Technical and Economic Investigation of Alternative Power Supply Scheme of Radial Medium Voltage Distribution Grid

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Abstract— **The electricity supply system of Stadtwerk Winterthur is undergoing modernisation and improvement, including the voltage increase of the medium voltage network (NE5) from 11 kV to 22 kV to enhance transfer capacity. However, this increase requires reinforcement of the existing cable lines in the Bruderhaus area, which are designed for 6 kV. Grid reinforcements are costly and alternative solutions must be considered to resolve or delay the problem. This paper aim is to show investigated and evaluated alternative solutions to ensure a continuous and reliable power supply for the Bruderhaus area in Winterthur. The results showed the technical and economic feasibility of various alternatives and propose suitable solutions for radial medium voltage grid.**

Keywords— AC/DC Hybrid Grids, Battery Energy storage system, Distribution Grid, Hydrogen, Microgrid, Power System Planning

I. INTRODUCTION

The Bruderhaus Wildlife Park, one of the oldest wildlife parks in Switzerland, needs a modernisation of its power supply. The park, which has been in existence since 1890, is located in the middle of the Eschenberg Forest, a recreational area immediately adjacent to the city of Winterthur. The management of the park and the surrounding infrastructure is the responsibility of Stadtgrün Winterthur. The Stadtwerke Winterthur (Winterthur public utility company), which supported this work, is responsible for the network development and energy supply.

Currently, the power supply is ensured by a 50-year-old, underground 11 kV medium-voltage line, which was laid from Eschenberg, under forest roads, to the Bruderhaus. Apart from the advanced age of the line, the dielectric strength for which it was originally designed is increasingly problematic. The existing cable is designed for 6 kV and is currently operated at 11 kV. The 11 kV has already led to problems several times, which have resulted in intermittent power cuts. In addition, Stadtwerke Winterthur (SW) is planning to double the voltage of the medium voltage network to 22 kV in the upcoming years. After this upgrade is implemented, the renewal of the line or another solution will be unavoidable.

The aim of this work is to investigate different technical options to ensure a secure and sustainable electricity supply in the future. The study includes technical clarifications on the feasibility of the different approaches as well as their economic consequences. For this purpose, SW provided energy consumption data, future scenarios, the relevant section of the network and will be partly shown within the work.

The novelty of the work lies in the analysis of non-standard energy supply solutions due to the development of new technological solutions such as <1500 volt direct current distribution grids [1]; use of lower AC voltage levels than the 1 kV case; AC/DC hybrid grids and combinations with Battery Energy Storage Systems (BESS). This leads to a variety of possible technical solutions to power supply problems and facilitates the integration of new, more cost-effective solutions into distribution networks. The purpose of this paper is to investigate alternative power supply solutions to traditional grid reinforcement solutions. In particular, it considers the implementation of a lower voltage network, reducing the existing 11 kV to 1 kV in AC and 0.7 kV in DC implementations. In addition, the paper discusses the case of off-grid power supply and the use of hydrogen-based storage technology instead of electrochemical BESS and its economic viability.

The main sections are explained below: Section 1 defines the aims and structure of the paper. The initial situation is intended to set the scene and introduce the reader to the topic. Section 2 presents the approach used, the scenarios considered and their operating and investment costs. Section 3 explains the photovoltaic (PV) system scenarios considered. Section 4 and 5 shows 1kV AC and 0.7 kV DC grid realisations in PowerFactory. Section 6 presents the BESS implementation in simulation environment and its operating principles. Section 7 summarises the results with discussions and outlook.

II. APPROACH AND METHODOLOGY

The following section describes the overall concept considered, as well as the operating and investment costs for each scenario.

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A. *Definition of scenarios*

Different power supply schemes are considered withing this work and are visually displayed in Fig. 1.

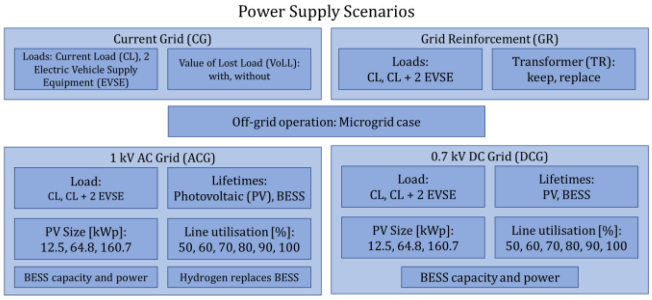

Fig. 1. Alternative power supply schemes

For each scenario in the 1 kV AC and 0.7 kV DC grids, the BESS size for energy and power must be determined. Some scenarios only have an impact on the power flows, others only on the Net present value (NPV) results. These scenarios will be considered sub-scenarios within the scenario. In detail, scenario description is given in Section B 1-8.

B. *Investment calculation and considered inputs*

A suitable instrument is necessary to calculate the economic benefit of an investment. Two main methods are distinguished for investment calculations [2]: the static and the dynamic method. In the dynamic method, the temporal structure of the investment, income and expenditure throughout the entire investment period is converted to a specific point in time through compounding or discounting, allowing for a direct comparison. The most well-known dynamic methods include the NPV method, the Internal Rate of Return (IRR) method and the Annuity method. When investments span multiple years, a dynamic method promises a more accurate assessment [3]. The formula for an NPV calculation is as follows:

$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+i_d)^t}, CHF \quad (1)$$

where:

- T is the economic life cycle period
- t is the current cycle year
- C_t is the expense of the t^{th} year
- i_d is the discount rate.

The main challenges for the NPV calculations lie in estimating future expenses and determining the discount rate, as these inputs significantly impact the NPV results. In comparison to the NPV, the IRR calculation determines the interest rate required to break even on the investment, while the NPV calculation provides an absolute value of the money gained or lost during the analysed period. Investments where the IRR > i_d can be described as profitable.

To enhance the NPV results, the costs incurred of SW will be considered, providing a more precise evaluation of the economic aspect of each scenario. In order to calculate the NPV, costs and parameters such as the discount rate and life cycle period must be provided. These parameters remain constant in all the NPV calculations and are as follows:

TABLE I. NPV ECONOMIC PARAMETERS [4]

Name	Value	Unit
Discount rate (i_d)	3.83	%
Economic life cycle period	25	years

Since the NPV analysis for each scenario contains multiple parameters, the parameters will be defined separately for each scenario. By providing distinct parameters for each scenario, the differences in operation and investment costs required to sustain the power supply can be evaluated. Most parameters are presented as a range, as all NPV calculations are done for three pricing scenarios:

- Low-cost scenario
- Average cost scenario
- High-cost scenario

The range specified for the parameters represents the limits of the low- and high-cost scenarios. The average cost scenario will be calculated using a default value within the given parameter range.

