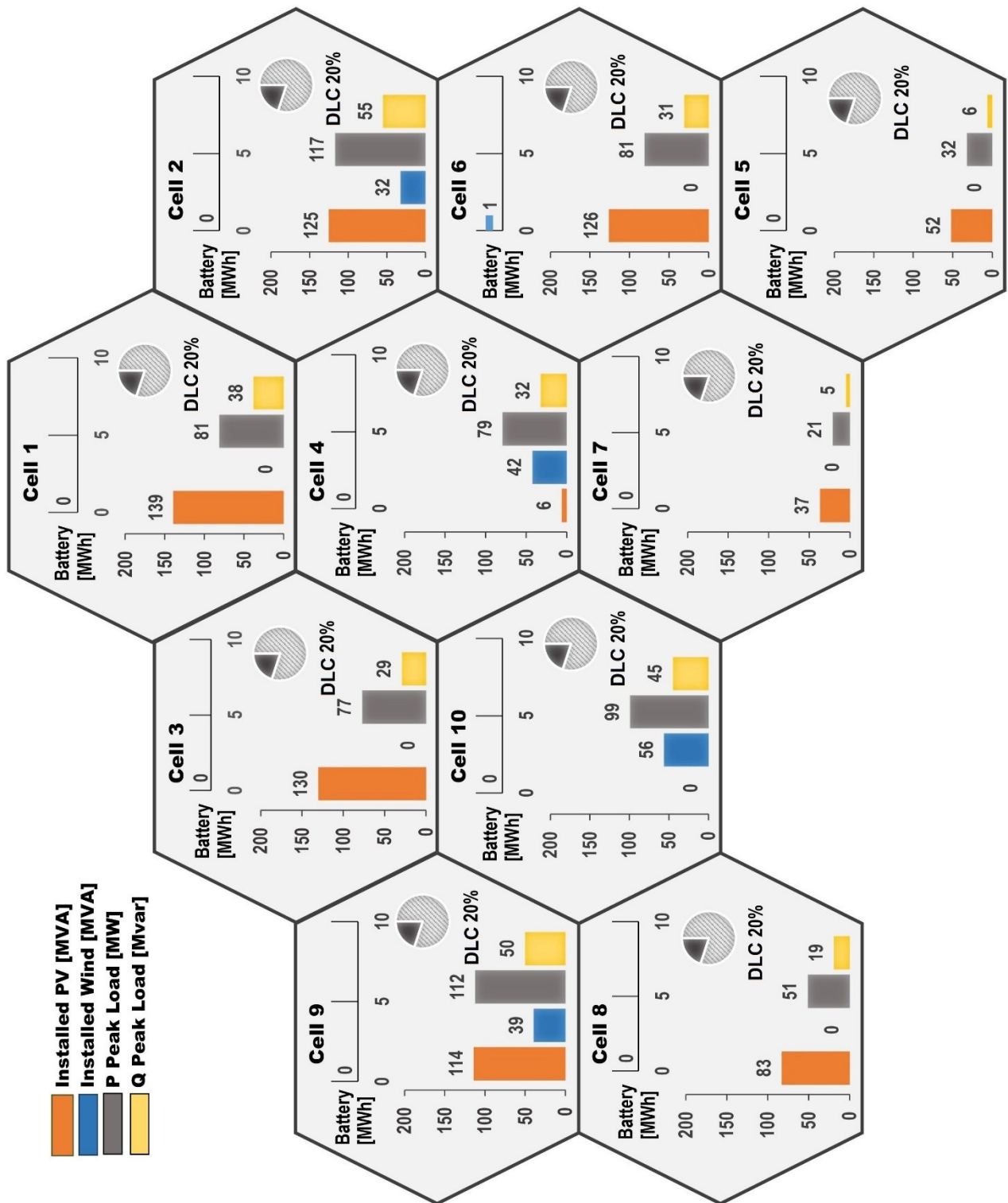


Figure 6-49: Results of the first optimization approach with DLC value of 20%

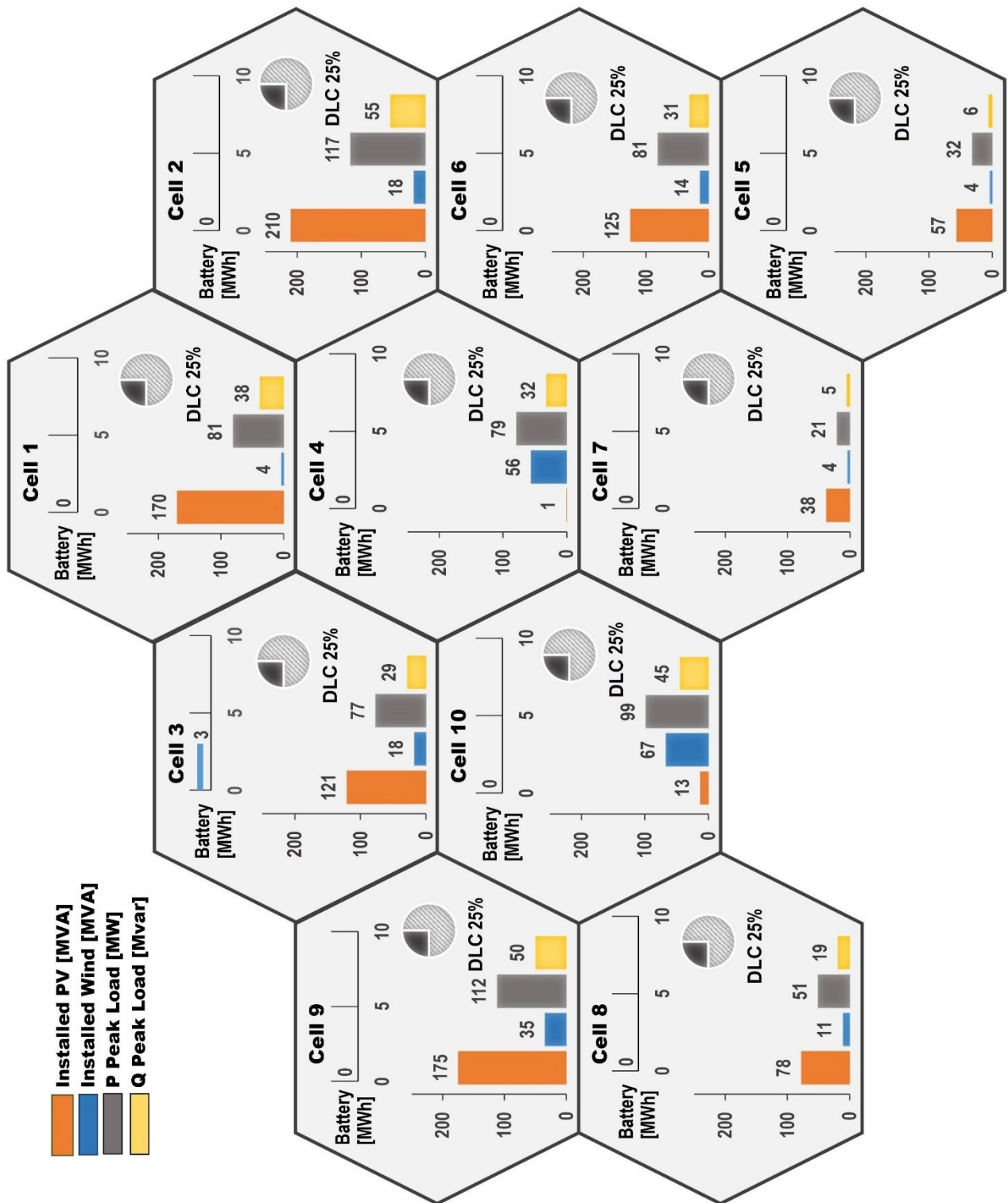


Figure 6-50: Results of the first optimization approach with DLC value of 25%

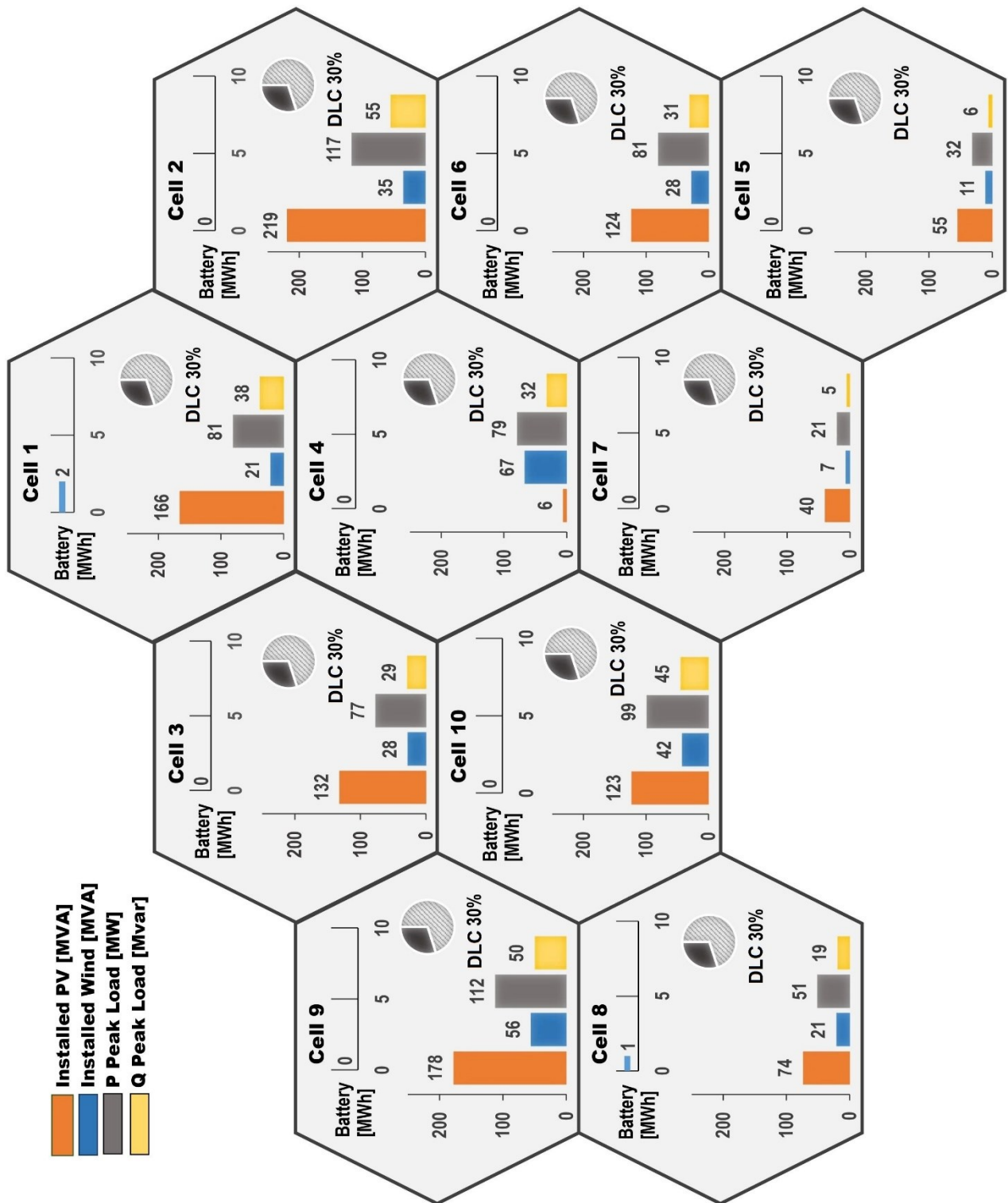


Figure 6-51: Results of the first optimization approach with DLC value of 30%

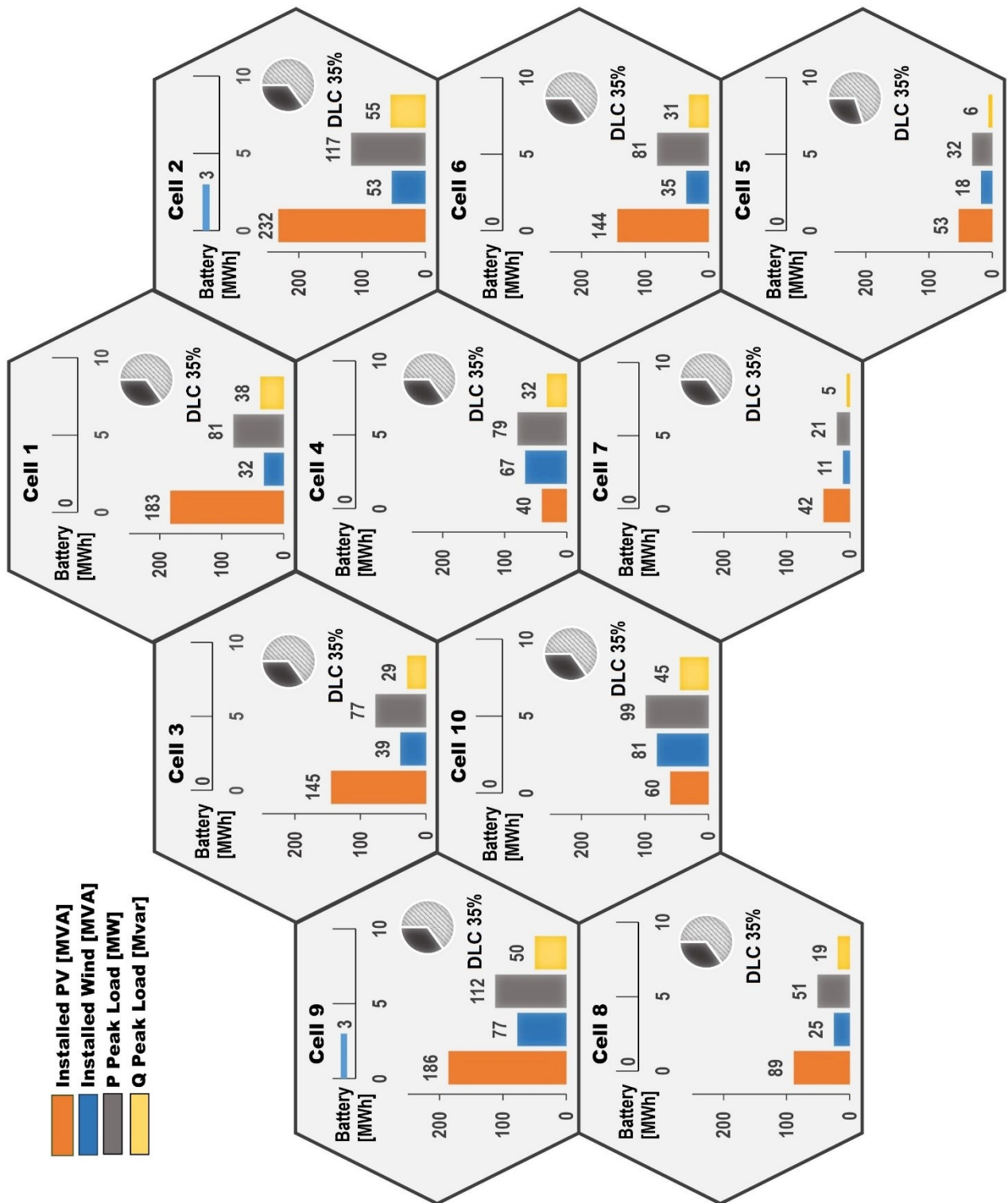


Figure 6-52: Results of the first optimization approach with DLC value of 35%

