Analysis of Smart Technical Measures Impacts on DER and EV Hosting Capacity Increase in LV and MV Grids in the Czech Republic in Terms of European Project InterFlex

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***Abstract*—The paper presents a methodology how to quantify a technical and economic impact of selected smart solutions on hosting capacity increase of Distribution Energy Resources (DERs) and electric vehicles (EVs) on low voltage (LV) and medium voltage (MV) level in a large distribution area in the future. The official Czech government documents called National Action Plan for Smart Grids (NAP SG) and Clean Mobility (NAP CM) published by Czech Ministry of Industry and Trade present several scenarios of future expected development of DERs and EVs. Comparison of business as usual and smart grid solutions is presented and monetized.**

Keywords—DER hosting capacity, EV integration, distribution grid models, smart technical solutions, investment cost

I. Introduction

With increase of DERs and EVs connected to European grids, many operators and associations such as E.DSO or Eurelectric are looking for studies measuring the economic impact. The methodology developed by Czech research team is considered as unique and quite advanced.

A necessary precondition to quantify an overall impact of the new generation and consumption on distribution grids is to divide the total numbers into smaller regions and districts. This was done for the Czech Republic based on climate conditions for renewables, population density, type of cities and villages, economic aspects, traffic infrastructure, etc. The applied granularity includes 50 district and about 200 HV/MV substations. Analysed Distribution System Operator's (DSO) area includes more than 2500 MV feeders with more than 60000 secondary transformers MV/LV. As such huge topology of distribution grid could not be modelled and calculated due to its complexity, the whole grid was mapped, and the structures were divided into 15 MV groups and 18 LV groups. The groups are called "representative models" and they represent fixed grid structures with representative topologies and feeder's electrical parameters.

To evaluate total grid hosting capacity in future years (up to 2040) the most critical states were selected. These statuses are represented by spring noon with low grid load for DER hosting capacity calculation and winter evening with high grid loading and low DER generation for EV hosting capacity calculation. Also, energy storage development scenarios were considered for both cases. To model future states in representative grids, not only DER and EV predictions were considered. Also influence of existing generation units and load levels as well as their expected natural development in time is considered. Standard distribution capacity investments and development was included which results in representative model topology changes for different years in future.

The main and final procedure step provides load flow hosting capacity calculation for both DERs and EVs (separately) for all representative models for all considered future years. The hosting capacity criteria result from Czech grid code. These hosting capacities were compared with the predicted demands for the representative grids in each considered district or substation. Summarizing of partial results gives the final information about the hosting capacity deficit or surplus in all districts in the distribution area. In case of hosting capacity deficit in representative grid models in selected scenarios (for DER or for EVs), LV and MV representative models are reconstructed (change in the topology) to increase hosting capacity. Length of LV and MV feeders and number of secondary transformers which need to be replaced by more powerful ones, are quantified. Based on type and length of reconstructions, costs for distribution capacity investments are quantified for Cost Benefit Analysis (CBA) purposes.

As the NAP predictions are very ambitious for both DERs and EVs, many districts are expected to have significant hosting capacity deficits. Therefore, implementation of smart technical measures was included in the hosting capacity calculations. Smart measures are represented by autonomous control functions Q (V) and P (V) in smart photovoltaic (PV) inverters on LV level, volt-var control in DERs installed on MV level, smart EV charging control and smart home energy storage. The paper compares how these smart solutions increase overall hosting capacities in all the country and how they can reduce the necessary additional distribution capacity investment cost to integrate expected DERs and EVs into the distribution grids.

II. Energy Policy and Future Scenarios in the Czech Republic

Energy Market has started to change into more decentralized system before any of Smart Grid projects and technologies were introduced. In last few years, higher pressure of government and market players to allow more small renewable sources to participate on the market was

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observed. This means higher responsibility for system operators to enable to connect, control and monitor grids. In this analysis the main energy policy documents developed under State Energy Policy are described to introduce the situation and future plans of national institutions, energy utilities and all market participants.

National Action Plan for Smart Grids [1] and Clean Mobility [2] are strategic documents and concepts of development of network infrastructure to ensure reliable and safe operation with respect to the required development of distributed generation (especially Renewable Energy Sources), small combined heat and power (CHP) generation plants, production management, energy storage and consumption from electric vehicles and considering the requirement of increasing of energy efficiency.