To ensure the accuracy of the NPV calculations, it is necessary to take the lifespan of each component into account since the lifetime of different equipment varies greatly. Considering equipment lifetimes will enable more precise NPV calculations and provide a more accurate estimation of the necessary investments over the specified period.

TABLE II. LIFETIME OF INVESTMENTS [5][6]

Name	Value	Unit
Grid Reinforcements	35 - 40	years
Photovoltaic panels	20 - 30	years
Battery energy storage system	8 - 12	years
Inverter	15 - 25	years

To account for the differences in the remaining lifetime of each component after the 25-year NPV life cycle, the investments will be reduced by a factor based on the remaining lifetime. For example, if a PV system is replaced after 20 years, there will be 15 years left on the second investment after 25 years, which is taken into account in the NPV calculations. Therefore, the second PV investment cost will be reduced by ¾.

1) *PV system investment and operational costs*

TABLE III. presents the investment and operational costs for a PV system of different sizes and the predicted price changes over the next 30 years. The price range represents the fluctuation of prices across Switzerland, the EU and the US.

TABLE III. PV SYSTEM COST SCENARIOS FOR 2020 – 2050 [9]

Year	kWp	2020	2030	2040	2050
Investment costs (CHF / kWp)	0 – 6	2'351 - 2'786	1'799 - 2'322	1'480 - 2'060	1'422 - 1'857
	6 – 10	2'241 - 2'546	1'715 - 2'241	1'300 - 1'854	996 - 1'411
	10 – 30	1'790 - 2'066	1'354 - 1'813	1'056 - 1'561	996 - 1'308
	30 – 100	1'178 - 1'382	864 - 1'036	691 - 1'083	644 - 989
	>100	754 - 885	553 - 784	442 - 694	412 - 633
Operational costs (Rp. / kWh)	0 – 6	2.60	2.10 - 2.20	1.80 - 1.90	1.60 - 1.70
	6 – 10	2.60	2.10 - 2.20	1.80 - 1.90	1.60 - 1.70
	10 – 30	2.60	2.10 - 2.20	1.80 - 1.90	1.60 - 1.70
	30 – 100	2.60	2.10 - 2.20	1.80 - 1.90	1.60 - 1.70
	>100	1.70	1.40 - 1.50	1.20 - 1.30	1.10 - 1.20

2) *Battery energy storage system*

Similarly, TABLE IV. presents the investment and operational costs for a BESS of different sizes and power categories, along with the predicted price changes over 30 years. The price range reflects the variations in prices across Switzerland, the EU and the US.

TABLE IV. BESS COST SCENARIOS FOR 2020 – 2050[9][10][11]

Year	2020	2030	2040	2050
Investment costs (CHF / kWh)	295 - 459	69 - 247	41 – 178	34 - 158
Investment costs (CHF / kW)	249 – 388	58 – 209	35 – 151	29 – 133
Operational costs (CHF / MWh)	1.10 - 1.72	0.26 - 0.92	0.15 - 0.67	0.13 - 0.59
Operational costs (CHF / kWp)	3.68 - 5.73	0.85 - 3.08	0.51 - 2.22	0.43 - 1.97

3) *Current Grid operation costs*

Considering the NPV for the current grid, SW's expenses consist of annual operating costs. The operating costs are determined as a percentage of the investment costs, which were assumed to match the investment costs of the grid reinforcement. Additionally, since most of the current grid is older than 50 years, the operation costs were increased by 10% to account for the increased costs associated with older supply lines.

Although SW does not pay a non-delivery fee to customers, this cost will be analysed to provide a rough estimate of the value of lost load (VoLL) resulting from power outages at Bruderhaus. As SW cannot provide exact statistics on the amount and duration of outages during a year, one yearly outage of 2.5 hours was assumed. The low and high values for the average energy consumption for the VoLL calculation were calculated as the average energy consumption during the day for the high value and the night for the low.

TABLE V. CURRENT GRID PARAMETERS [5][7][8]

Name	Value	Unit	Details
Operation: Transformer	577.50 - 742.50	CHF/year	1.5% of the transformer + 10%
Operation: Cable system	266.65 - 495.21	CHF/year	0.2% of the cable line + 10%
Operation: Tunnel	342.84 - 647.58	CHF/year	0.2% of the tunnel + 10%
Operation: VoLL	10.00 - 14.00	CHF/kWh	Value of lost load
Average energy	11.00 - 28.00	kWh	Average energy consumed

4) *Grid Reinforcement investments and operation costs*

To investigate the NPV for the reinforced grid, the expenses include annual operating costs and investment costs for the grid reinforcement. The annual operating costs were calculated as a percentage of the initial investment costs for the grid reinforcement. As the lifespan of all reinforced devices exceeds the considered lifetime of 25 years, the lifespan is only considered to calculate the investment reduction for this scenario. Additionally, as there is no necessity to replace the transformer as it is operated within the specifications, the NPV calculation will be divided into two parts: one with the investment for a new transformer and one without the transformer.

TABLE VI. REINFORCED GRID PARAMETERS [5]

Name	Value	Unit	Details
Operation: Transformer	525.00 - 675.00	CHF/year	1.5% of the transformer
Operation: Cable system	242.41 - 450.19	CHF/year	0.2% of the cable systen
Operation: Tunnel	311.67 - 588.71	CHF/year	0.2% of the tunnel
Investment: Transformer	35'000.00 - 45'000.00	CHF/piece	
Investment: Cable system	70.00 - 130.00	CHF/m	Including installation
Investment: Tunnel	90.00 - 170.00	CHF/m	Tunnel in forest
Investment: Management	25.00 - 50.00	CHF/m	Planning of reinforcemen
Investment: Dismantling	35.00 - 65.00	CHF/m	Dismantling old cable lin
Investment: Reactive comp.	10.00 - 20.00	CHF/m	Reactive compensation

5) *1 kV AC Grid*

Considering the NPV investigation of the 1 kV AC grid, the expenses consist of annual operating costs and investments in a PV system, a BESS and two transformers. The investment and operational costs can vary considerably depending on the size of the PVs and BESS. To ensure an accurate NPV, the reduction of investment costs for PV systems and BESS are considered based on TABLE III. and TABLE IV. , while the reduction in operational costs is not considered as its influence is marginal.

The NPV calculations for the 1 kV AC grid will analyse the NPV with line loads varying from 50 to 100%, considering only the average prices and lifetimes of each piece of equipment, to provide an overview of the changes in the NPV with different line loads.