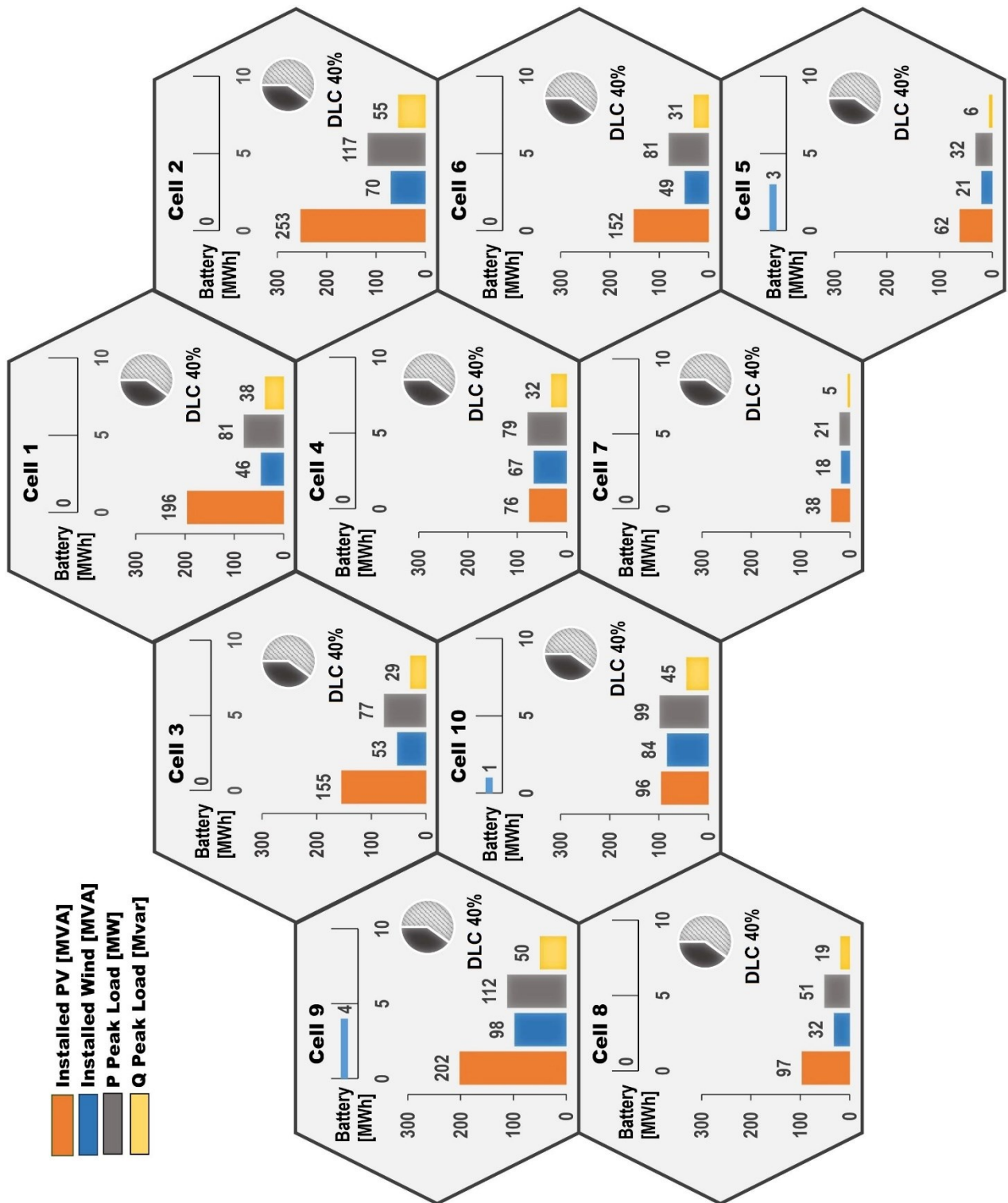


Figure 6-53: Results of the first optimization approach with DLC value of 40%

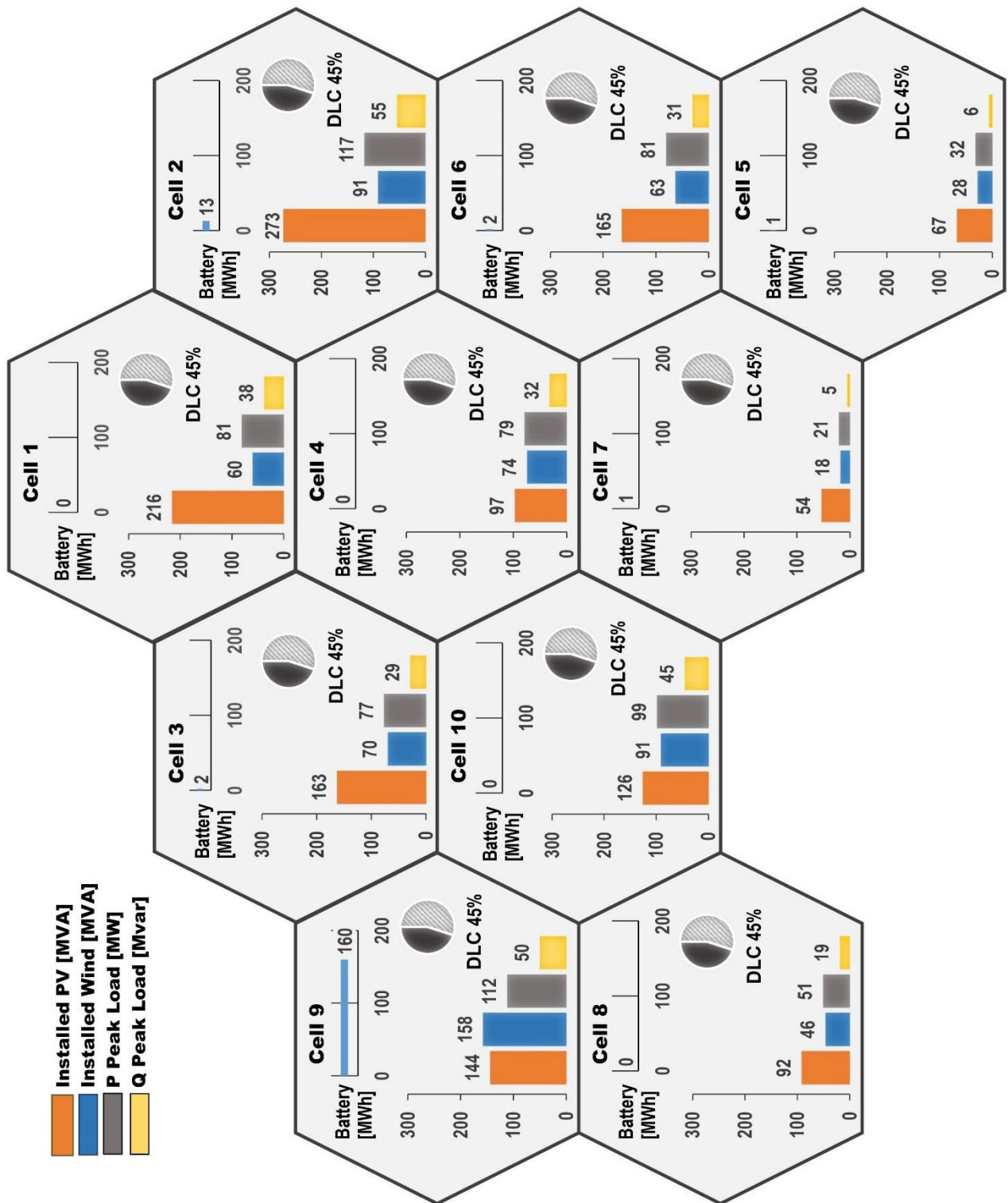


Figure 6-54: Results of the first optimization approach with DLC value of 45%

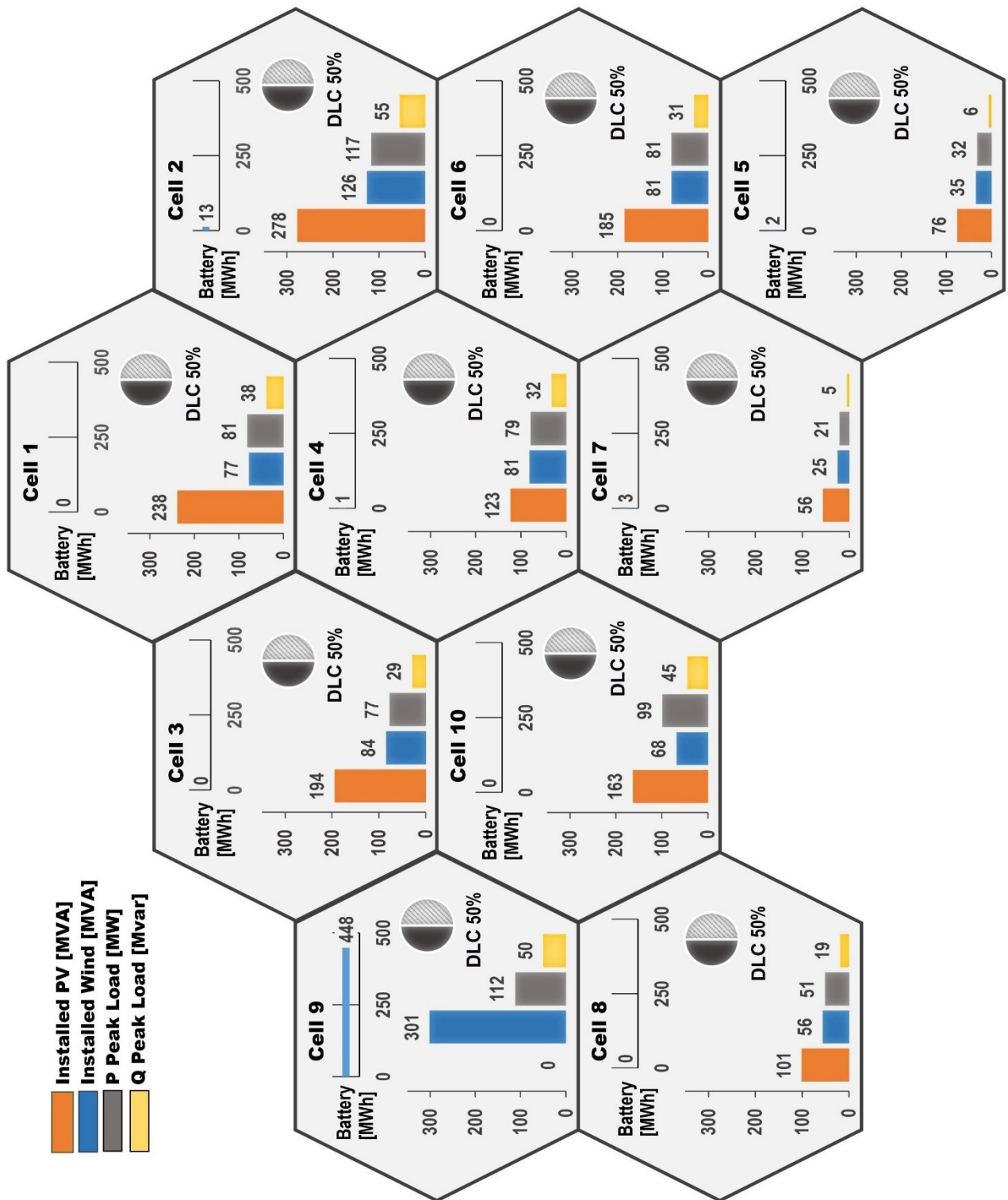


Figure 6-55: Results of the first optimization approach with DLC value of 50%

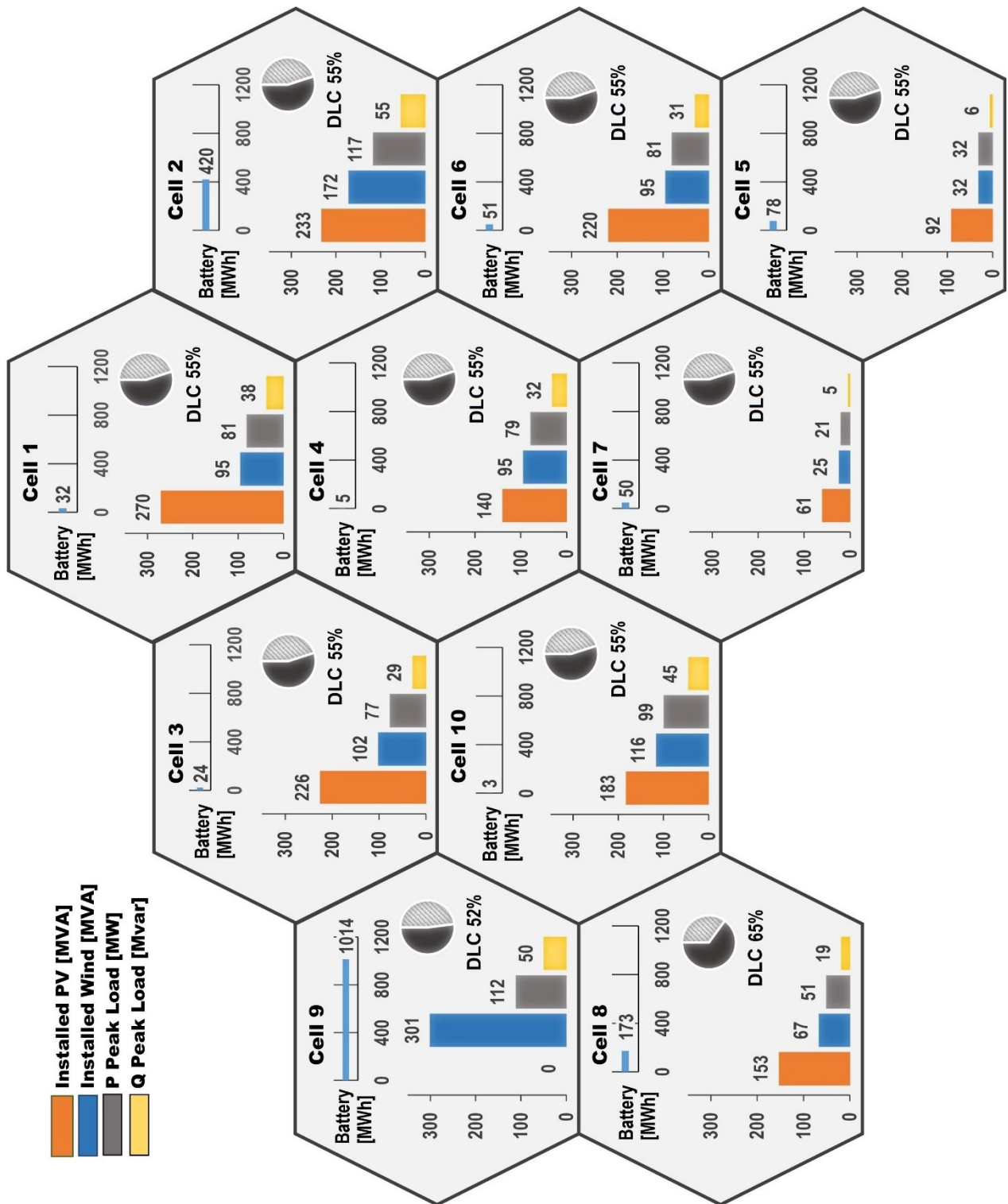


Figure 6-56: Results of the first optimization approach with DLC value of 55%