NAP SG assumes a gradual introduction of smart grids and other measures in several stages. Investments in smart grid are also investments into the infrastructure and will be reflected in regulated components of electricity price. Therefore, it is necessary to adapt the way and speed of the smart grid deployment to benefits for consumers.

A. DER scenarios on LV grid

According to NAP SG, the scenarios imply assumptions of the dominant share of DER at the LV level and most visible share in future years is supposed to realize with small roof PV installations and with micro CHP units in households.

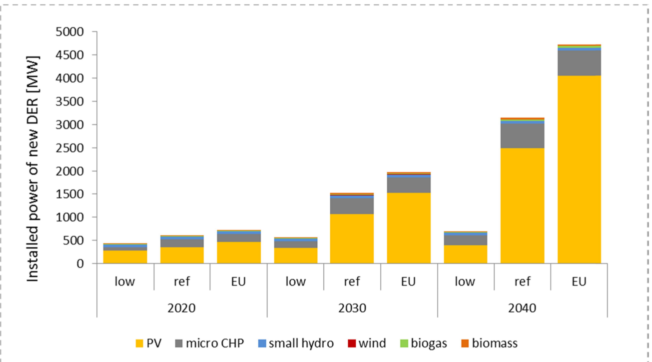

Fig. 1. Comparison of three different DER development scenarios on LV

B. DER scenarios on MV grid

On MV level, majority of DER is predicted in large scale PV installations and wind parks. The legislation and subsidy strategy are not supposed to be in favour to greater increase in comparison to current state where most of PV installed in years 2008 to 2011 were subsidised and connected to MV.

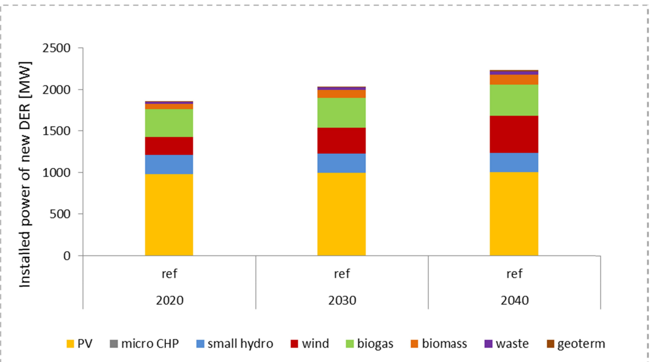

Fig. 2. Predicted referenced scenario for DER development on MV

C. EV and new loads scenarios on LV

NAP CM defines predicted EV sales in future years. Those numbers can't be naturally used directly as an installed power of charging stations but could help to recognize how many EVs will be operated per day.

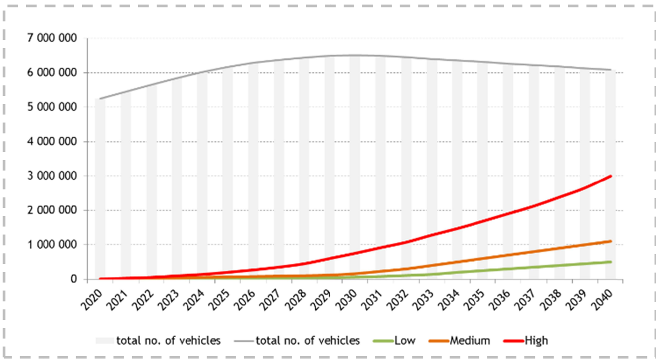

Fig. 3. Predicted EV share on light vehicle market in three scenarios

III. LV and MV Grid Analysis

The basic idea for Scalability and Replicability Analysis (SRA) for European project InterFlex [3], [4] was to simplify whole distribution grid into less complex but still appropriate representative grid models. The analysis has been done for whole CEZ Distribuce areas and so it represents both urban and rural areas with different grid topology.

A. Representative LV grid models

For creation of representative grids and feeders technical and statistical data from the grid database and geographic systems were collected and analysed. To handle the analysis one common identifier were established, which represents code of municipality and beneath there is direct connection to different secondary substations and LV grids.

Data describing municipality part of the grid are the size by number of populations, municipality status, type of connection to superior grid, number of buildings, number and parameters of existing DER, description of connected customers, number and details of secondary substations, LV feeder attributes (length, type, material, cross-section).