TABLE VII. 1 KV AC GRID PARAMETERS [5]

Name	Value	Unit	Details
Operation: Transformer	525.00 - 675.00	CHF/year	1.5% of the transformer
Operation: Cable system	242.41 - 450.19	CHF/year	0.2% of the cable systen
Operation: Tunnel	311.67 - 588.71	CHF/year	0.2% of the tunnel
Operation: Photovoltaic	26.00	CHF/MWh	
Operation: Battery energy	1.10 - 1.72	CHF/MWh	
Operation: Battery power	3.68 - 5.73	CHF/kW	
Investment: Transformer	35'000.00 - 45'000.00	CHF	
Investment: Photovoltaic	1'178 - 2'786	CHF/kWp	
Investment: Battery energy	295.00 - 459.00	CHF/kWh	
Investment: Battery power	249.00 - 388.00	CHF/kW	

6) *0.7 kV DC Grid*

To investigate the NPV for the 0.7 kV DC grid, the expenses consist of annual operating costs and investments in a PV system, a BESS and two inverters. Similar to the AC grid, the investment and operational costs can vary considerably depending on the size of the PV system and BESS. To ensure an accurate NPV result, the reduction of investment costs for PV systems and BESS is considered based on TABLE III. and TABLE IV. , while the reduction in operational costs is not considered as its influence is marginal.

TABLE VIII. 0.7 KV DC GRID PARAMETERS [1][5][9][12]

Name	Value	Unit	Details
Operation: Inverter	60.00 - 120.00	CHF/year	1% of the inverter
Operation: Cable system	242.41 - 450.19	CHF/year	0.2% of the cable systen
Operation: Tunnel	311.67 - 588.71	CHF/year	0.2% of the tunnel
Operation: Photovoltaic	26.00	CHF/MWh	
Operation: Battery energy	1.10 - 1.72	CHF/MWh	
Operation: Battery power	3.68 - 5.73	CHF/kW	
Investment: Inverter	100.00 - 200.00	CHF/kW	
Investment: Photovoltaic	1'178 - 2'786	CHF/kWp	
Investment: Battery energy	295.00 - 459.00	CHF/kWh	
Investment: Battery power	249.00 - 388.00	CHF/kW	

7) *Off-grid scenario*

In this scenario, off-grid operation of the entire Bruderhaus area with sustainable energy are considered. Therefore, a PVs including a BESS must be considered. Due to the typical production of PVs, the BESS will have to store excess energy provided in summer to sustain the energy consumption that is required in winter. Secondly, the line capacities will prove a decisive factor for the feasibility of this solution. Therefore, this scenario is divided into two main sub-scenarios. Firstly, considering purely the total amount of PV generated energy that can be installed (245.5 kWp) without taking the line capacities into consideration, to examine the potential of the PV. Second considering the line capacities to sustain 176.6 kWp potential.

8) *Hydrogen scenario*

Hydrogen storage, compared to a BESS, has high investment and operational costs. Therefore, the NPV will only be calculated for the 1 kV AC grid with a line load of 80% with and without the two EVSE units. The hydrogen fuel cell will only be used as a discharging unit and will not be used to create hydrogen, as the efficiency for this process is very low and would only make sense as a long-term storage of energy. The scenario will give a rough estimation of whether hydrogen can provide an economically viable alternative to the BESS.

TABLE IX. HYDROGEN AVERAGE PARAMETERS [13]

Name	Value	Unit	Details
Operation: 600 l H_2	4'500	CHF	Refill 12 bottles
Operation: Energy	216	kWh	Energy per 600 l Hydrogen
Investment: H_2 Fuel Cell	27'500	CHF	1 Fuel Cell with 2.5 kW
Investment: H_2 Bottle	25'000	CHF	12 Bottles

C. *Power flow and NPV calculation approach*

For investigation of different medium voltage grid alternatives, PowerFactory [14] software was used as it allows dynamically simulate the charging and discharging of the BESS using selectable setpoints. PowerFactory, like OpenDSS [15], uses the Newton-Raphson method to execute the power flows. Hence, the various scenarios were performed and the results obtained. Fig. 2 provides a visual representation of the approach to the power flow calculation. PowerFactory, compared to OpenDSS, offers a quasi-dynamic simulation of the system by including a timestamp in the calculations. The resulting data can then be plotted in PowerFactory with the provided timestamps, reducing the effort required to visually display the results using MATLAB.

To visualise the results, certain definitions of where in the model the results will be extracted must be made:

- Obtain voltage deviations from the low-voltage network (NE7) of Bruderhaus
- Extract line power from the second sector of the cable line through A4
- Extract losses from the entire system, including transformers and cable lines.

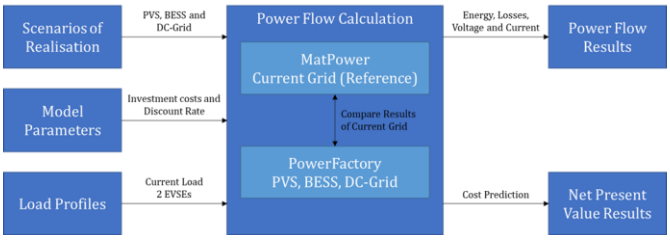

Fig. 2. Power flow and and NPV calcualtion approach

In order to generate accurate results, data from the existing power supply grid was exported from Adaptricity [16], the cloud-based platform SW uses as its grid monitoring tool. The exported data, including all line coverings, lengths and parameters, was integrated into PowerFactory. For those simulations that partly deviate from the existing installation, suitable resources were inserted that fulfil the desired requirements. Fig. 3 and Fig. 4 presents the schematic representation of the current power supply from Eschenberg to Bruderhaus. On the low-voltage side, the load Bruderhaus_Load contains the consumption data of Bruderhaus for the entire year 2022. For this purpose, the smart meter data of the restaurant and the animal park were collected and stored as active and reactive power. The generation unit existing_PV_12.5_kWp represents the already installed PV system.

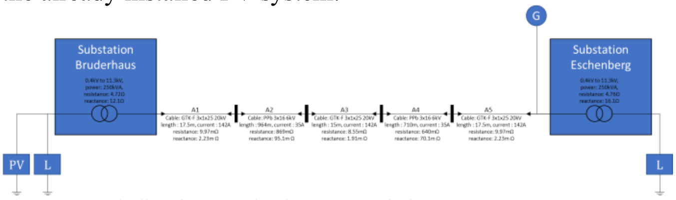

Fig. 3. Supply line from Eschenberg to Bruderhaus

Fig. 4. PowerFactory representation of the current state

III. PV SYSTEM: SCENARIOS AND GENERATION

Since no generation data is available, the generation was simulated using data from Photovoltaic Geographical Information System (PVGIS), developed by the European Commission Joint Research Centre [17] . The PVGIS data is obtained based on the location, azimuth, tilt and size of the PV system provided by the solar cadastre of the city of Winterthur. To minimise the influence of weather variations in a specific year, the radiation data from the PVGIS-SARAH2 database is averaged over a period from 2005 to 2020. The extracted generation profiles already account for an overall system loss of 14%, which includes losses due to cables, inverters and dirt or snow on the PV modules. Additionally, the hourly generation profiles are converted to a 15-minute interval using MATLAB's interpolation function. Therefore, the PVGIS data can be directly used for the power flow calculations without further adjustments for losses in PowerFactory.