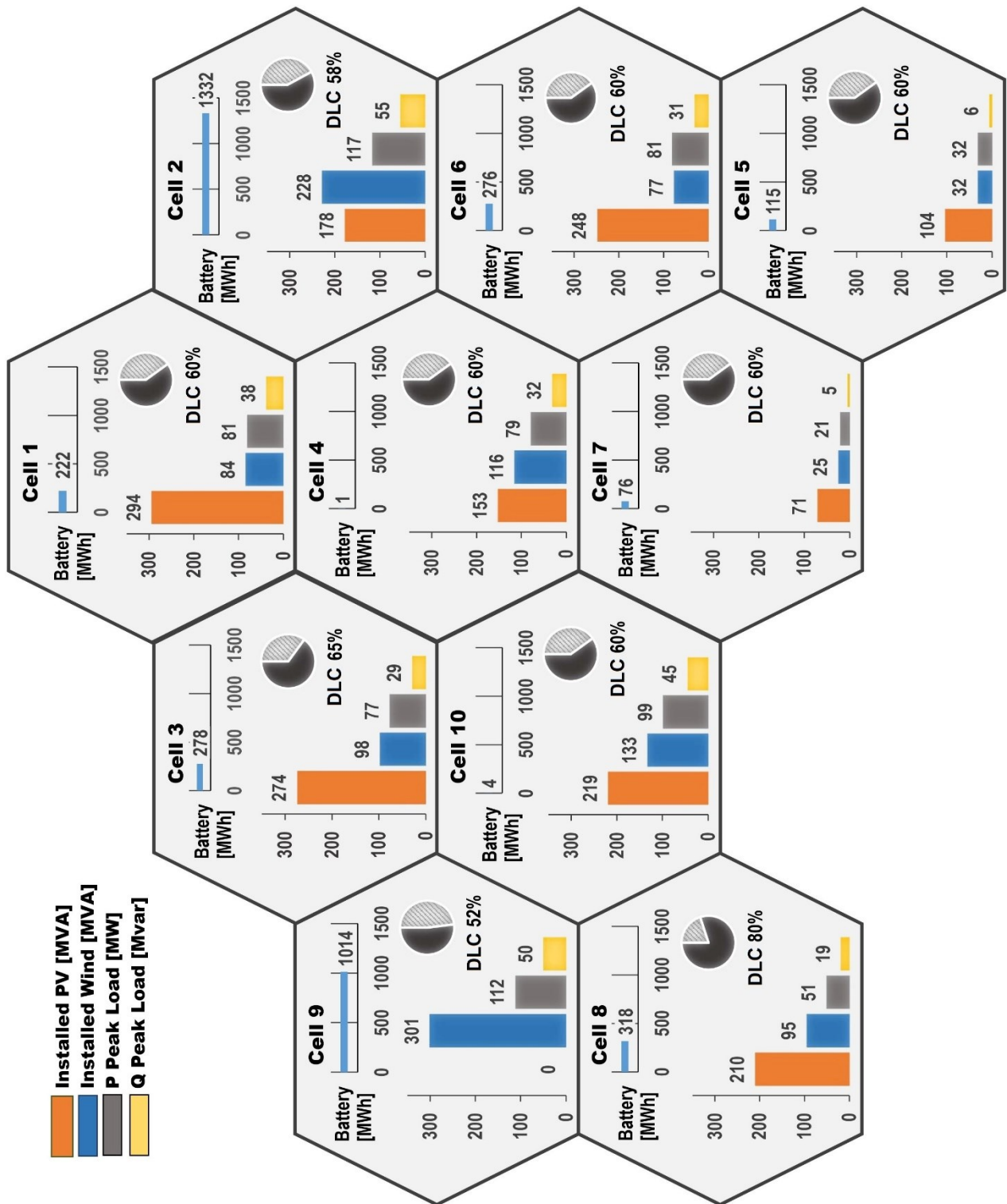


Figure 6-57: Results of the first optimization approach with DLC value of 60%

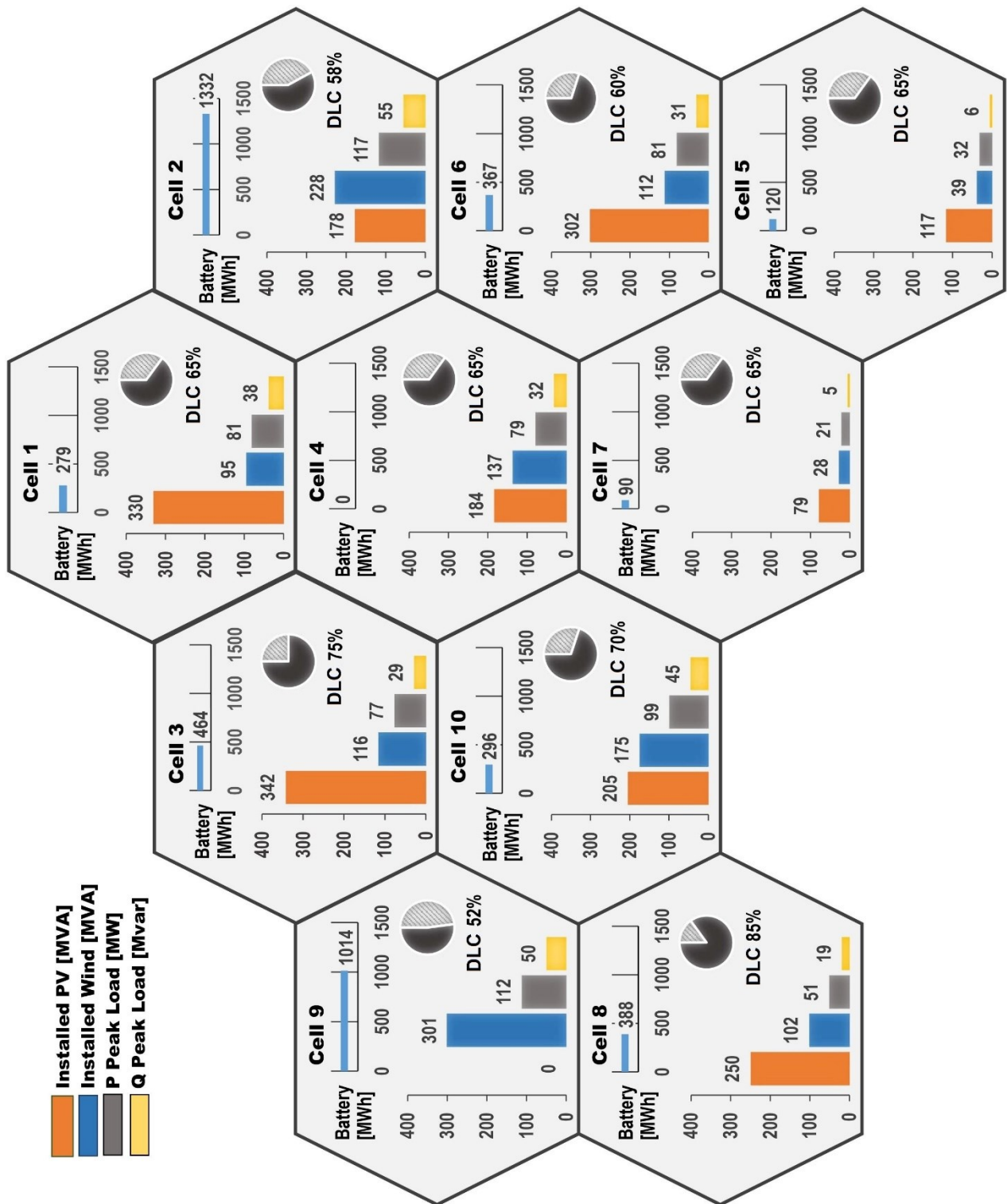


Figure 6-58: Results of the first optimization approach with DLC value of 65%

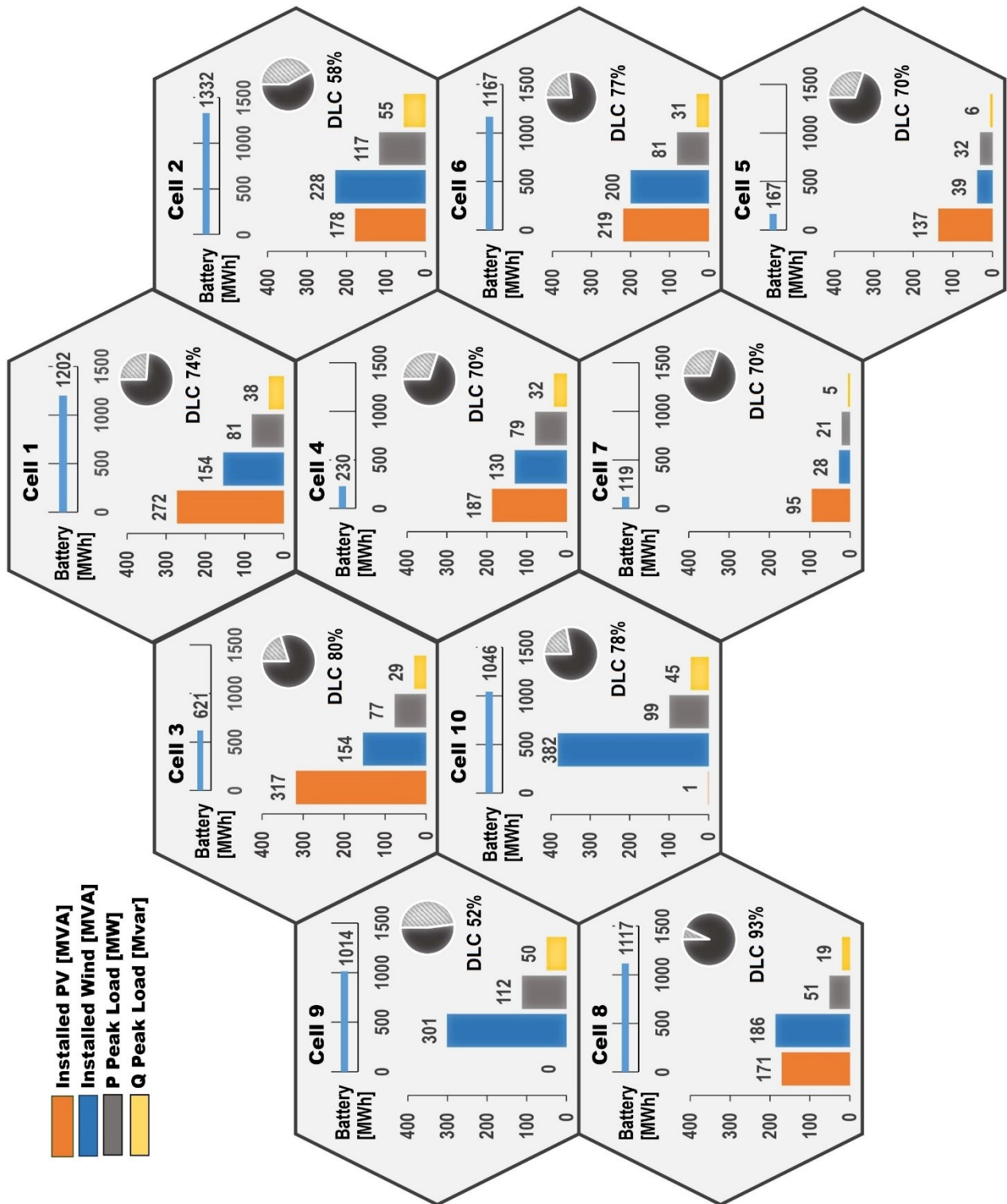


Figure 6-59: Results of the first optimization approach with DLC value of 70%

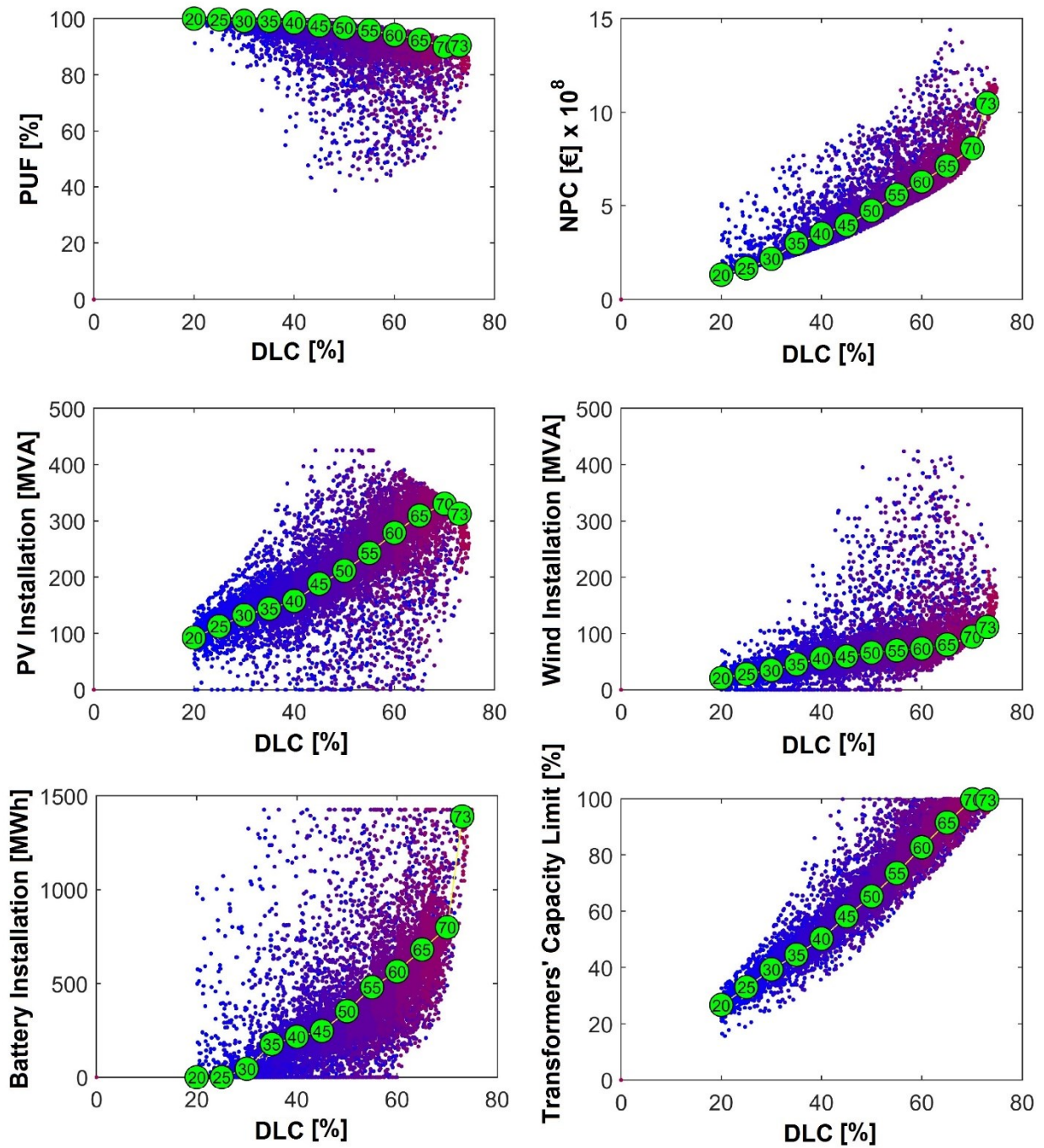


Figure 6-60: Results of the second optimization approach in cell 1