Subsequently, for each size of the municipality representative grid models by statistical representation were selected to meet all the above requirements. To reach the largest number of real feeders, up to four variants of representative grids were selected for each municipality size. These variants differ in the feeder length and conductor types of the individual sections. All designed 18 representative LV grid models are also made in variations for the years 2020, 2030 and 2040 – this covers the expected renewal and development of LV grids. In result there are 54 different representative LV models.

B. Representative MV feeders

Unlike LV representative models in MV grid topology the statistical approach to build representative models was not convenient due to high complexity of MV grid. There are many branches from one primary feeder, which is supposed to be designed from the highest capacity on the side of primary substation to the lowest capacity in the connection point of furthest secondary substation of the current topology. However, the topology changes in time and with use of remotely controlled line switches and reclosers and with connecting of more and more DERs there is limited probability to find similarities just with statistical analysis.

Hence the grid dispatchers and employees of operation preparation were asked to identify most relevant real grids that fulfil conditions defined by the research team. There are etc. 4000 different MV feeders in the grid, maximum of 20 representative feeders is requested with different parameters (length, material, type of the feeder, number and attributes of existing installed DER). Those feeders have particular real topology extracted from Distribution Management System (DMS) and Supervisory Control And Data Acquisition (SCADA), its real load, generation from DER and real connection in HV/MV substation. Every real MV feeder was for the SRA replaced by one of representative MV feeder. Every representative MV feeder was connected to real HV substation (230 in the year 2018). Existing DERs are connected into representative feeders in the model. New DERs according to different development scenarios were divided in similar principle as in low voltage, with district granularity (which could be simply joined to HV substations). There are both 22 kV and 35 kV feeders (35 kV feeders are typically longer and used in mountain areas). At the end of the research set of 15 representative feeders were established (see example in fig. 5). The biggest challenge was to create a link between existing and planned HV/MV primary substations to representative feeders and districts. This was done partially by semi-automated assignment and partially manually by strategic grid development department.

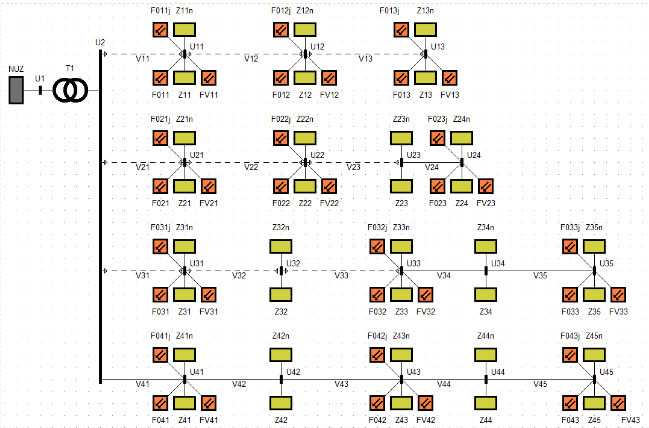

Fig. 4. Representative LV grid model designed in load flow calculation SW

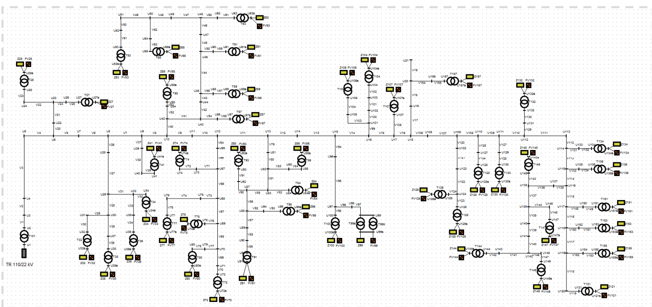

Fig. 5. Representative MV grid model designed in load flow calculation SW

Development of MV grids for SRA purposes consists of three main parts. There are almost 50 new HV/MV primary substations which are planned to be built also added into analysis in years 2020, 2030, 2040. Every representative feeder was prepared in variation of future development, so another set of 2020, 2030 and 2040 year models was done. DSO programme for yearly MV cable development is considered. Currently approximately 21% of MV lines are cables, in 2040 it will be approx. 31%.

IV. Scalability and Replicability Methodology for Generators

The methodology for connection study described in [8] stipulates that the worst condition is about to be tested. Situation when DER is producing maximum power but in the same time there is no electricity consumption in the grid. This is only theoretical situation. In real operation before connecting any generator there is always at least nonnegative consumption. In SRA methodology this was taken into consideration. First year consumption and generation on LV was analysed and several significant season periods were found. Winter season (high consumption, high CHP generation, very low PV generation), summer season (low consumption, no CHP production, maximum PV generation), and mid-term season (average – rather low consumption, considerable CHP production, very high PV generation).