Different sizes of PV systems are required for the various scenarios. To assess the PV potential of the Bruderhaus, the PV generation profiles from all available rooftops are taken into consideration. The solar cadastre of Winterthur provides information on the rooftops at Bruderhaus, as shown in Fig. 5. Considering all rooftops, the cumulative PV installation potential at Bruderhaus amounts to 245.5 kWp [18].

Fig. 5. Solar cadastre of Bruderhaus

To ensure that the line capacity of the 400 V grid at Bruderhaus is not exceeded, the maximum capacity of the grid is considered. Consequently, the PV peak power is reduced to 148.55 kWp. The peak value of the PV system is not determined by the solar cadastre's peak value but rather by the maximum value of the PVGIS data, which is always lower due to factors such as tilt, azimuth and system losses that affect the efficiency of the PV systems. Moreover, not all PV systems will generate their maximum power simultaneously. Therefore, the installed capacity will always be slightly lower than the maximum capacity of the cables and the line will not be operated at its capacity limit. Given this limitation, different scenarios can be defined. Currently, Bruderhaus has a 12.5 kWp PV system installed, which is included in the total PV power calculation.

To provide information on which rooftops are used for the PV scenarios defined in TABLE X. and displays the numbering of the PV systems. All other rooftops not displayed in Fig. 6 are not considered in the 1 kV AC and 0.7 kV DC scenarios. The excluded rooftops were only used for the microgrid scenario.

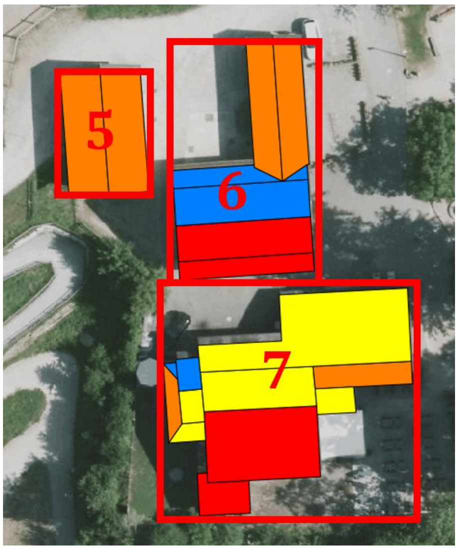

Fig. 6. Rooftops used for PV scenarios

TABLE X. CONSIDERED PV SYSTEM SCENARIOS

	Installed Power	Max. Generated Power	Info
Max.capacity		175.95 kW	230 V * 3 Phase * 255 A
Scenario 1	12.50 kWp	8.62 kW	Currently installed PV system
Scenario 2	160.70 kWp	114.21 kW	all main rooftops (PV5 - PV7)
Scenario 3	64.80 kWp	44.65 kW	Restaurant rooftop (PV7)

IV. 1 KV AC GRID IMPLEMENTATION

The schematic of the 1 kV AC grid as designed in PowerFactory is displayed in Fig. 7. Compared to the current grid shown in Fig. 4, the external power grid was placed at the low voltage level of Eschenberg compared to the medium voltage level to minimise the influence of the load at Eschenberg and thereby be able to consider the voltage deviation happening in the analysed supply line instead of including the voltage deviation induced by the load at Eschenberg.

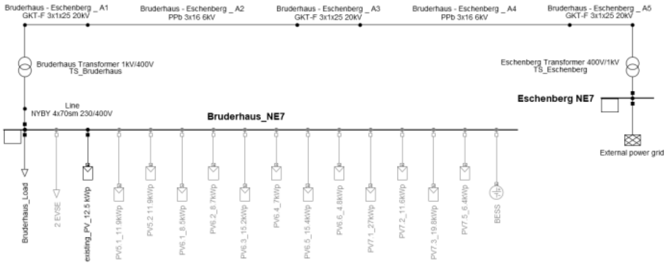

Fig. 7. PowerFactory: 1 kV AC Grid

V. 0.7 KV DC GRID IMPLEMENTATION

Driven by international decarbonisation goals, the DC grid is becoming increasingly interesting, as it addresses challenges faced by AC distribution networks, such as overloading and excessive voltage fluctuation. A DC grid offers several advantages in the networks for operating PV systems, BESS and EVSEs. Typical DC system configurations include unipolar and bipolar voltage polarities, both of which can be implemented in low and medium voltage DC power supplies. Each polarity option has advantages and disadvantages and highlighted in the [1] work. Realization principle of bipolar system and conversion from an AC to a DC grid is shown in Fig. 8 and Fig. 9, where two phases of the AC grid can be used as the positive and negative conductors of the DC grid, while the remaining phase, including the neutral conductor of the AC grid, can be used as the middle conductor of the DC grid.

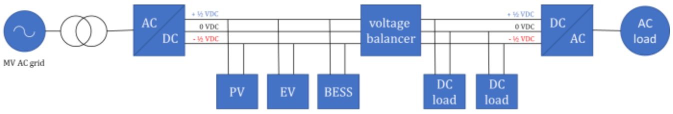

Fig. 8. Example bipolar DC system

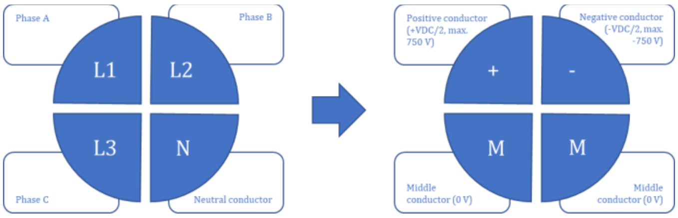

Fig. 9. AC conversion to bipolar DC system

The schematic of the 0.7 kV DC grid as designed in PowerFactory is displayed in Fig. 10. As in the 1 kV AC grid, the external power grid was placed at the low voltage level of Eschenberg compared to the medium voltage level as in the current grid to minimise the influence of the load at Eschenberg and thereby be able to consider the voltage deviation happening in the analysed supply line instead of including the voltage deviation induced by the load at Eschenberg. The power of the inverter is defined as 60 kW, slightly larger than 20% more than the maximum line capacity of 49 kW.