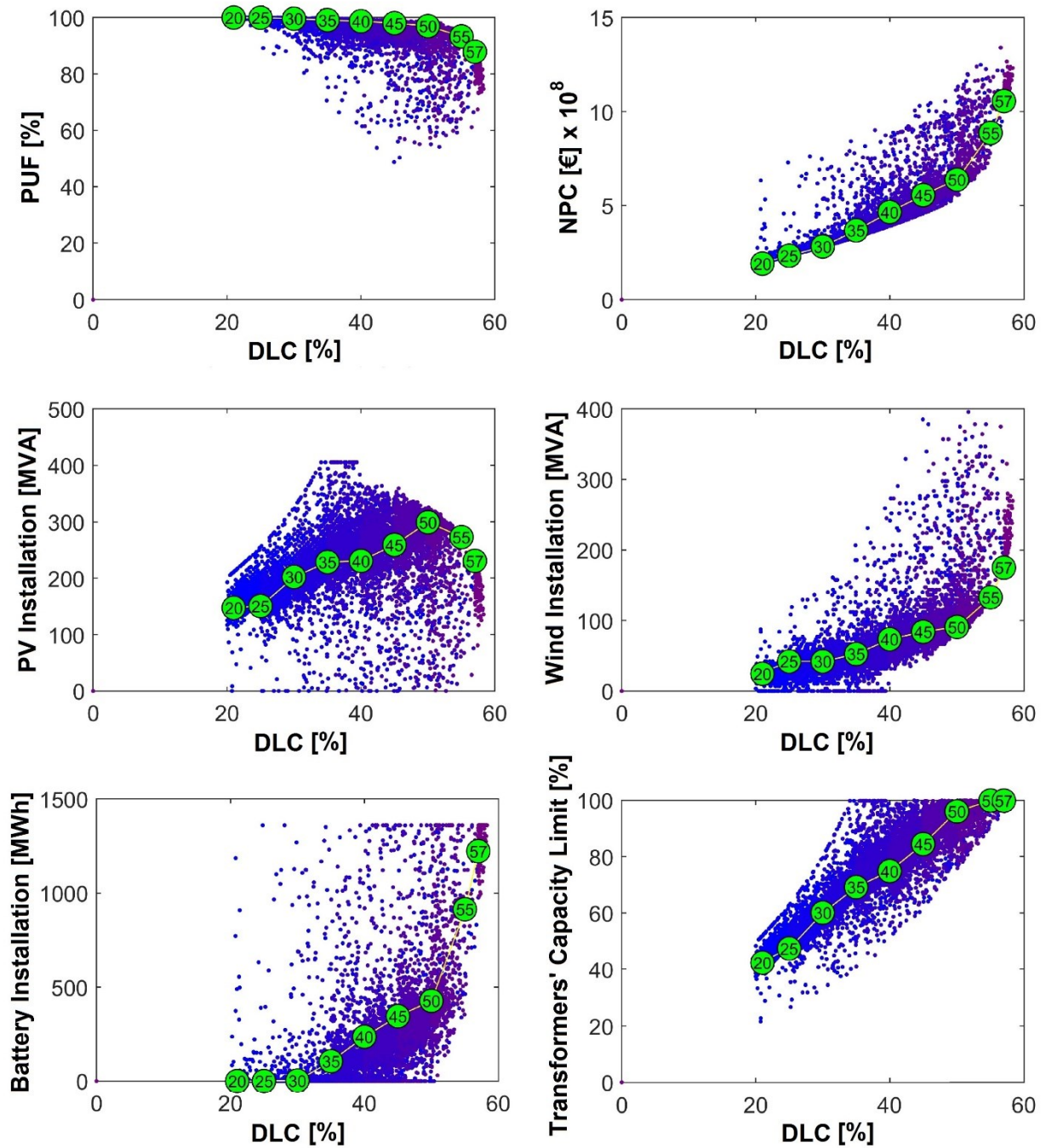


Figure 6-61: Results of the second optimization approach in cell 2

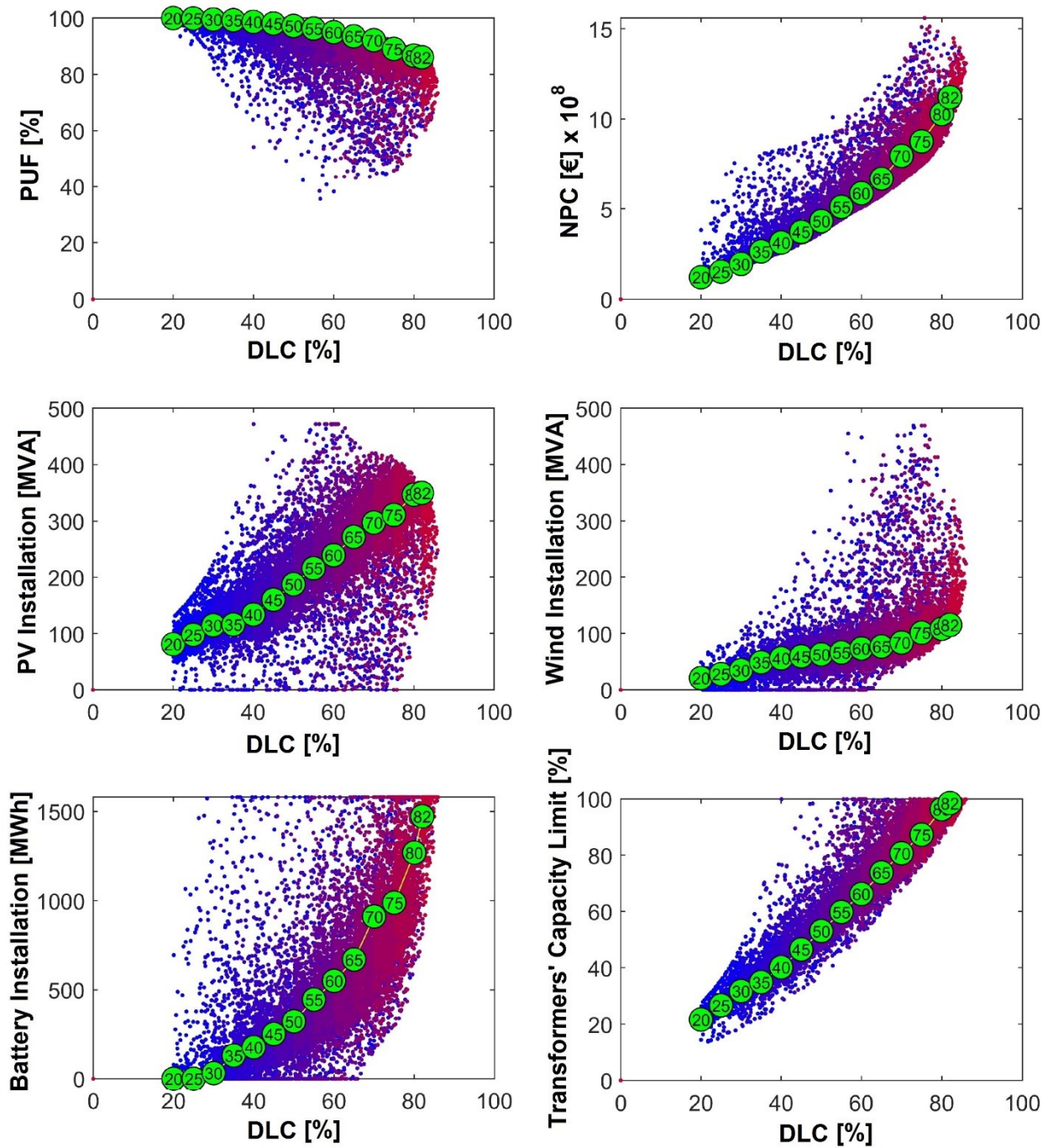


Figure 6-62: Results of the second optimization approach in cell 3

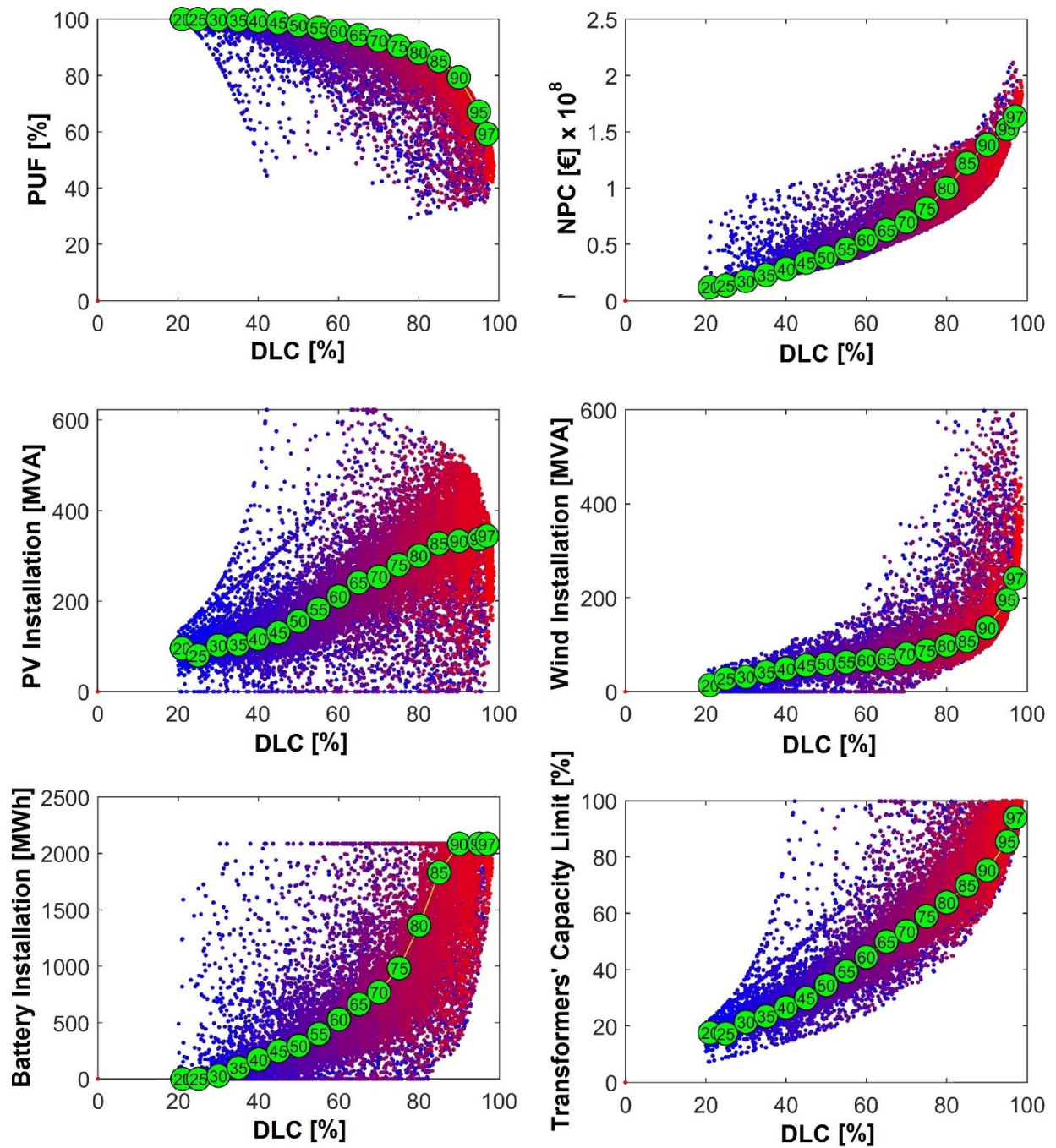


Figure 6-63: Results of the second optimization approach in cell 4

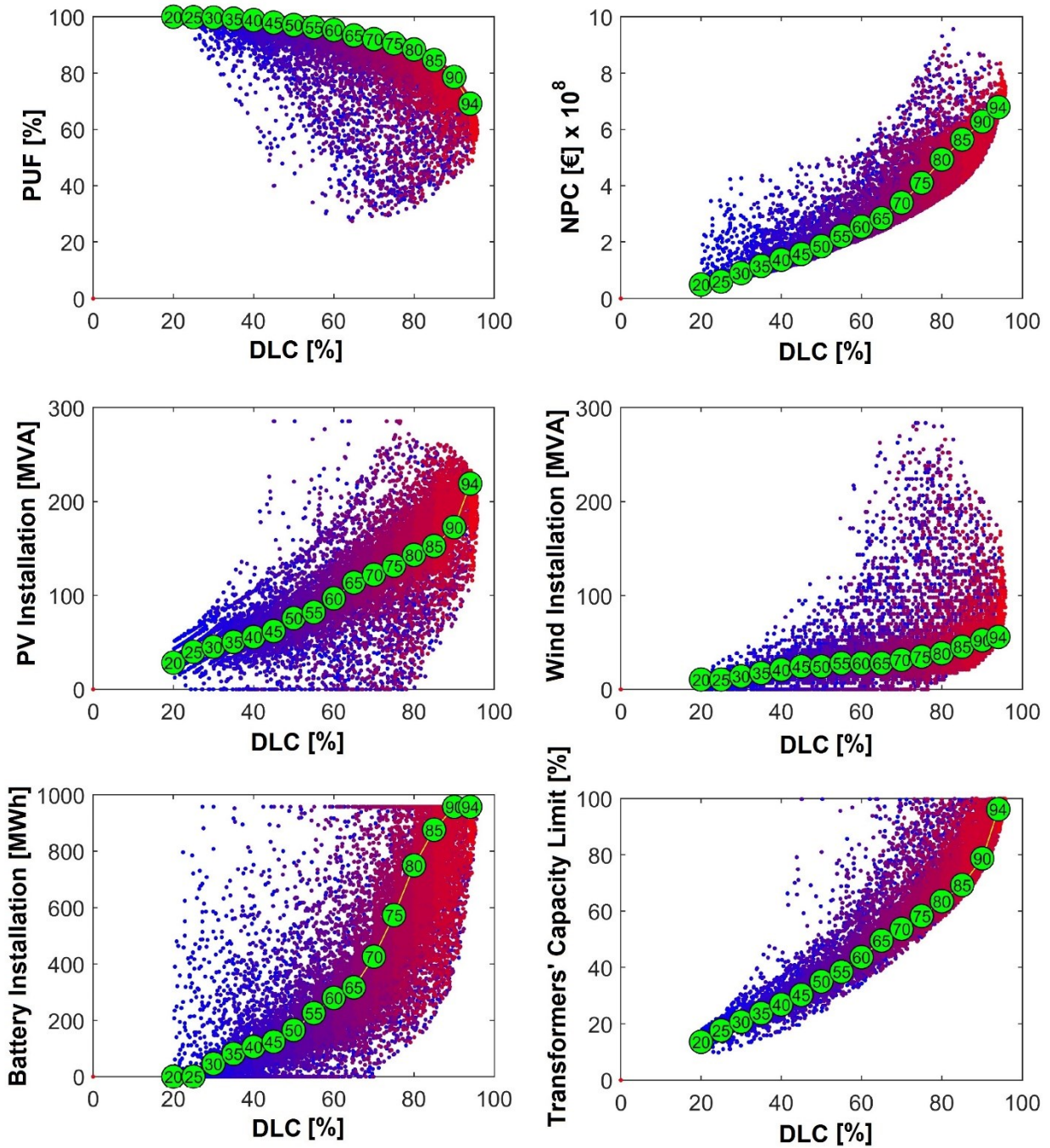


Figure 6-64: Results of the second optimization approach in cell 5