Due to rather little differences between summer and mid-term PV production (PV efficiency decrease with summer outdoor temperatures), the mid-term season was chosen, specifically 3rd Sunday in May 2017 2PM.

A. Distribution of predicted DER power into representative LV models

DER development scenarios are set for the whole Czech Republic, or for each DSO. In previous chapters about representative LV voltage feeders, the municipality unit was introduced. For division of overall scenario figures similar work needed to be done with the difference, that the administrative unit is district. In CEZ Distribuce there are 54 districts. There are criteria how those districts differ from each other, which radically refines the give out of connected DER installed power. Namely number of households, solar irradiation, gas connection availability, purchasing power of the population or existing power plants location.

In the load flow computation software all DER are simulated as PV generator, but with different parameters. There are 5 types of DER elements in representative LV models, namely 3-phase PV generator without voltage regulation (only in 2020), 3-phase PV generator with reactive power regulation, single-phase PV generator (phase A) without reactive power regulation (only in 2020), single-phase PV generator (phase A) with reactive power regulation and single-phase PV generator without reactive power regulation, but connected to the same phase (phase B) as household load, and with solution preventing feed-in the grid. In the legislation it is called “simplified connection”. For InterFlex use case 4, smart energy storage solution which reduces power feed-in caused by PV systems is considered.

All DER elements are parametrized in accordance with rules defined after discussion between specialists who have vast experiences and know-how with LV grid and DER operation, division from districts (54) to ML/LV substation (18 representative grids) is according to installed power of MV/LV transformers in the station, distribution of installed DER power to outlets by total feeder impedance, distribution of installed DER power along feeder in ratio – 10% at the beginning of the feeder, 60% in the middle, 30% at the end, asymmetrical division of DER power was used - 75% single-phase and 25% three-phase, simultaneous factor of DER and loads (based on simultaneity in simulated time season). Based on the results of MV/LV transformer load analysis, the load of 10% Sn (it is relatively low average value appropriate to the methodology) and a current unbalance of 50% was selected for load modelling in LV networks.

B. Distribution of predicted DER power into representative MV feeders

Topology and number of elements in MV grids is more complex, so predicted energy sources are divided based on different rules. Total number of DER power on LV is distributed into districts, then HV/MV substations, representative feeders and into secondary substations by their installed power. In model LV DERs are one 3-phase element per one secondary substation with cos fi equal to 0.99 (inductive mode) with respect to Q (V) and P (V) functions already in operation. Models respect existing DERs on MV installed power per MV feeder (from grid database). In Business as usual (BAU) scenario power factor equals to 1, in SG scenarios in 2020 is 0.99, in 2030 is 0.97 and in 2040 is 0.95 (all inductive modes) – this represents increased share of DER with volt-var control system (reactive power could reduce voltage fluctuation caused by DER generation). Distribution of new DERs installed power on MV is like existing ones, with exception of new DER 5 to 10 MW. Half of them are supposed to be connected directly into HV/MV primary substation. New storage on MV is considered as new generator with the same attributes as new DER (storage is expected to be operated based on owner needs and this will probably not correspond with DSO needs).

C. Evaluation of hosting capacity for generators

The calculation of DER hosting capacity of every representative LV model or MV feeder was done by valid methodology mandatory for all new connections described in Distribution Grid Code [8]. Requesting connection of new generator brings duty to fulfil several conditions. DER must pass connection study for quality of electricity according to EN 50160. For purposes of SRA & CBA methodology only technical parameters influencing directly grid condition were considered.

In LV models, voltage in every node in the modelled grid after simulated connection with maximum current injection should not exceed limit of 110% Un (253 V in each phase). Voltage unbalance in every node should not exceed 2%. Difference between voltage before and after connection should not exceed 3% in every node of the tested grid. Lines, conductors and cables should not exceed 70% of their nominal current ampacity. MV/LV transformers should not exceed 70% of their nominal current load.