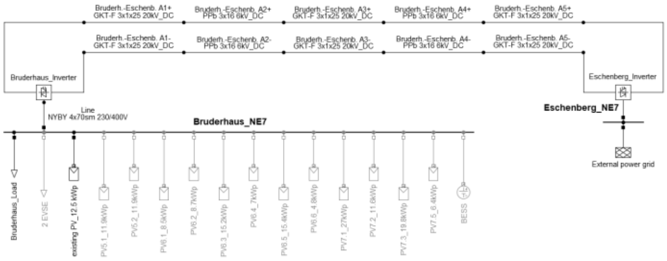

Fig. 10. PowerFactory: 0.7 kV DC Grid

VI. BESS IMPLEMENTATION

The voltage of the power supply is significantly reduced in the 1 kV AC and the 0.7 kV DC scenario. Therefore, the maximum transmittable power of the supply is also greatly reduced and an additional energy storage system is required, which provides the necessary power and energy for power peaks that exceed the capacities of the supply line. In the following subsections, the implementation and functionality of the developed BESS model will be considered in detail.

Fig. 11 shows the PowerFactory schematics of the 1 kV AC scenario, including the power measurement for the BESS simulations. The low-voltage line, shown as *Line* in Fig. 11, represents the line section that leads from the secondary side of the transformer in the TS Bruderhaus to the connection box of the Bruderhaus area. The measured power, shown as *PLine* in Fig. 11 of this cable serves as an input signal for the dynamic model and thus as a control variable. Depending on the measured power and the parameterisation of the model, the BESS is charged, discharged or paused. The power that is absorbed or delivered by the BESS flows through the "Bruderhaus_NE7" busbar. This structure ensures that the power absorbed by the BESS is recorded and taken into account by the power measurement. If the storage unit delivers power, this can be drawn directly from the existing consumers locally via the busbar.

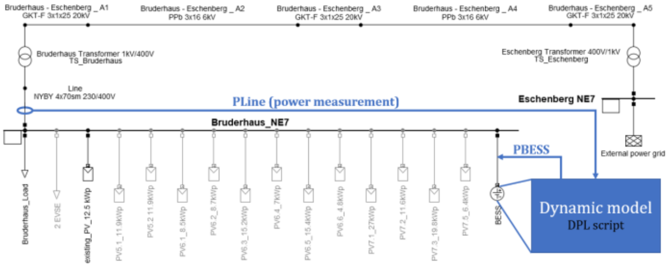

Fig. 11. PowerFactory scheme with power measurement for BESS

PowerFactory uses a programming language called DIgSILENT Programming Language (DPL). Using the DPL programming language, a dynamic model was programmed that meets the accuracy requirements for the simulations of the predefined scenarios. The model monitors the power of the charging and discharging process and the compliance of the energy content of the storage. TABLE XI. shows all input parameters that can be selected before each simulation. In addition to the parameters that define the power and capacity of the BESS, setpoints can be defined that allow the supply line to be limited to a specified power.

TABLE XI. BESS POWERFACTORY PARAMETER

Parameter	Ex. Value	Unit	Details
Eini	0.2	MWh	Maximum energy content BESS
SOCini	50	%	The initial state of charge
SOCmin	10	%	Minimum state of charge
SOCmax	90	%	Maximum state of charge
PBESSDischarge	0.02	MW	Rated discharging power
PBESSCharge	0.02	MW	Rated charging power
PStopCharge	0.02	MW	Pmeas from which is charging stopped
PStartCharge	-1	MW	Pmeas from which is charging started
PStartDischarge	0.02	MW	Pmeas from which is discharging started
Orientation	1	-	Measurement (if negative = -1)

The dynamic model consists of two sub-areas. Power control contains those functions that ensure the desired behaviour in power consumption and output. Another part ensures that the capacity limits are maintained, considering internal losses and that the required values such as total losses and total energy flow are recorded. Both parts are interdependent.

Fig. 12 shows the operating principle of the model's power control. The measured power is fed into the model via the variable *PLine*. The amount of the measured power is deducted (discharge) or added (charge) to prevent an oscillation-like control. The variable *Pmeas* contains the entire power requirements of the Bruderhaus area. Taking the pre-parameterised setpoints, BESS capacity and power limits into account, the required charging or discharging power is then determined according to the logic sequence shown in figure.

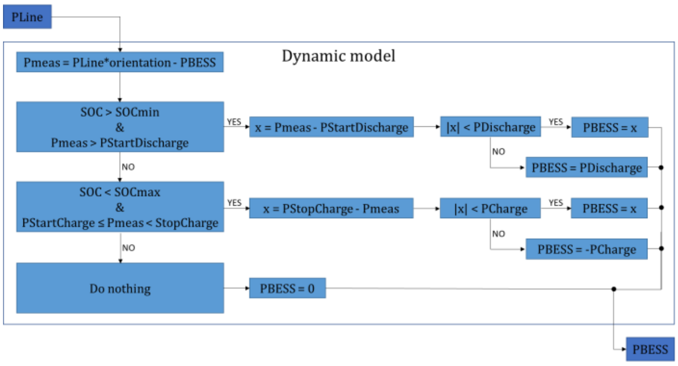

Fig. 12. Operating principle of the BESS power control

A. Example simulation with Bruderhaus-load

Fig. 13 shows a section of the 1 kV simulation including the existing 12.5 kW PV system and the two electric charging stations on 16 July 2022. The colored curves represent the loads and the PV generation power, and the highlighted black line represents the resulting power in the feeder line. The BESS model was switched off for this simulation. The power peak at 10 a.m. ensures that at this time the supply line is loaded with 132.24% of its capacity, which represents a clear overload. The grey dashed auxiliary line represents the 60% load threshold of the supply line, which for the 1 kV AC scenario is approximately 32 kW. The red areas represent the potential charging power and the blue areas the required final discharging powers, which could be obtained or would have to be delivered in a battery-supported 60% line load scenario.

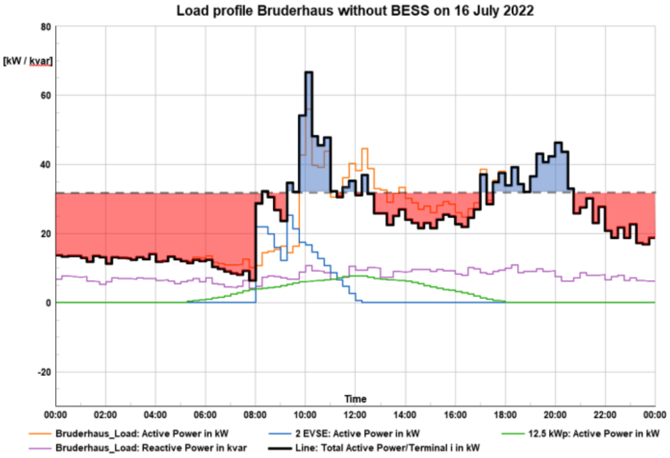

Fig. 13. Load profile without BESS

Fig. 14 shows the identical load and production curves as Fig. 13. Now the BESS model is active and the setpoints *StopCharge* and *StartDischarge* are set to 32kW. The highlighted red line shows the power flows of the BESS model and the black line shows the power in the supply line. The red and blue areas now represent the effectively consumed and delivered energy. It is clear, that the areas classified as potential from the previous figure are now effectively used. For this simulation, the maximum supply line utilisation is 59.97%.