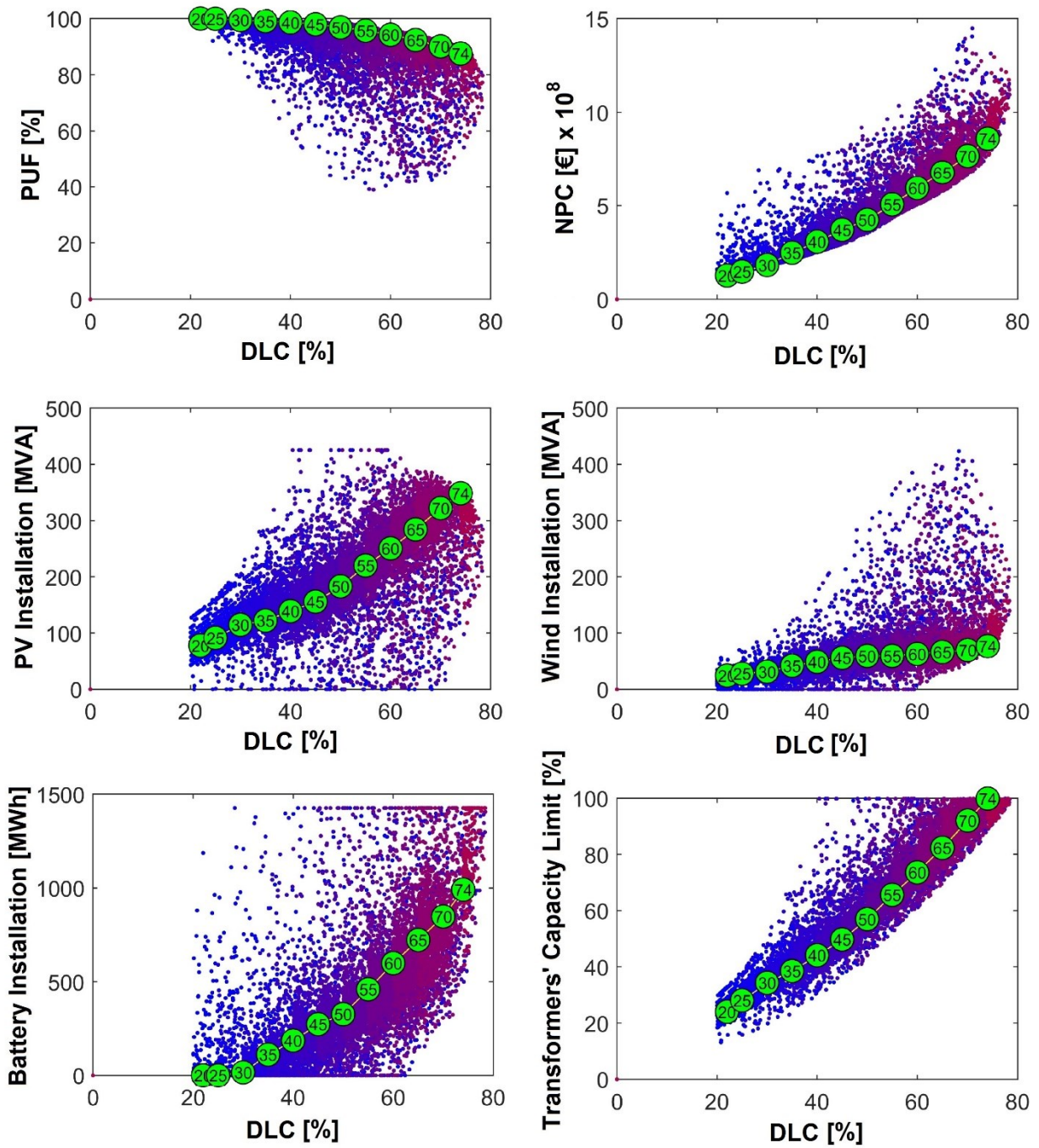


Figure 6-65: Results of the second optimization approach in cell 6

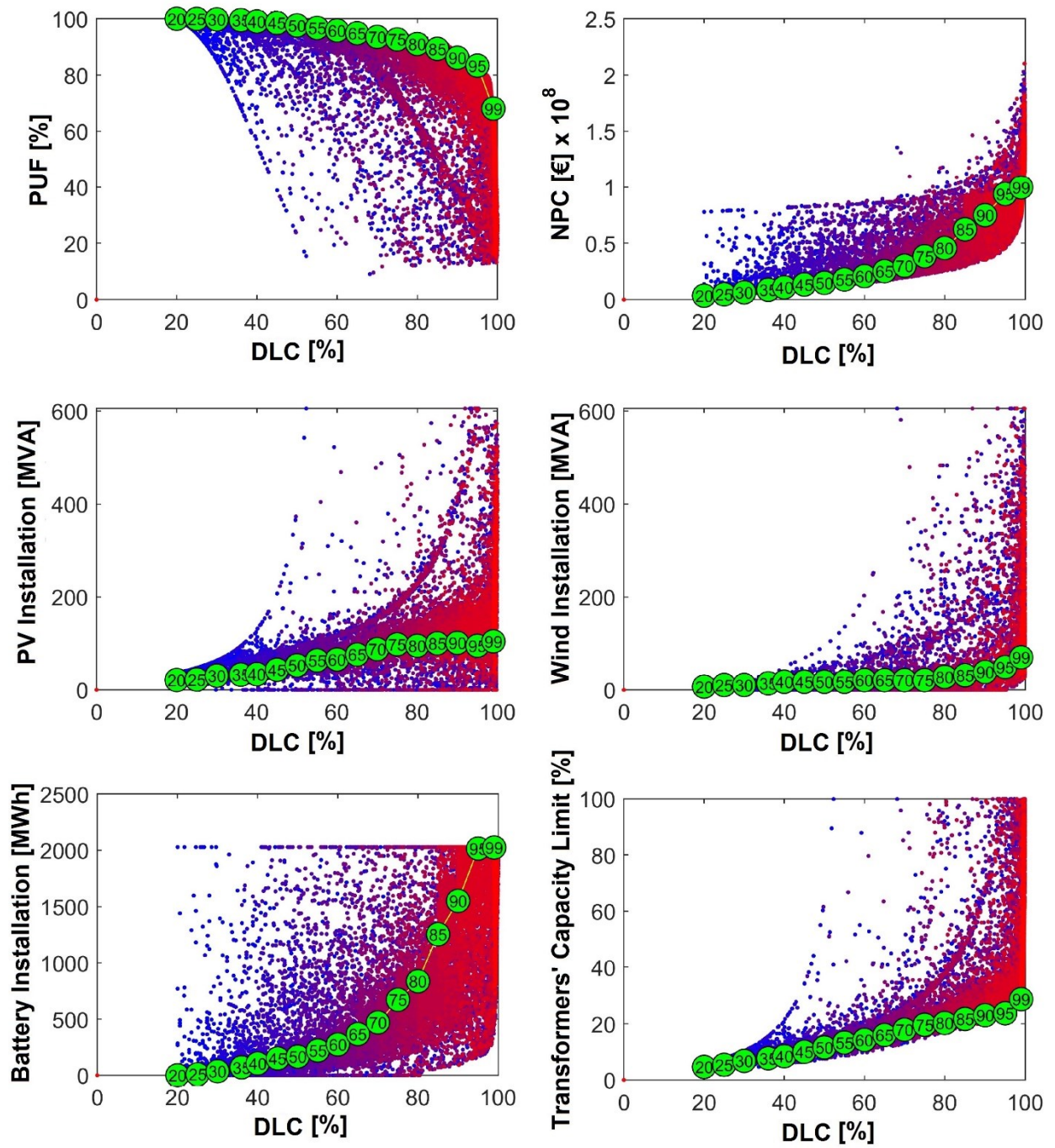


Figure 6-66: Results of the second optimization approach in cell 7

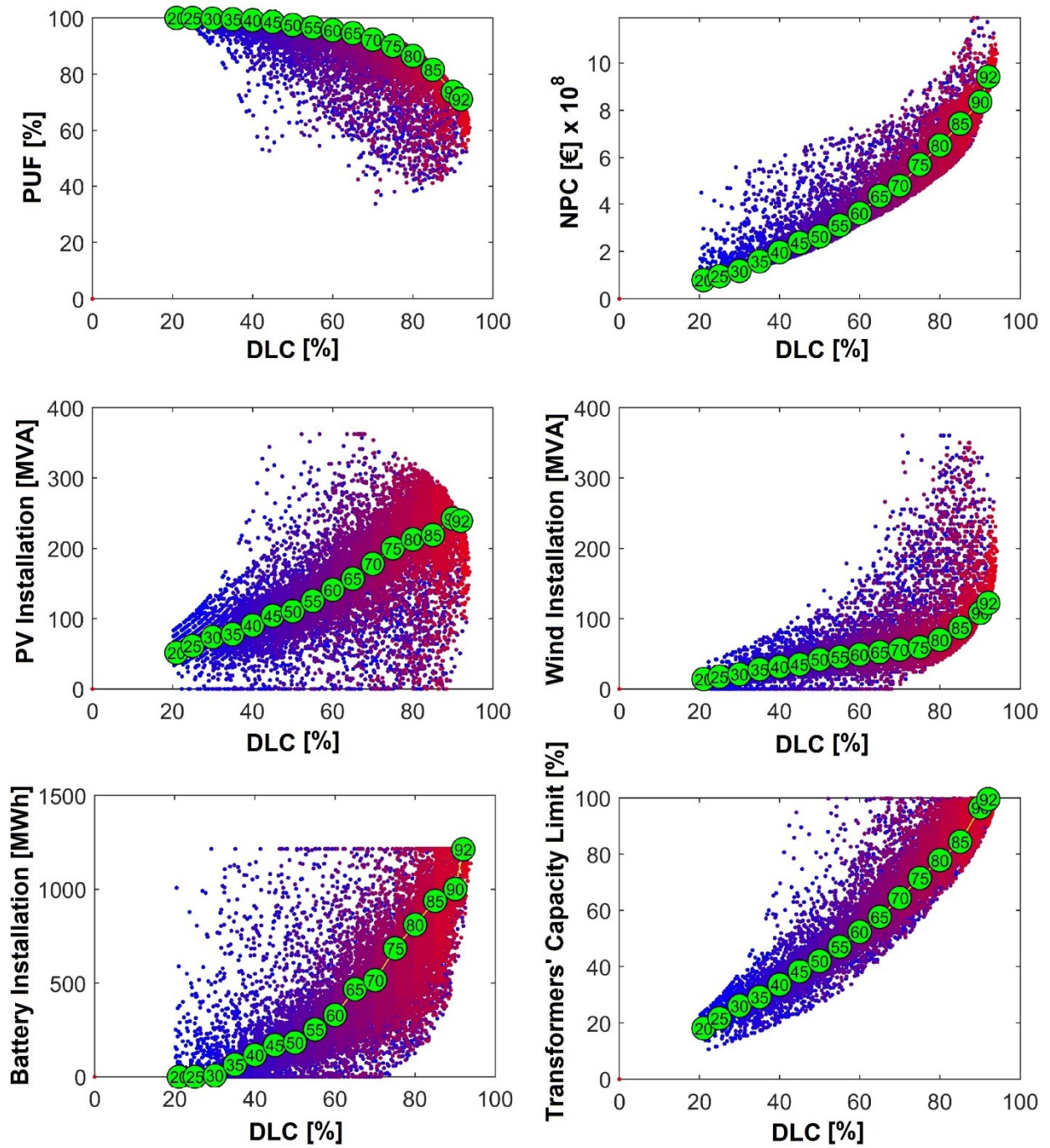


Figure 6-67: Results of the second optimization approach in cell 8

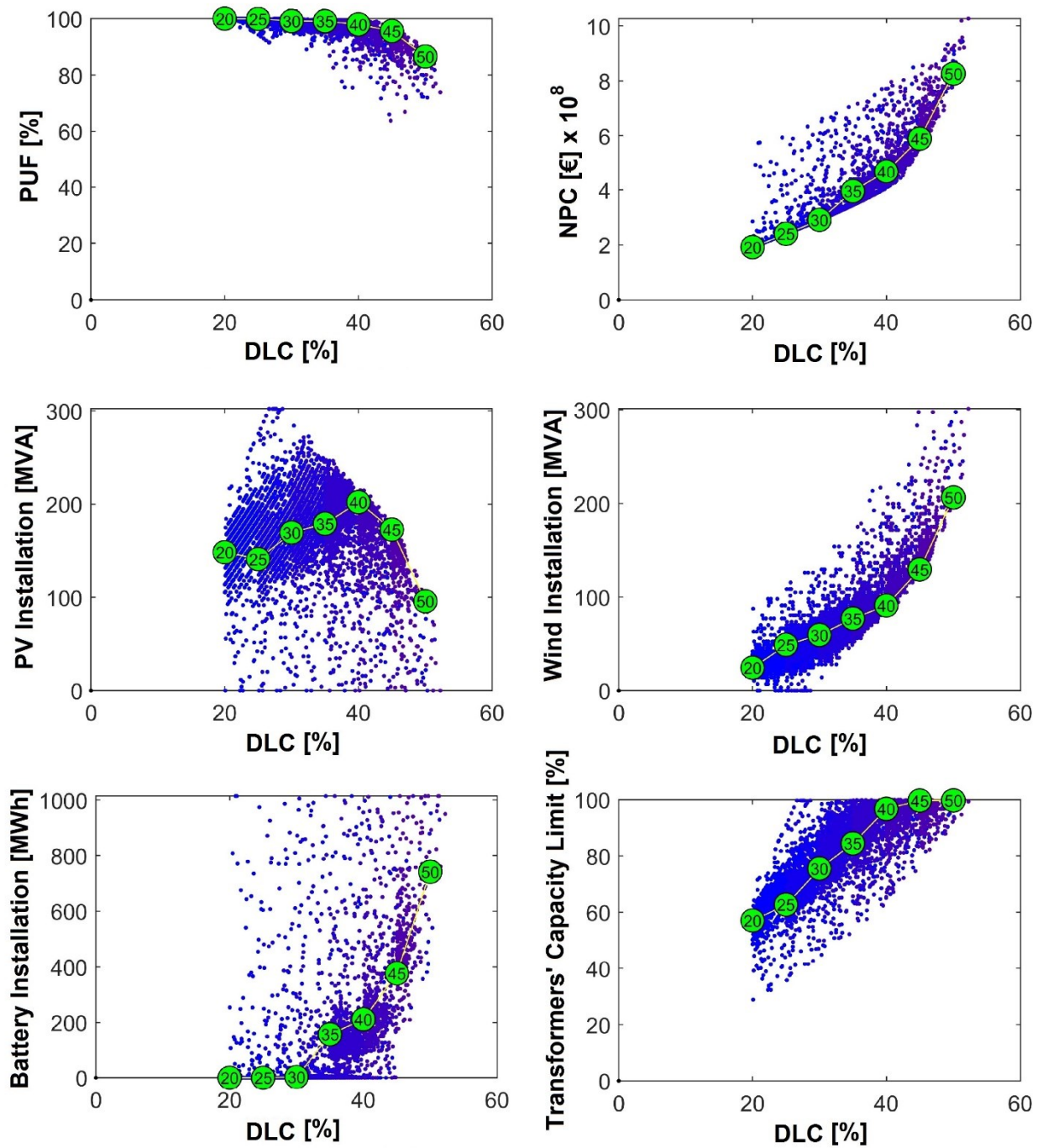


Figure 6-68: Results of the second optimization approach in cell 9

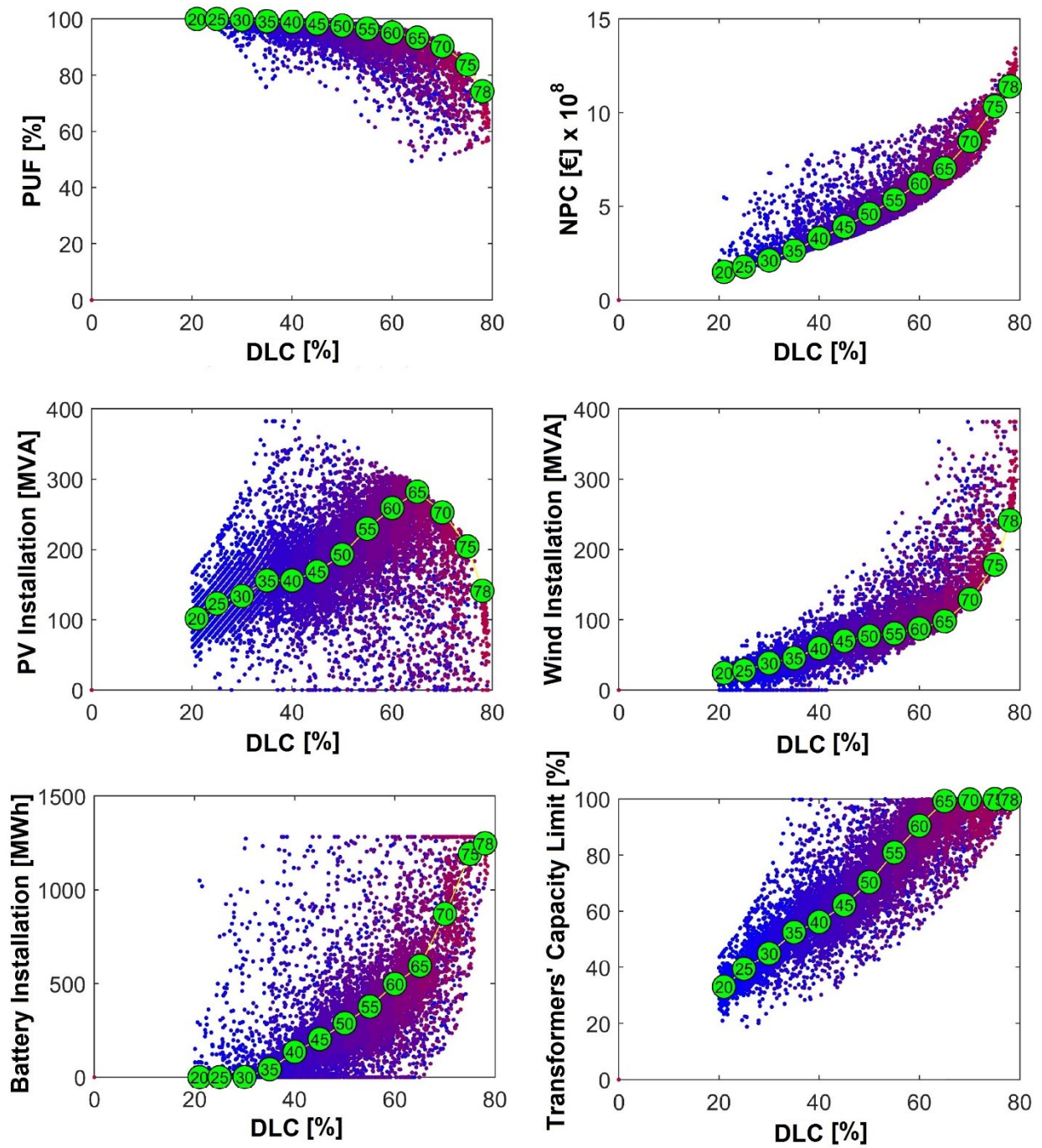