In MV models, voltage in every node in the modelled grid after simulated connection with maximum current injection should not exceed limit of 110% Un (24.2 kV or 38.5 kV). Difference between voltage before and after connection should not exceed 2% in every node of the tested grid. Overhead lines should not exceed 70% of their maximum current ampacity. Underground cables should not exceed 50% of their maximum current ampacity. HV/MV transformers should not exceed 70% of their nominal current load (if at least two transformers in primary substation are in operation). HV/MV transformers should not exceed 50% of their nominal current load (if at least two transformers in substation are in operation).

Usual connection request only concerns one specific DER. In this methodology all the DERs are tested simultaneously and all of them must succeed and pass the computation. If at least one Point of Common Coupling (PCC) exceeds the limits, the hosting capacity of the grid is reached, and subsequent modification needs to be done. Modifications are subject of the chapter "CBA and economic impact" where also costs of those modifications are calculated and different BAU and Smart Grid (SG) scenarios are compared.

V. Scalability and Replicability Methodology for Electric Vehicles

Unlike simulation of DER connection, the EV integration brings biggest issues in times of peak consumption. In this scenario, a few thousand of randomly selected secondary substation annual measurements were analysed and on 5th January 2016 at 6PM the average highest peak in LV was identified as 36.5% of secondary substation installed power. In next decades the load without EVs is expected to increase, in 2020 it is 38% in 2030 is 40.9% in 2040 is 43.3% (due to the increase of non EV loads).

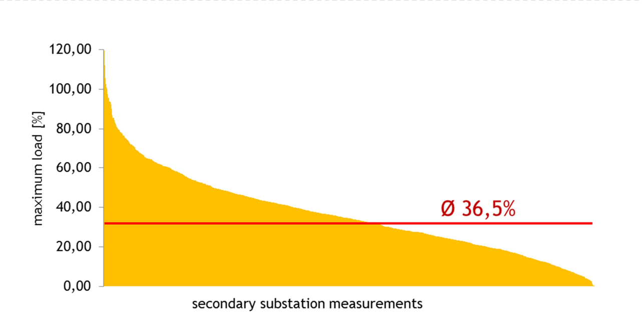

Fig. 6. MV/LV transformer average load assessment

In MV level grid maximum winter consumption was found on 17th January 2017 (the MV analysis was done year after LV analysis). From all measured HV/MV primary substations 6PM as a load peak hour was identified. The percentage load of HV/MV installed power was 18.3% in 2017, so it is foreseen 18.9% in 2020, 20.32% in 2030 and 21.51% in 2040.

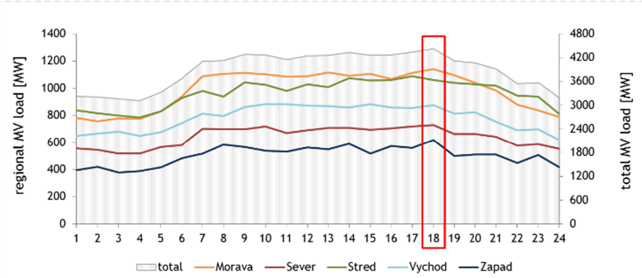

Fig. 7. MV grid loading during the year maximum day

A. Distribution of predicted EVs into representative LV feeders

New loads development scenarios are set for the whole Czech Republic, for each DSO and districts. Criteria how those districts differ from each other, are different from DER example and refines the give out of connected loads connected power. Number of houses represents the theoretical potential EV purchase. Based on the Statistical Office data, the number of family and apartment houses was defined for each district. Gas connection availability helps to have more accurate presumptions about future micro CHP units distribution. The higher purchasing power of the district the higher probability to purchase a new DER.

There are 4 types of new load elements in representative LV models. EV with single-phase internal charger (connected to phase A), EV with 3-phase internal charger, 3-phase heat pump (electric heating mode) and 3-phase electric heating.

B. Distribution of predicted EVs into representative MV feeders

Topology and number of elements in MV grids is more complex, so predicted new loads are divided. Total load on LV is distributed into districts, then HV/MV primary substations, representative feeders and into secondary substations by their installed power. In model LV loads are one 3-phase element per one secondary substation with power factor equal to 0.95 in 2020, 0.96 in 2030 and 0.97 in 2040 (inductive mode). New storage on MV is considered as new load. (Storage is expected to be operated based on owner needs and this will probably not correspond with DSO needs).

