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The Influence of Energy Cell's Size and Generation-Load-Ratio on Economic Benefits

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***Abstract*—In this paper, results of the demonstration project Hybrid-Optimal are presented. The project partners are installing a hybrid battery storage, which consists of a Vanadium Redox Flow Battery (VRFB) and a Lithium-Ion Battery (LIB), in an energy cell with high photovoltaic (PV) generation. First, this paper compares the economic situation of different possibilities to use PV-generation and battery storage systems, such as the selling of energy on the spot market or the statutory feed-in compensation, as well as the self-consumption of the generated energy or taking part at the control-reserve market with the battery storage. In a second step, the influences on the economic benefits of the energy cell are calculated, varying the size and generation-load-ratio of the energy cell. Additionally, the calculation method is transferred from the demonstration project Hybrid-Optimal to other energy cells.**

I. Demonstration Project Hybrid Optimal

In the project Hybrid-Optimal a grid section in the distribution network of the Stadtwerke Bühl GmbH in Bühl is developed into an energy cell to demonstrate the benefits of the cellular approach [1] in practice. The project partners are the Stadtwerke Bühl GmbH, the Karlsruhe Institute of Technology and SCHMID Energy Systems. Main objective of the project is to demonstrate that a grid section with a high penetration of PV generation can be developed into an energy cell through the installation of a central hybrid battery storage system (HBSS), consisting of a 5 kW/45 kWh VRFB, delivered by SCHMID Energy Systems and an additional 40 kW/56 kWh LIB. Besides an increasing power grid stability through the HBSS, the economic situation of the energy cell regarding current market opportunities shall be determined in the project to analyse the public profit during the energy transition. The project started in September 2016 and will be completed in July 2019. A detailed project description can be found in [2].

II. Input Data

The input data is related to the input data of [3]. To calculate the economic benefits, the PV generation and the energy consumption of the households besides the costs and prices are important. To determine the PV generation, data of a reference PV plant close to the grid section was used. For 2016 data is available in form of average values of a 15 minutes period. In total PV systems with P_{PV} = 45 kWp are installed in the energy cell. In 2016, the total energy production E_{PV} was 44.132 MWh. This results in an Insolation (annually generated kWh per installed kWp) E_{Ins} of 980.7 kWh/kWp.

For the energy consumption in the energy cell only the yearly consumption per household is measured. The yearly consumption E_C from all ten households was 42.674 MWh in the year 2016. 1000 different household consumption profiles, which have been developed in [4], are used to generate realistic time series data for the energy consumption.

To compare different market opportunities for the energy cell, realistic costs and German market prices from 2018 are used. One important assumption regarding taxes is that a company operates the energy cell and therefore no VAT is necessary. The investment cost of PV $c_{PV,In}$ is set to 1260 €/kWp [5] [6]. Additionally, yearly operating costs $c_{PV,op}$[1] depending on the installed PV power are assumed with

$$c_{PV,op} = \begin{cases} 270€ + 6.25\frac{€}{kW_p} & \text{for } P_{PV} < 10\,kW_p \\ 160€ + 15.25\frac{€}{kW_p} & \text{for } 10\,kW_p \leq P_{PV} < 30\,kW_p \\ 90€ + 17.65\frac{€}{kW_p} & \text{for } 30\,kW_p \leq P_{PV} < 100\,kW_p \\ 115€ + 17.65\frac{€}{kW_p} & \text{for } 100\,kW_p \leq P_{PV} < 250\,kW_p \\ 145€ + 17.65\frac{€}{kW_p} & \text{for } P_{PV} \geq 250\,kW_p \end{cases} \quad (1)$$

With Equation (1) for the Hybrid Optimal energy cell costs of 884.25 €/a are taken into account. The investment costs $c_{Bat,In}$ for battery storages are set to 1150 €/kWh [11] and the interest rate z is assumed to be constantly 3 %. The lifetime of the PV system and the battery storage N is set to 20 years. In addition, a degradation of 1 % per year for the capacity of the HBSS and for the power of the PV system is taken into account. For charging and discharging of the HBSS an efficiency of 95 % is assumed.

For the different market opportunities the (average) energy prices of the year 2018 are taken into account:

[1]The operational costs include yearly rent for the electric meter [7], maintenance [8] [9], insurances [10] as well as a recommended professional cleaning every second year [8] [9]. All prices are also actual market prices from 2018. In reality, however, it is possible, that the owner of the PV system doesn't spend money for cleaning, maintenance or insurances, what can affect the results.

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- Electric supply price [12] c_{sup} is 29.88 ct/kWh
- Spot market price [13] p_{spot} is 4.4 ct/kWh
- Statutory feed-in rate for PV energy [14] p_{feed} is
  - 12.05 ct/kWh for systems < 10 kWp
  - 11.72 ct/kWh for systems > 10 kWp and < 40 kWp
  - 10.47 ct/kWh for systems > 40 kWp
- Control-reserve market prices in € per offered kW and year [15]
  - Primary control reserve $p_{con,prim} = 112.03\,\frac{€}{kW \cdot a}$
  - Secondary control reserve $p_{con,sec} = 245.20\,\frac{€}{kW \cdot a}$
  - Minute reserve $p_{con,min} = 40.86\,\frac{€}{kW \cdot a}$
- Realistic average self-consumption levels, which have been calculated in [3] are used.