Figure 6-69: Results of the second optimization approach in cell 10

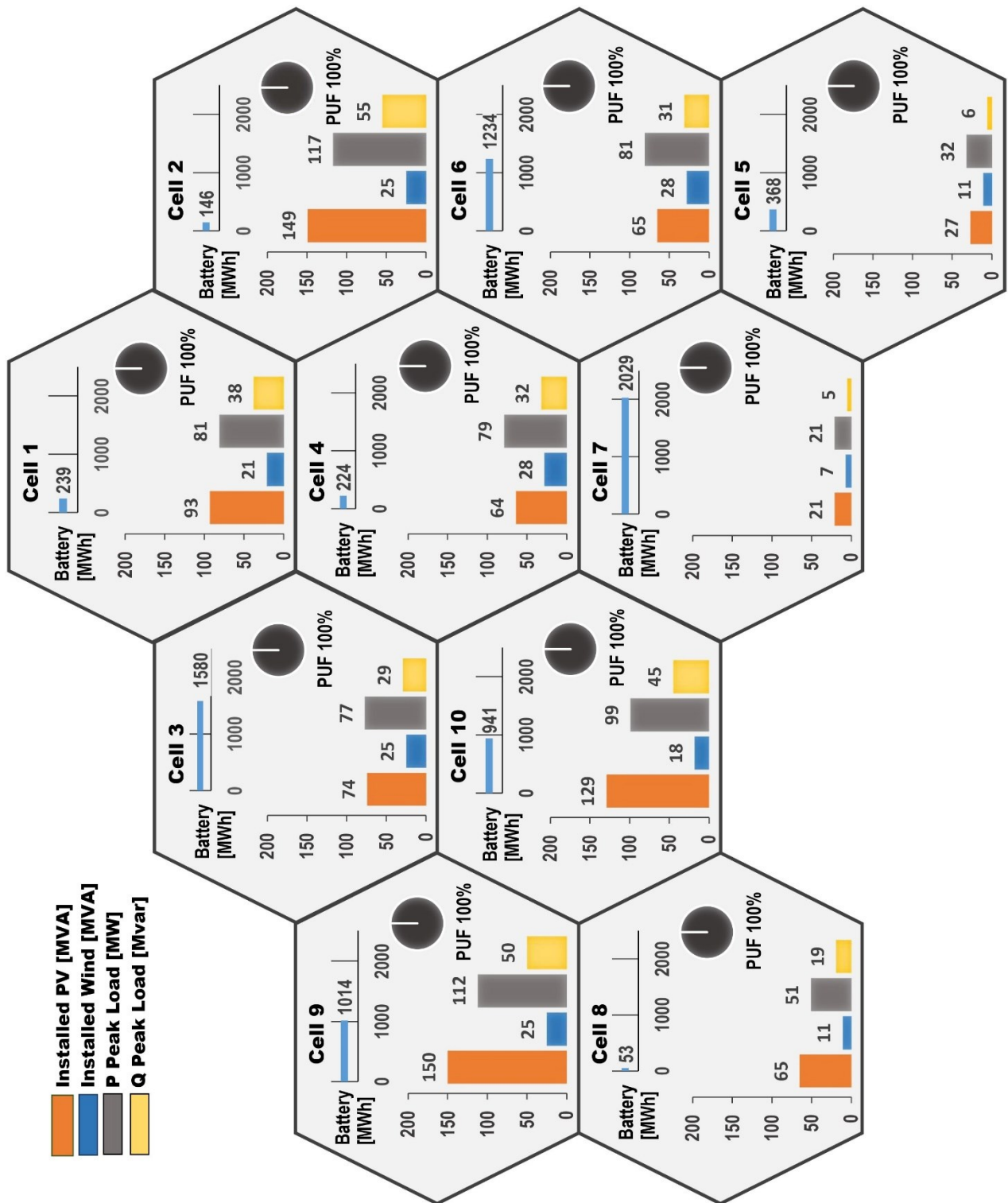


Figure 6-70: Results of the second optimization approach with DLC value of 20%

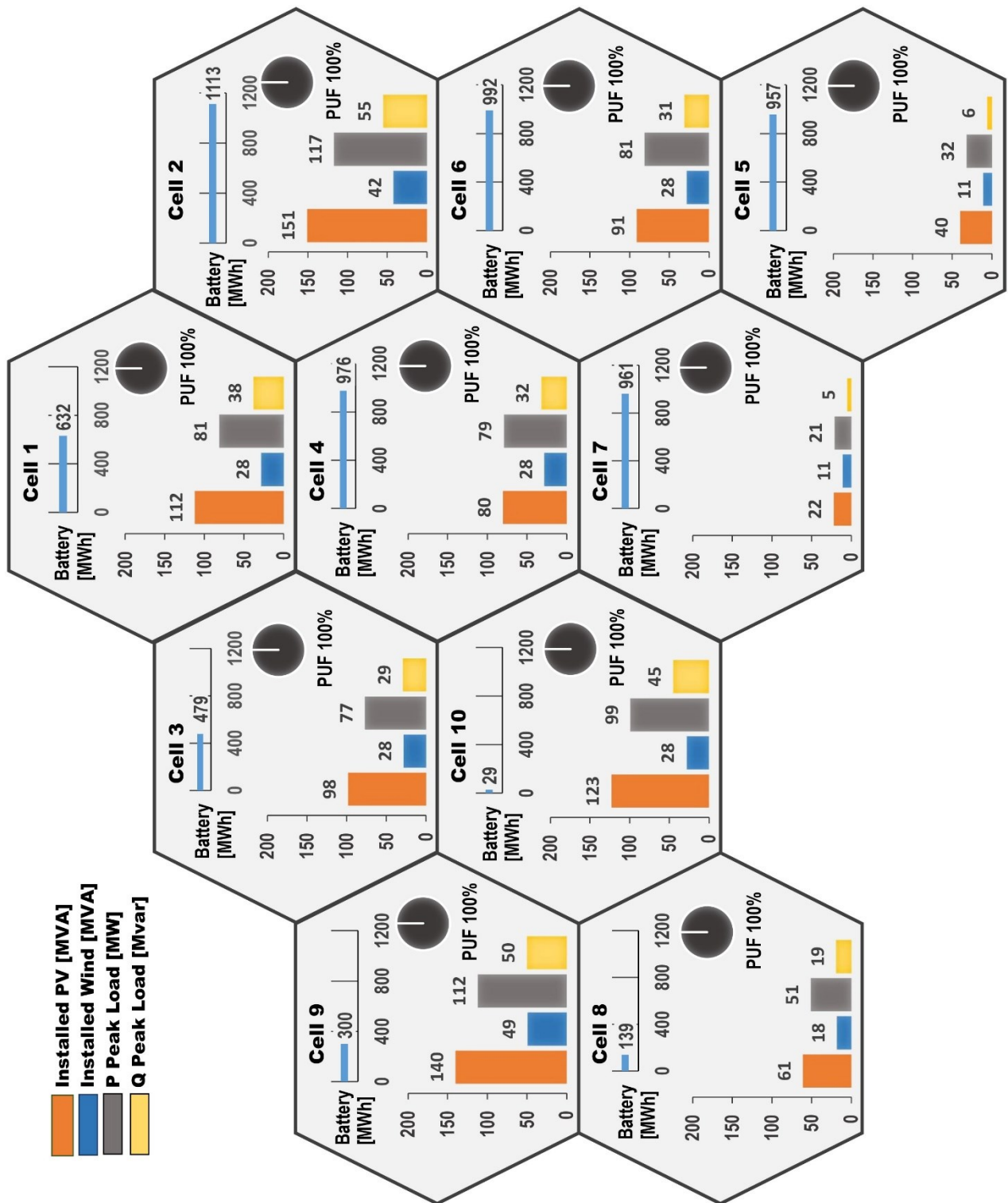


Figure 6-71: Results of the second optimization approach with DLC value of 25%

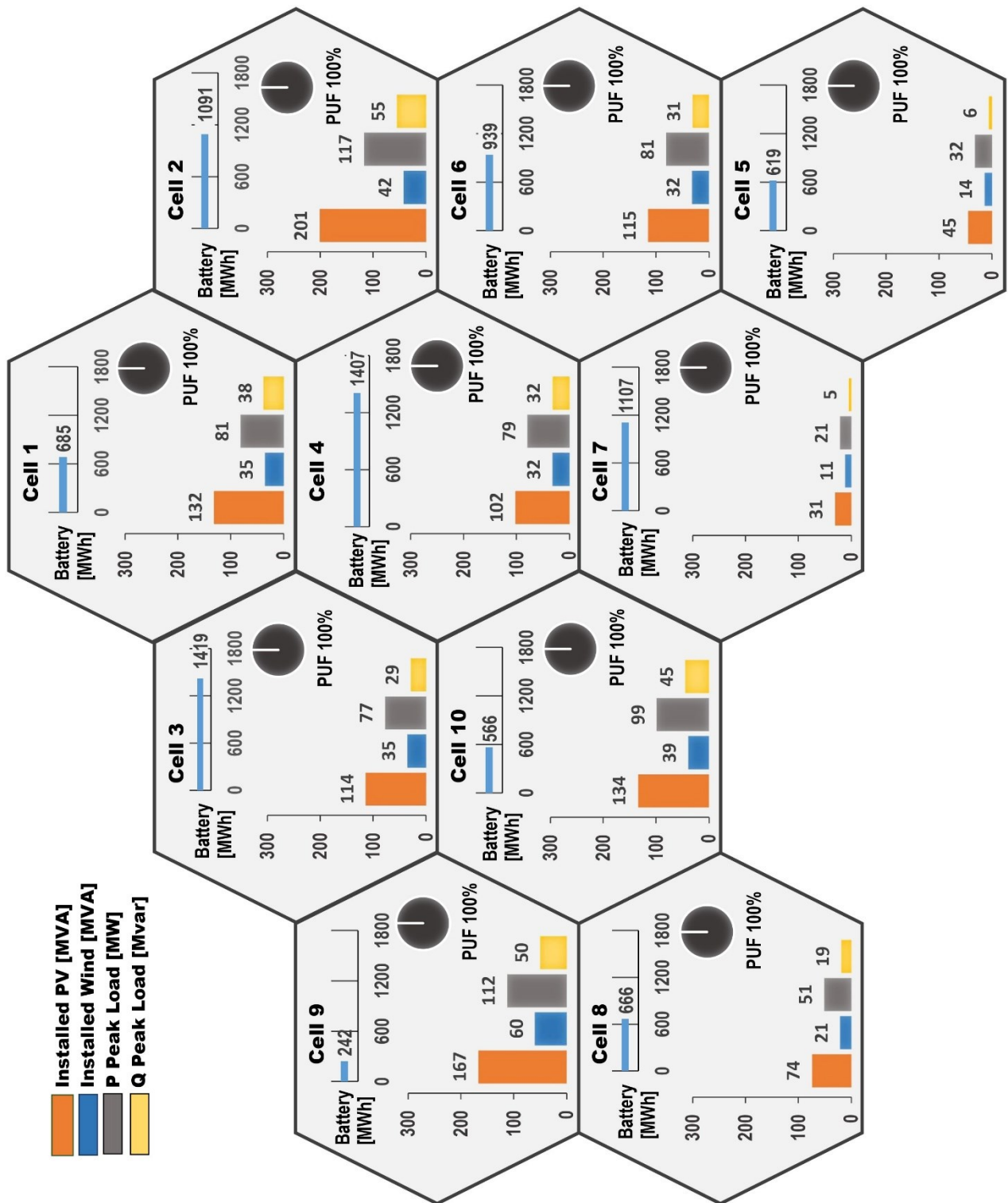


Figure 6-72: Results of the second optimization approach with DLC value of 30%

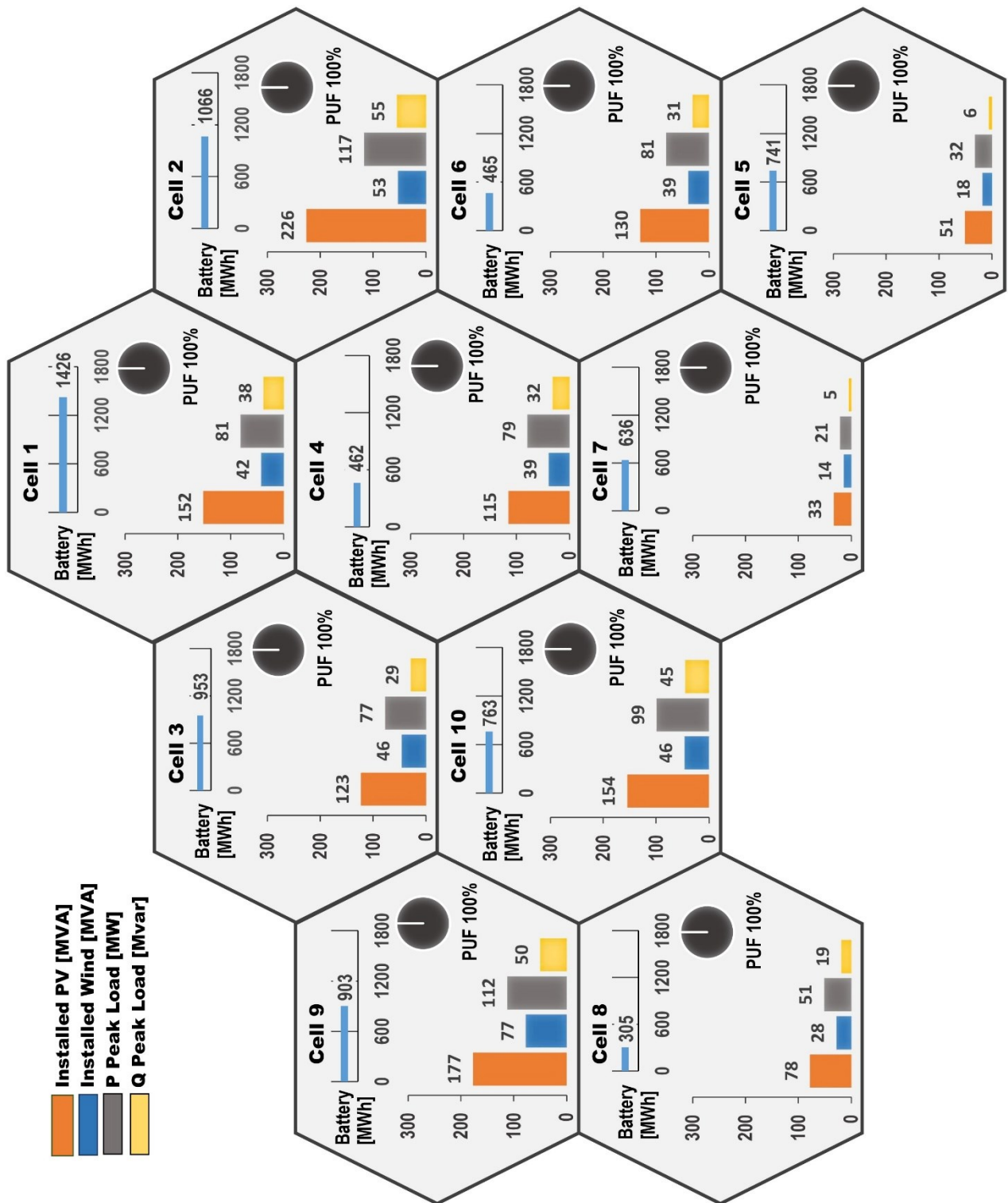