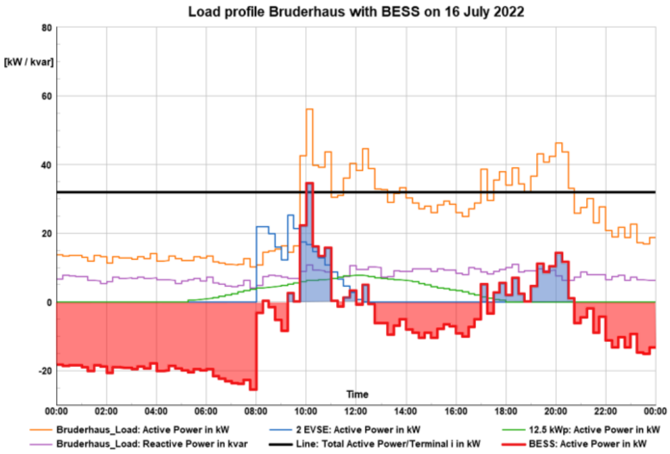

Fig. 14. Load profile with BESS

In order to determine the minimum BESS capacity and power required for a given maximum line load, the following procedure was followed. First, the setpoints *StopCharge* and *StartDischarge* were calculated and set. These two setpoints are decisive for the maximum line utilisation of the supply line and can be calculated as a percentage of the maximum transmittable power. They were set equally for all simulations. This ensures that the storage unit is completely recharged as quickly as possible after an energy discharge. Subsequently, the minimum capacity of the BESS was determined approximately. This was done in compliance with the SoC limits, which were defined between 10% and 90% for all simulations. As soon as the minimum capacity was found, the maximum occurring power could be determined on the basis of the course of the charging and discharging powers, which ultimately determines the BESS power. In addition, all steps were always checked for plausibility and compliance with the different criteria.

The BESS model and the results generated with it, do not take the ageing of the BESS into account. The decrease in capacity over time, depending on the number of charging and discharging cycles, is not included in the simulations nor the NPV calculations. Environmental influences such as temperature and humidity, which can also have an impact on the performance of the BESS, have also been neglected.

VII. RESULTS AND OUTLOOK

Having outlined the methodology used in this study, this chapter will detail the results of the study and present main advantages and disadvantages of the scenarios according to the received results.

A. Hydrogen scenario

The scenario with hydrogen was only analysed for the scenario with a 1 kV AC grid and a line load of 80% to give an idea of whether hydrogen is a feasible option.

The NPV results from this scenario show that replacing the BESS with hydrogen is not sensible, as the annual expenses for hydrogen are 50'145.83 CHF (to refill bottles 11 times during the year) and the investment for the EFOY Hydrogen [13] 2.5 kW is 350'145.83 CHF (for 10 cabinets). This results in an NPV of 1'147'796.24 CHF, which is more than seven times higher than the NPV results gained for the 1 kV AC grid with a BESS.

B. Off- grid operation: Micro Grid scenario

The results of this scenario showed that the first scenario is technically viable considering 245.50 kWp case, but financially not feasible, as the NPV is extremely high. A microgrid implies that all energy is provided either by the PV or BESS. Therefore, the excess energy provided by the PVs in the summer must be stored in the BESS for the colder months with less PV production. As the power flow calculation is solvable, the scenario is technically feasible with a PVs of 245.50 kWp and a BESS with an energy storage capacity of 47.50 MWh and a possible power of 135 kW. A BESS with these parameters requires a space of approximately 850 m^3 (13 x 12 m containers). The BESS is generally charged during the summer when PV production is high and discharged during the winter when PV production is low, as displayed in Fig. 15.

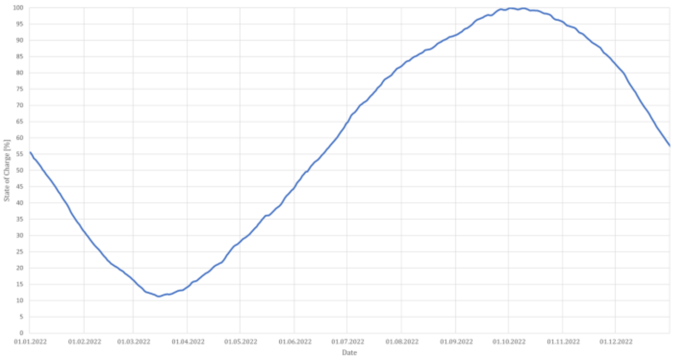

Fig. 15. BESS state of charge

In the second scenario, limiting the PVs to the line capacities of the Bruderhaus grid, reduces the maximum power from all solar panels adds up to 176.6 kWp, whereby the peak power produced by the PVs only amounts to 97.43 kWp. This peak still covers the maximum power consumption of 67 kW. The larger concern is the annual energy consumption of the area, as the PV system will not provide these power peaks during winter.

The annual energy consumption of Bruderhaus in 2021 amounted to nearly 183.6 MVAh. If only solar panels are installed that do not exceed the line capacity, the energy generated amounts to 156.7 MWh. This result shows that, an off-grid scenario is technically not feasible as long as the line capacities within Bruderhaus do not get increased.

C. Overview of the results

The most important technical and economical values of Low/Average/High cost scenarios are displayed in TABLE XII. and highlighted in red if the values exceed the defined limits or in the case of the NPV, exceed the results of the grid reinforcement to highlight scenarios that are technically or financially not feasible.

TABLE XII. OVERVIEW RESULTS OF POWER SUPPLY SCHEMES

Scenario	NPV [kCHF]			PV [kWp]	Line Cap. [%]	Voltage Dev. [%]	BESS size
	Low	Avg.	High				
CG: CL (no VoLL)	20	25	31	12.50	9.06	0.52	-
CG: CL + 2 EVSE (no VoLL)	20	25	31	12.50	11.80	0.70	
CG: CL (VoLL)	23	36	51	12.50	9.06	0.52	
CG: CL + 2 EVSE (VoLL)	23	36	51	12.50	11.80	0.70	
GR: CL (no TR)	303	428	567	12.50	2.23	0.49	-
GR: CL + 2 EVSE (no TR)	303	428	567	12.50	2.91	0.65	
GR: CL (TR)	327	456	598	12.50	2.23	0.49	
GR: CL + 2 EVSE (TR)	327	456	598	12.50	2.91	0.65	
ACG: CL	109	128	148	12.50	97.93	11.75	5kWh/15kW
ACG: CL + 2 EVSE	130	159	189	12.50	99.70	11.88	50kWh/30kW