C. Evaluation of EV impact on distribution grid

The calculation of connection of new loads into representative LV model or MV feeder was done by valid methodology mandatory for all new connections described in Distribution Grid Code [8]. Requesting connection of new load brings duty to fulfil a number of conditions such as quality of electricity according to EN 50160. For purposes of SRA & CBA methodology only technical parameters influencing directly grid condition were considered.

In LV models, voltage in every node in the modelled grid after simulated connection new load is not less than 90% Un (207 V in each phase). Voltage unbalance in every node is not to exceed 2%. Lines, conductors and cables should not exceed 80% of their nominal current ampacity. MV/LV transformers should not exceed 80% of their nominal current load.

In MV models, voltage in every node in the modelled grid after simulated connection with maximum current injection should not be lower than limit of 97% Un (21.34 kV or 33.95 kV), overhead lines should not exceed 70% of their maximum current ampacity, underground cables should not exceed 50% of their maximum current ampacity, HV/MV transformers should not exceed 70% of their nominal current load (if at least two transformers in substation are in operation) and HV/MV transformers should not exceed 50% of their nominal current load (if at least two transformers in substation are in operation).

If at least one node or line exceeds the limits, the hosting capacity for new loads of the grid is reached and subsequent modification needs to be done. Modifications are subject of the chapter "CBA and economic impact" where also costs of those modifications are calculated and different BAU and SG scenarios are compared.

VI. Cost Benefit Analysis and Economic Impact

Cost-benefit analysis (CBA) in this document is based on technical and economical comparison of different business-as-usual (BAU) and Smart Grid (SG) solutions. Within InterFlex project only a few location, installations and customers are affected, but with scalability and replicability defined in previous chapters applied, those SG solutions could save inconsiderable costs for distribution capacity investments. CBA compare costs for distribution capacity investments for business-as-usual (BAU) and Smart Grid (SG) solutions. As the costs and benefits are business sensitive information, CBA results included in this document contain comparison in costs and benefits only in relative values.

A. Boundary conditions and parameters

This chapter refers to Joint Research Centre (JRC) "Guidelines for conducting a cost-benefit analysis of Smart Grid projects" methodology [9] and follows document's structure. As for economic parameters, discount and inflation rate of 1.5% per year for Capital Expenditures (CAPEX) investment is set. Reference time perspective is for years 2020, 2030 and 2040. The reason for such long separation is the input data itself. Future scenarios from authorities, ministries and research organizations are looking to 2030, some to 2040 and only few to 2050. Implemented SG technologies covered by Work Package 6 in InterFlex project are described in detail in [5], [6] and [7]. Baseline scenarios contain grid development without SG solutions. Key assets and benefits are:

- UC1 – smart PV inverter with Q (V) and P (V) functions, increased DER hosting capacity in LV grids
- UC2 – volt-var control algorithm implemented in local DER control system, increased DER hosting capacity in MV grids
- UC3 - smart EV charging station, reduction of peak loads in distribution grids
- UC4 – smart PV inverter with residential battery, increased DER hosting capacity in LV grids

B. CBA Scenarios technical comparizon

SRA analysis quantified how much and which type of distribution capacity investments will be needed for selected time periods (up to year 2020, 2030 and 2040) for baseline as well as for SG scenarios. SRA results shows great potential of SG solutions for increasing DER and EV charging stations hosting capacity which results in reduced distribution capacity investments needs for SG scenario.

In figure 8 there is comparison of numbers and lengths of assets needed to be strengthened because of insufficient hosting capacity for connecting DERs (UC1, UC2, UC4) or EVs (UC3). For example, SG solution in case of UC1 in year 2040 needs 16 521 kilometres of LV lines to be refurbished, but without SG solution (BAU scenario) it is 20 110 kilometres. Expenditures for almost 4 thousand kilometres could be saved.

Solution	scenario	2020	2030	2040
UC1 LV [km]	BAU	0	0	20 110
	SG	0	0	16 521
UC2 MV [km]	BAU	1 261	5 37	1 507
	SG	898	155	463
UC3 EV [pcs transformer]	BAU	0	0	8 943
	SG	0	0	4 938
UC4 LV storage [km]	BAU	0	0	16 049
	SG	0	0	9 444

Fig. 8. BAU and SG scenario comparison in length and pcs of assets

Example of impact of increase share of DER and EVs in CEZ Distribuce areas in the Czech Republic for selected scenarios for year 2040 is shown in figures 9 and 10 (insufficient hosting capacity in districts is coloured in red).