Figure 6-73: Results of the second optimization approach with DLC value of 35%

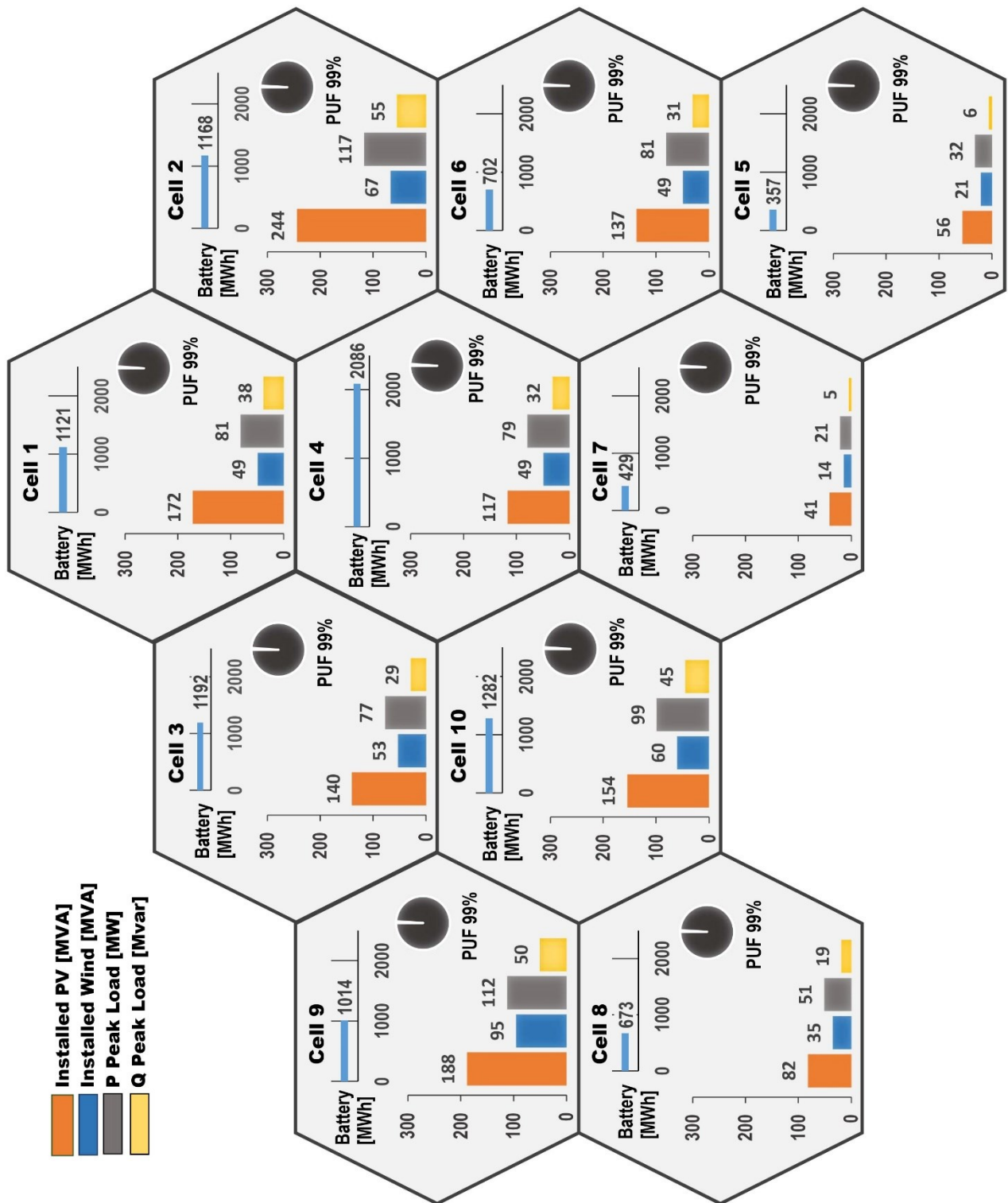


Figure 6-74: Results of the second optimization approach with DLC value of 40%

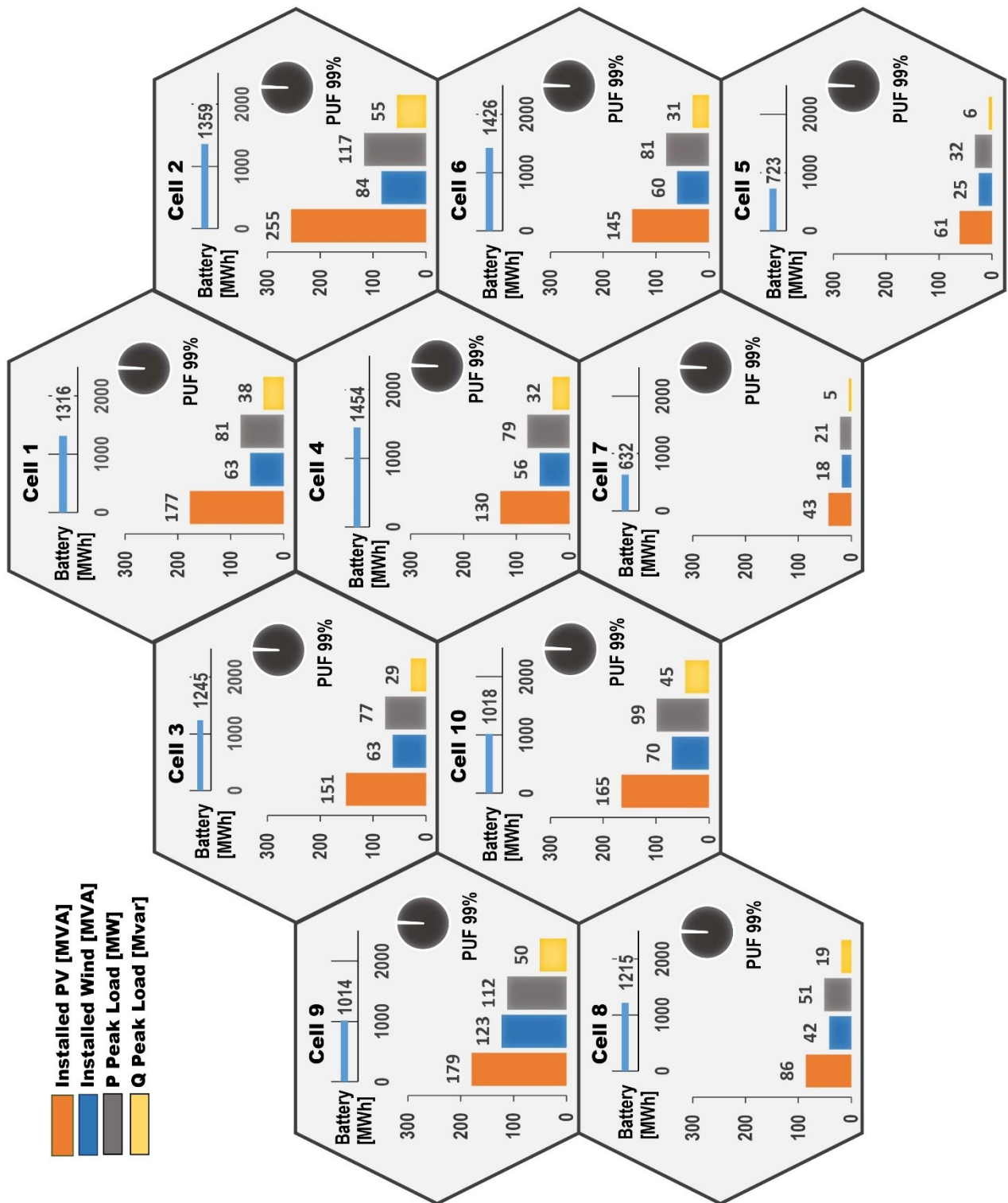


Figure 6-75: Results of the second optimization approach with DLC value of 45%

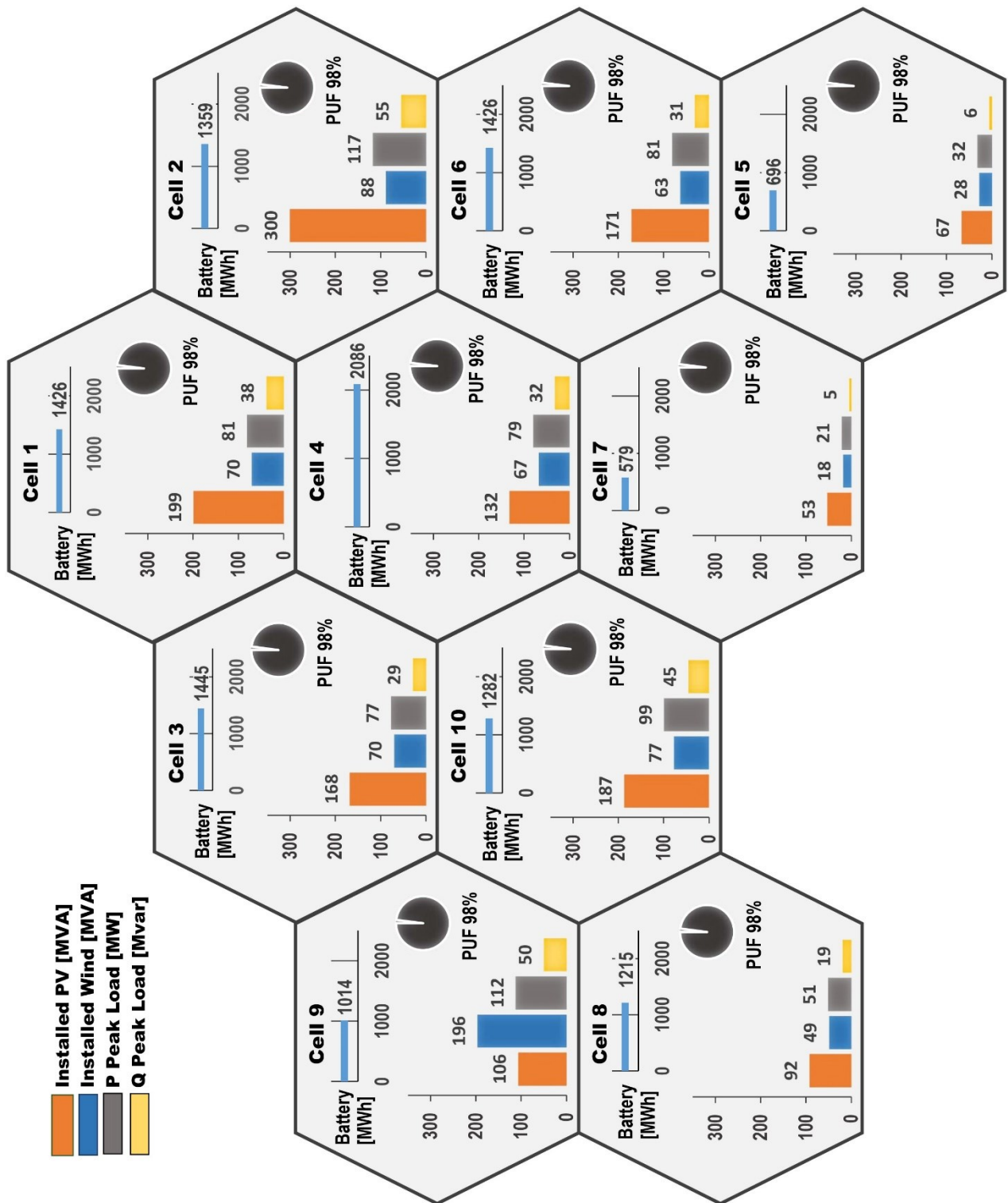


Figure 6-76: Results of the second optimization approach with DLC value of 50%