ACG: CL	113	134	155	12.50	89.59	10.63	10kWh/20kW
ACG: CL + 2 EVSE	136	167	199	12.50	90.38	10.73	60kWh/35kW
ACG: CL	129	157	185	12.50	79.87	9.43	50kWh/25kW
ACG: CL + 2 EVSE	142	176	212	12.50	79.87	9.43	80kWh/40kW
ACG: CL	148	185	222	12.50	69.97	8.18	100kWh/30kW
ACG: CL + 2 EVSE	161	203	246	12.50	69.97	8.18	120kWh/45kW
ACG: CL	178	229	280	12.50	59.80	6.88	200kWh/35kW
ACG: CL + 2 EVSE	191	247	304	12.50	59.80	6.88	200kWh/50kW
ACG: CL	223	293	364	12.50	50.21	5.63	300kWh/40kW
ACG: CL + 2 EVSE	246	327	408	12.50	50.21	5.63	350kWh/55kW
ACG: CL	338	369	403	160.70	95.25	11.18	0kWh/0kW
ACG: CL + 2 EVSE	345	379	416	160.70	99.86	10.55	10kWh/10kW
ACG: CL	340	372	408	160.70	89.90	11.18	2kWh/5kW
ACG: CL + 2 EVSE	348	384	423	160.70	90.23	10.55	15kWh/15kW
ACG: CL	345	379	416	160.70	79.74	11.18	10kWh/10kW
ACG: CL + 2 EVSE	352	389	429	160.70	80.16	10.55	20kWh/20kW
ACG: CL	352	389	430	160.70	69.88	11.18	25kWh/15kW
ACG: CL + 2 EVSE	359	399	443	160.70	69.96	10.55	35kWh/25kW
ACG: CL	338	369	403	160.70	59.94	11.18	50kWh/20kW
ACG: CL + 2 EVSE	380	415	463	160.70	59.91	10.55	60kWh/30kW
ACG: CL	382	433	487	160.70	49.80	11.18	100kWh/25kW
ACG: CL + 2 EVSE	387	440	497	160.70	49.80	10.55	105kWh/35kW
ACG: CL	197	219	243	64.80	99.05	11.90	0kWh/0kW
ACG: CL + 2 EVSE	206	232	260	64.80	99.97	12.00	10kWh/15kW
ACG: CL	200	224	250	64.80	90.16	10.83	5kWh/5kW
ACG: CL + 2 EVSE	209	237	267	64.80	90.17	10.65	15kWh/20kW
ACG: CL	208	234	263	64.80	79.86	9.53	15kWh/15kW
ACG: CL + 2 EVSE	214	245	277	64.80	80.11	9.53	25kWh/25kW
ACG: CL	218	250	283	64.80	70.08	8.33	40kWh/20kW
ACG: CL + 2 EVSE	227	263	300	64.80	70.14	8.25	55kWh/30kW
ACG: CL	245	288	334	64.80	60.31	7.00	110kWh/25kW
ACG: CL + 2 EVSE	255	304	354	64.80	59.98	6.90	130kWh/35kW
ACG: CL	278	334	394	64.80	49.80	5.58	200kWh/30kW
ACG: CL + 2 EVSE	284	345	408	64.80	49.70	5.55	220kWh/40kW
ACG: CL	-	1'147	-	12.50	80.00	9.43	Hydrogen solutions
ACG: CL + 2 EVSE	-	1'977	-	12.50	80.00	9.43	
Off-grid operation: CL	-	15'970	-	245.50	0.00	0.00	48MWh/135kW
Off-grid operation: CL	-	15'790	-	176.60	0.00	0.00	48MWh/135kW
DCG: CL	53	75	97	12.50	99.91	0.00	45kWh/45kW
DCG: CL + 2 EVSE	66	93	120	12.50	99.91	0.00	80kWh/45kW
DCG: CL	64	90	117	12.50	89.98	0.00	80kWh/40kW
DCG: CL + 2 EVSE	71	100	131	12.50	89.98	0.00	100kWh/40kW
DCG: CL	80	113	147	12.50	79.75	0.00	130kWh/35kW
DCG: CL + 2 EVSE	85	121	158	12.50	79.96	0.00	145kWh/35kW
DCG: CL	98	139	181	12.50	70.10	0.00	180kWh/35kW
DCG: CL + 2 EVSE	101	144	188	12.50	70.10	0.00	190kWh/35kW
DCG: CL	117	168	219	12.50	59.82	0.00	240kWh/30kW
DCG: CL + 2 EVSE	135	194	253	12.50	59.77	0.00	290kWh/30kW
DCG: CL	363	524	686	12.50	50.47	0.00	940kWh/25kW
DCG: CL + 2 EVSE	1683	2'443	3203	12.50	50.01	0.00	4.7MWh/25kW
DCG: CL	266	292	321	160.70	99.90	0.00	15kWh/10kW
DCG: CL + 2 EVSE	273	302	334	160.70	99.90	0.00	25kWh/20kW
DCG: CL	271	299	331	160.70	89.98	0.00	25kWh/15kW
DCG: CL + 2 EVSE	278	309	344	160.70	89.98	0.00	35kWh/25kW
DCG: CL	280	312	348	160.70	80.78	0.00	45kWh/20kW
DCG: CL + 2 EVSE	285	320	358	160.70	80.00	0.00	50kWh/30kW
DCG: CL	291	327	368	160.70	70.10	0.00	70kWh/25kW
DCG: CL + 2 EVSE	298	338	381	160.70	70.10	0.00	80kWh/35kW
DCG: CL	305	348	395	160.70	60.02	0.00	110kWh/25kW
DCG: CL + 2 EVSE	312	358	408	160.70	60.02	0.00	120kWh/35kW
DCG: CL	330	384	442	160.70	50.01	0.00	175kWh/30kW
DCG: CL + 2 EVSE	337	395	455	160.70	50.01	0.00	185kWh/40kW
DCG: CL	129	147	168	64.80	99.91	0.00	20kWh/15kW
DCG: CL + 2 EVSE	134	155	178	64.80	99.91	0.00	25kWh/25kW
DCG: CL	134	155	178	64.80	90.81	0.00	35kWh/15kW
DCG: CL + 2 EVSE	145	170	198	64.80	89.98	0.00	50kWh/30kW
DCG: CL	148	175	205	64.80	80.00	0.00	70kWh/20kW
DCG: CL + 2 EVSE	159	191	225	64.80	80.00	0.00	85kWh/35kW
DCG: CL	169	206	245	64.80	70.10	0.00	125kWh/25kW
DCG: CL + 2 EVSE	176	217	259	64.80	70.14	0.00	135kWh/35kW
DCG: CL	191	237	286	64.80	60.02	0.00	180kWh/30kW
DCG: CL + 2 EVSE	201	253	306	64.80	60.02	0.00	200kWh/40kW
DCG: CL	227	290	356	64.80	50.01	0.00	285kWh/35kW
DCG: CL + 2 EVSE	252	326	402	64.80	50.01	0.00	340kWh/45kW

Fig. 16 displays the average NPV results for all feasible scenarios with a line load limitation of 80%. The results demonstrate that the 1 kV AC and 0.7 kV DC scenarios are financially more appealing than grid reinforcement. Technically speaking, grid reinforcement offers a very reliable scenario with high costs. The 0.7 kV DC scenario with the current 12.5 kWp PV system is the cheapest option, with a resulting NPV of 113'599.09 CHF. The 80% line load is a good choice, as it provides an energy reserve that can be transferred on the line and compensates for not- considered factors such as degradation of the BESS and simplifications such as linear efficiencies in the BESS and inverters. Additionally, the voltage deviation on the 400V line at Bruderhaus is within the defined limit of 10%.