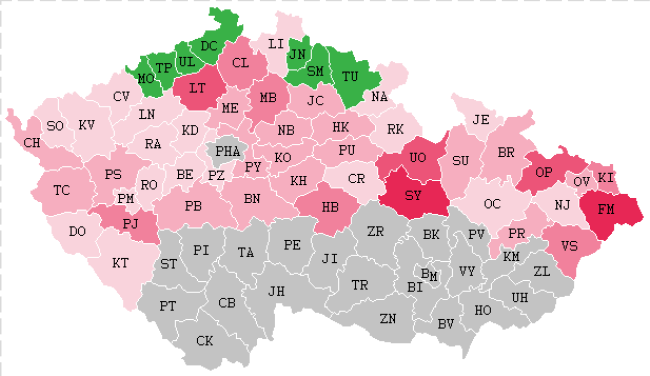

Fig. 9. Areas without sufficient MV hosting capacity without SG

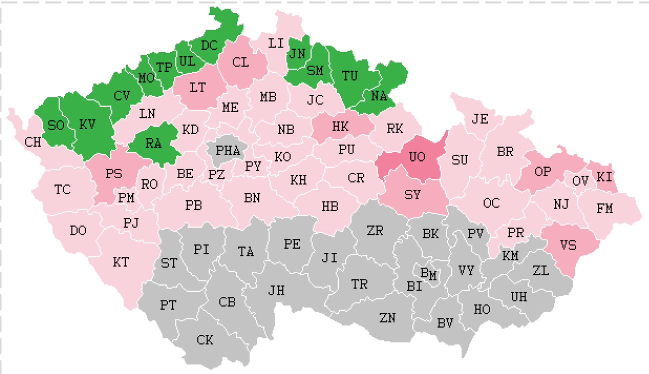

Fig. 10. Areas without sufficient MV hosting capacity with SG solutions

C. *CBA Scenarios monetized comparizon*

Costs on CEZ Distribuce side are in Operational Expenditures (OPEX) category only and are marginal compared with CAPEX benefits. Minor OPEX costs for all use cases are caused by changes in existing internal DER and EV charging stations commissioning process or parameterization of existing communication paths between DER and EV charging stations. Due to this fact, OPEX costs are considered as 0 for this CBA purpose. There are no CAPEX costs on CEZ Distribuce side for implementation of SG solutions compared with business as usual or baseline (for all use cases). For some periods in selected use cases, no additional distribution capacity investments are generated due to the fact that predicted new installed capacity for DER and number of EVs in NAP SG scenarios are not so high to deplete hosting capacity.

It's important to mention that for new DER and EV charging stations, solution tested within InterFlex, which are subject of SRA and CBA, could be easily integrated for costs less than 1% of original investment costs of DER or EV charging station installations. As the costs and benefits are business sensitive information, CBA results included in this document contain comparison in costs and benefits only in relative values.

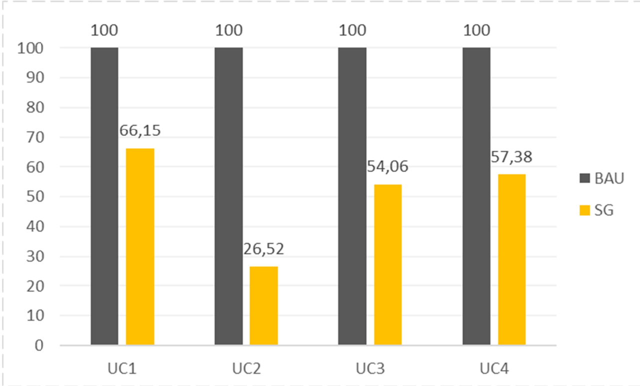

Fig. 11. BAU and SG grid investment costs comparison in year 2040

VII. Conlusions

This CBA analyse costs and benefits for SG solutions in case of large scale implementation in the Czech Republic. Based on positive CBA analysis CEZ Distribuce decided to use or promote these solutions to mitigate risks which are related to the expected future increased share of DER and EV charging stations in distribution grids. CBA analysis proved that in case of large scale implementation, SG solution is cost effective approach for DER and EV charging stations implementation, however some grid capacity investments will be still needed in the future. CBA is based on existing knowledge of legal, regulatory and technical boundary conditions and on inputs which are taken from the Czech government's initiative NAP SG.

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