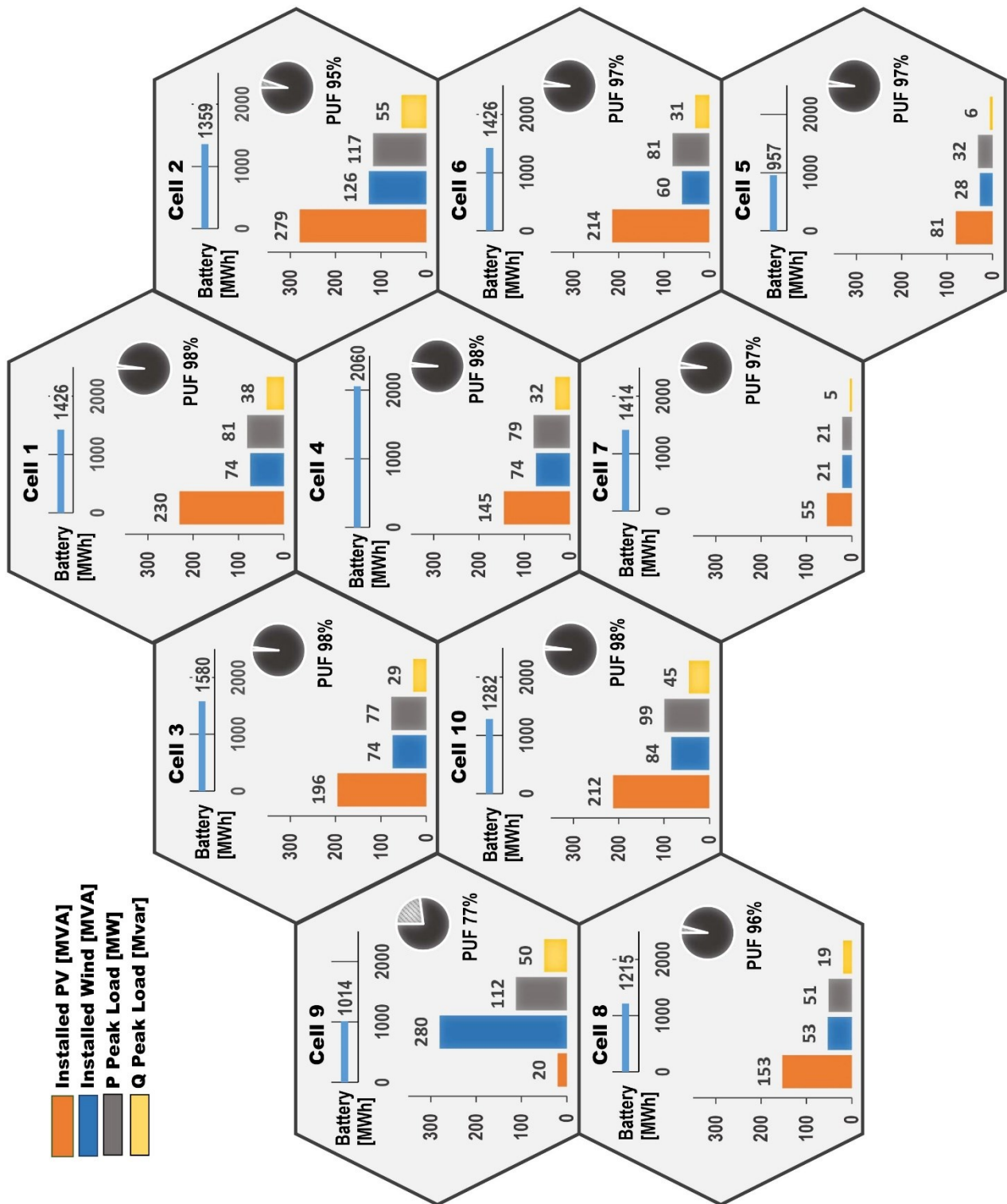


Figure 6-77: Results of the second optimization approach with DLC value of 55%

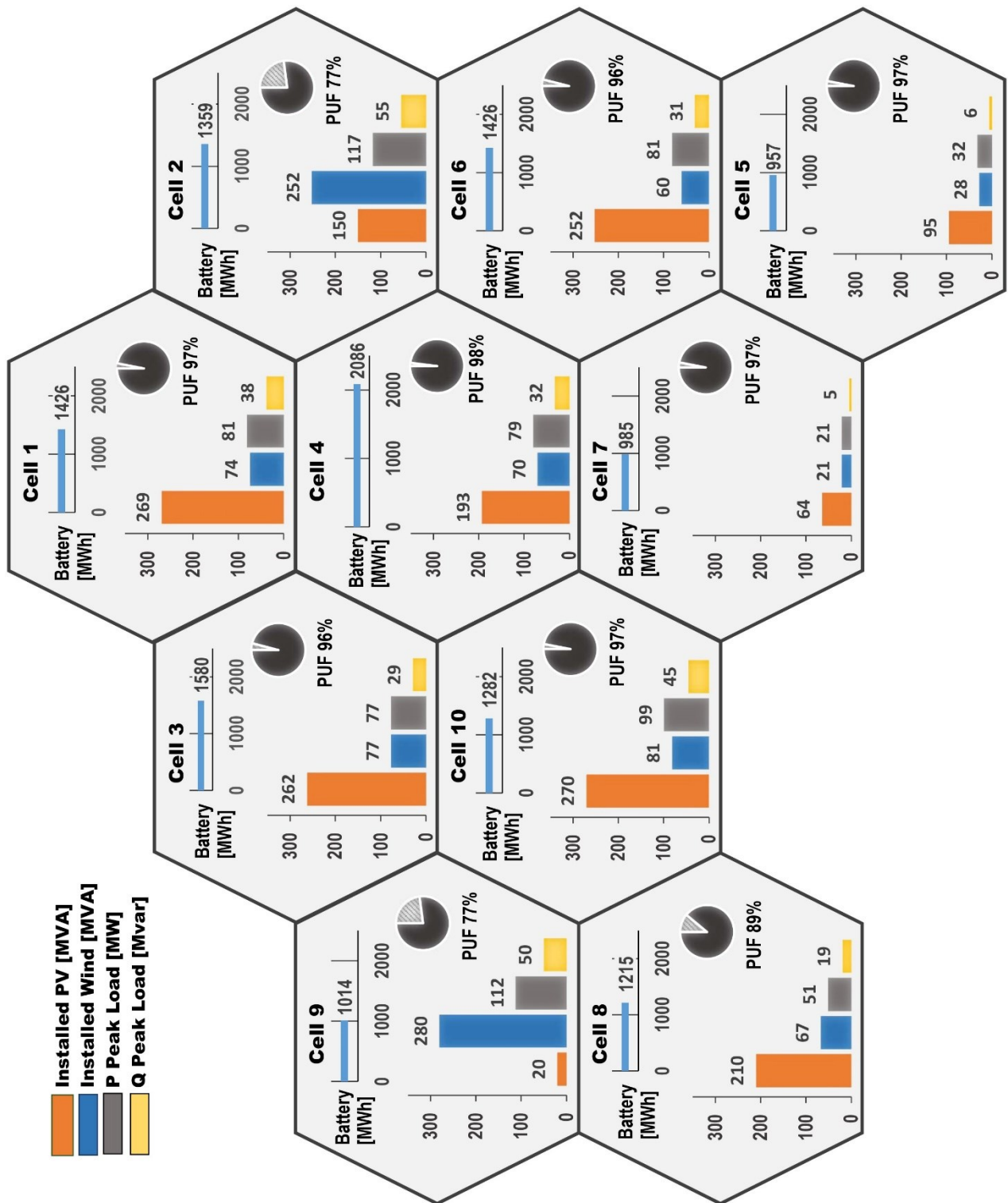


Figure 6-78: Results of the second optimization approach with DLC value of 60%

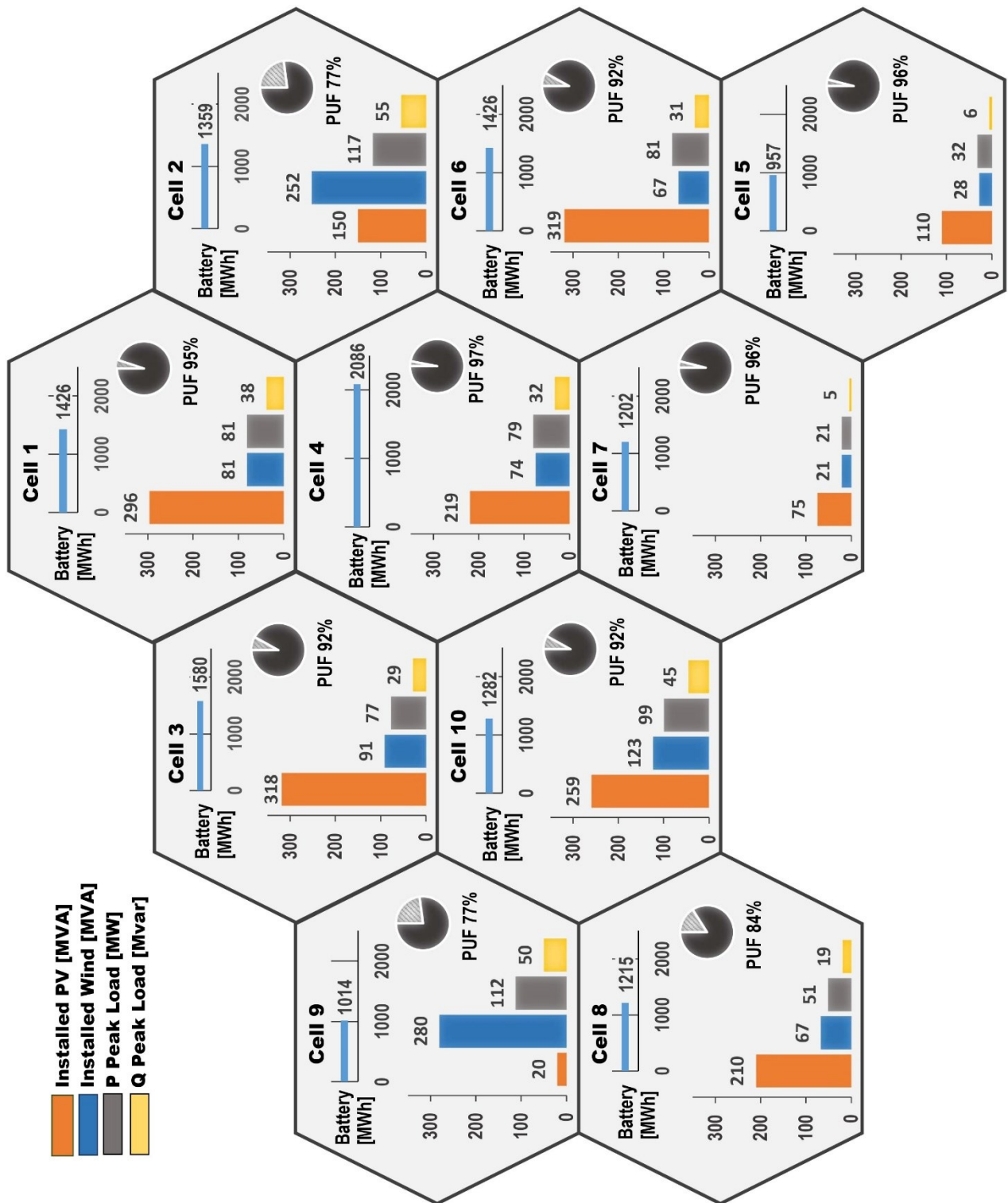


Figure 6-79: Results of the second optimization approach with DLC value of 65%

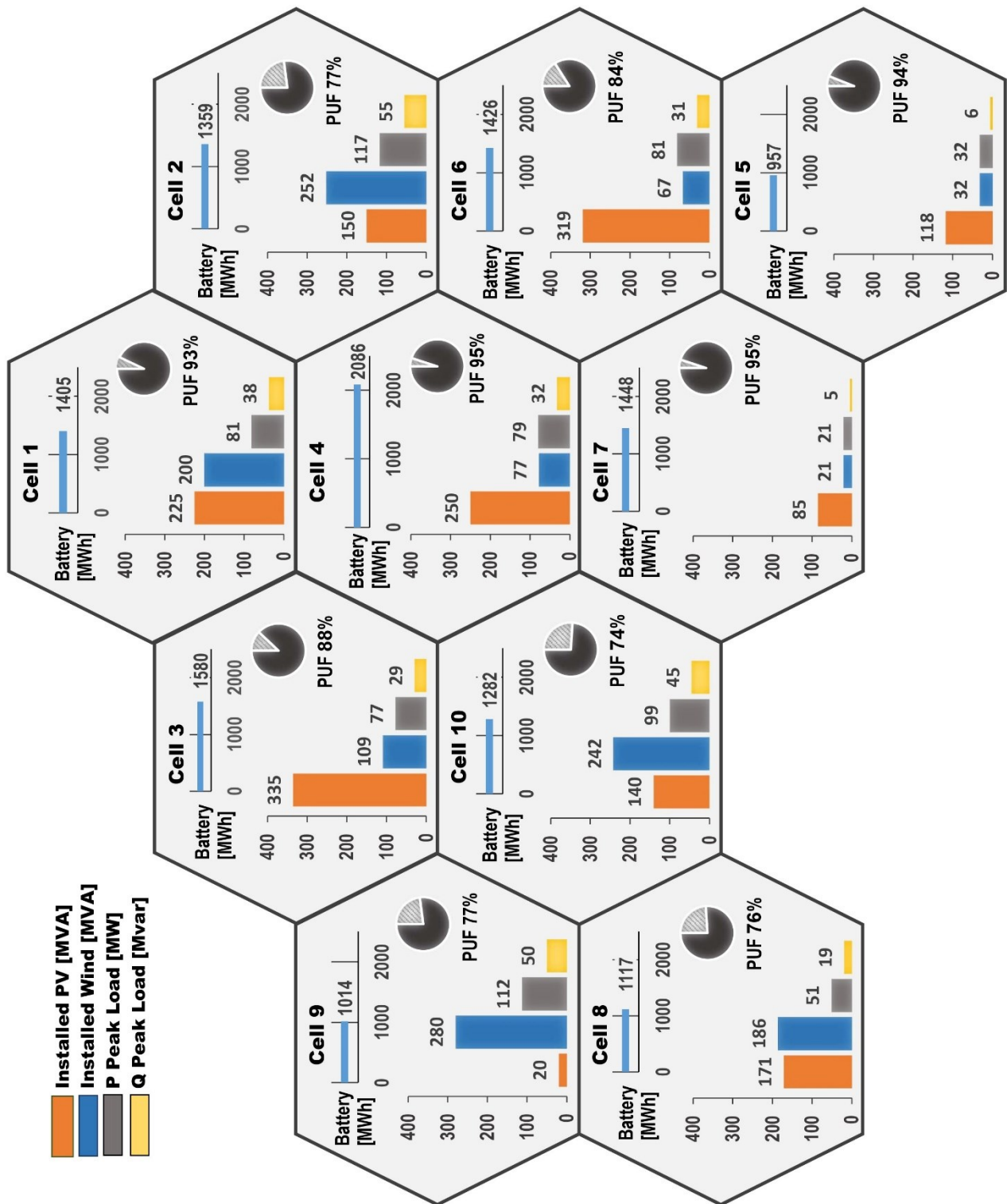


Figure 6-80: Results of the second optimization approach with DLC value of 70%