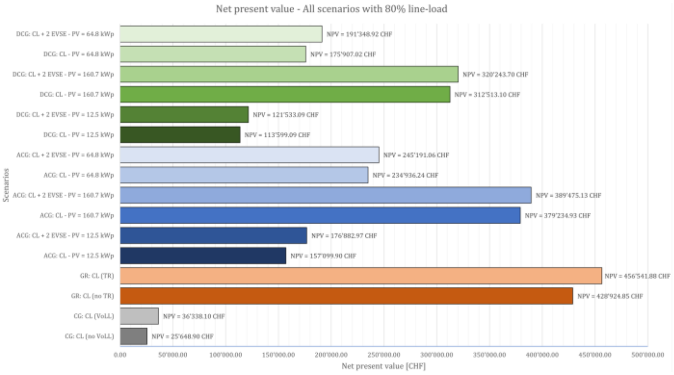

Fig. 16. NPV comparison at 80% line load

Fig. 17 shows a comparison between all 1 kV AC and 0.7 kV DC grid average scenarios. The results indicate, that the resulting NPV is increased when the line load is reduced or the PVs is increased. Additionally, the results indicate a slightly lower NPV for the 0.7 kV DC grid compared to the same scenarios with the 1 kV AC grid. This can be explained by the lower price of the inverter compared to the transformer. Nevertheless, due to the smaller line capacity in the DC scenario, the BESS increases more quickly than in the AC grid. At some point, this increase in BESS size results in a larger NPV for the DC scenario than the AC scenario. The increase in BESS size can be recognised in the sudden large NPV for the 0.7 kV DC scenario with a 12.5 kWp, where the NPV results in a value exceeding the 500'000 CHF value.

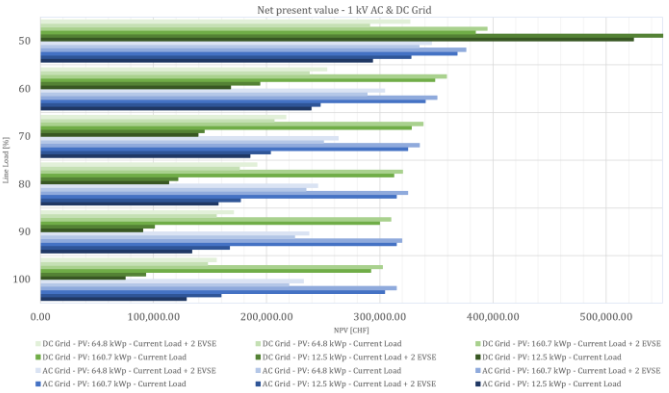

Fig. 17. Comparison NPV of AC and DC solution

D. Outlook and future work

This work, as defined in the title, mainly analysed the technical - economic aspect and approximated the costs for the different scenarios. Nevertheless, this work can be extended by including a more detailed of other aspects such as:

- The carbon footprint of scenarios;
- Degradation, ageing and temperature influences of BESS.

The aspect that was not analysed, which has an important role in the modern world is the consideration of the environmental aspects, such as the carbon footprint of each scenario including the production of the equipment invested in. By including the CO2 emissions to the technical and economic aspects, the most attractive scenario might change, due to high CO2 emissions. Environmental considerations have become very important and could thereby increase the willingness to increase the PV system even though the costs will increase. Especially regarding modern CO2 taxes, the investment costs for a PV system or a BESS could change drastically.

The other, less influential aspect, that can be analysed more precisely is the simulation and regulation of the BESS. The BESS was considered to have a fixed efficiency curve, energy storage capacity. Considerations, such as battery degradation, ageing or environmental influences such as temperature or humidity were all neglected, as the line load was defined not to be higher than 80%, therefore providing spare line capacity for lower energy storage values or power outputs.

VIII. CONCLUSION

Comparing the different scenarios as alternative solutions to a grid reinforcement, both 1 kV AC and 0.7 kV DC scenarios seem to provide a feasible and sensible solution. When considering a line load of 80% with and without two additional EVSE units, the NPV results represent a cost reduction for all PV sizes considered. Generally, by increasing the size of the PV system, the BESS sizes for energy and power are reduced. As the investment costs for the PVs are higher than for the BESS, the NPV rises when increasing the PV system in both 1 kV AC and 0.7 kV DC scenarios. The microgrid scenario and the solutions with hydrogen do not provide a feasible alternative to the grid reinforcement, as all scenarios have higher NPV results. The 1 kV AC and 0.7 kV DC scenarios will be operated at line loads of approximately 80% to firstly provide an energy reserve for any kind of changes in the load profiles or other not considered factors such as degradation of the BESS and secondly, to ensure the voltage deviation does not exceed the defined maximum of 10%. The 1 kV AC grid with a 160.7 kWp PV had to be defined as not feasible, as the voltage deviation for all line loads exceeded the 10% limit. Therefore, scenarios with PV systems larger than 160.7 kWp are all to be considered not feasible.

After comparing all feasible scenarios and the included sub-scenarios, the DC scenario with the current 12.5 kWp PV and a line load of 80% is recommended. The main advantage of the DC scenario is the low NPV, with a value of 75'014.88 CHF in average scenario. The low NPV ensures that even if there are further smaller cable breakdowns that must be replaced, the NPV stays below the grid reinforcement. Another advantage is that the inverters regulate the voltage at the Bruderhaus to exactly 400 V regardless of the load, whereas the AC scenario, for instance, has a voltage deviation of nearly 10% for the 80% line load scenario. The only concern for the DC grid is that the supply lines are already 50 years old and could completely break down in the future. Then grid reinforcement is unavoidable. Nevertheless, even in the worst-case scenario, the DC grid provides a good solution, as the inverter and BESS (45 kW / 45 kWh) required for the 0.7 kV DC grid can be used for the bus supply system of Winterthur, which also operates at 0.7 kV DC, whereas the transformer used for the 1 kV AC grid cannot be easily reused.

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