The different market opportunities for the energy cell are compared over their Net Present Value (NPV).

III. Comparison of different market opportunities

A. Scenario definition and methodology

To compare the different market opportunities 7 Scenarios are defined:

1) Self-consumption and statutory feed-in rate without HBSS (just PV system)
2) Self-consumption and statutory feed-in rate with HBSS
3) Self-consumption and spot market price without HBSS (just PV system)
4) Self-consumption and spot market price with HBSS
5) Selling the LIB on the primary control reserve market (maximum power in kW), and using the left capacity of the LIB and the VRFB like in Scenario 2
6) Selling the LIB on the secondary control reserve market (a quarter of the capacity as offered power in kW), and using the VRFB like in Scenario 2
7) Selling the LIB on the minute reserve market (a quarter of the capacity as offered power in kW), and using the VRFB like in Scenario 2

In the Scenarios 5 - 7 it is assumed, that the capacity of the LIB, which is sold on the control reserve markets, isn't available for the optimization of the self-consumption of the energy cell. Even if the actual regulatory conditions don't allow offering such small lot sizes in the periodically call of tenders, the scenarios are as close as possible to the real market processes, for example considering the ratio between offered power and therefore needed capacity. Further information about the workflow of the control reserve markets can be found in [15].

In the scenarios, self-consumption is defined as the use of the PV-generated energy directly without using the electric grid. Because the energy consumption, which is covered by the PV system or through discharging the HBSS, mustn't be taken from the grid, this generates earnings in height of the electric supply price minus the VAT of 19 % in Germany.[2]

[2]Based on the assumption that the energy cell is operated by a company, German tax law defines the self consumed PV energy as income of the company. The company has to pay VAT on this income, which reduces the earnings. This reduction in earnings isn't necessary for the statutory feed-in rate, as the feed-in rate is a net tax rate.

Therefore self-consumption of PV energy generates profits p_{SC} in height of

$$p_{SC} = c_{sup} - \frac{19\,\%}{119\,\%} \cdot c_{sup} = 25.1\,\frac{ct}{kWh}. \tag{2}$$

As the earnings p_{SC} through self-consumption are higher than the earnings through feeding in the generated energy ($p_{spot} = 4.4$ ct/kWh or $p_{PV} = 10.47$ ct/kWh) it is more beneficial to increase the self-consumption instead of feed-in the energy.

For the calculation of the NPVs of the different market opportunities the yearly cash flows for the energy cell are calculated. After regarding the degradation, the resulting PV generation and HBSS capacity is used to calculate the realistic self-consumption level (SCL) according to [3]. Out of the SCL and the PV generated energy E_{PV} the self-consumption E_{SC} is calculated with

$$E_{SC} = SCL \cdot E_{PV}. \tag{3}$$

The remaining energy

$$E_{feed} = E_{PV} - E_{SC} \tag{4}$$

is fed into the grid. Therefore the cash flow CF of each year can be calculated as

$$CF = E_{SC} \cdot p_{SC} + E_{feed} \cdot p_{PV} - c_{PV,op}. \tag{5}$$

While in Scenario 3 and 4 p_{PV} is replaced by p_{spot}, the profit from the control reserve market has to be added in Scenario 5 - 7. The cash flows are discounted regarding the lifetime N and the interest rate z and are summed up to the NPV

$$NPV_{abs} = -c_{Invest} + \sum_{n=1}^{N} \frac{CF(n)}{(1+z)^n} \tag{6}$$

which is divided by the investment costs, to give a relative NPV.

B. Economic profitability of Hybrid-Optimal

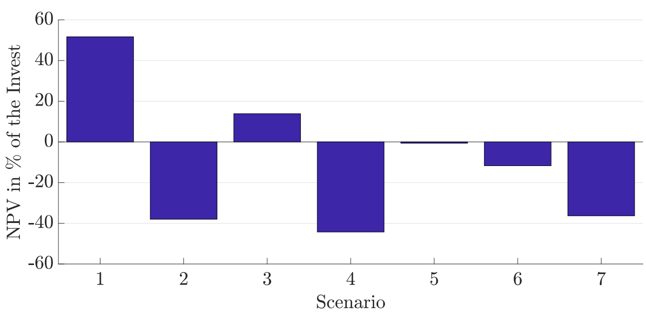

Fig. 1. Comparison of different market opportunities; Hybrid-Optimal with 101 kWh HBSS capacity

In Figure 1, it can be seen, that only the Scenarios 1 and 3 are economic beneficial, what is shown by their positive NPV. The positive NPV of Scenario 3 shows, that an energy cell with PV generation even then gets economic beneficial, if there isn't a statutory in-feed compensation. This is the result of an approximate increase of 30 % of spotmarket prices from 2017 to 2018. However, it has to be mentioned that spotmarket prices are assumed constant over the lifetime of 20 years in this paper, which is not very probable.

All other scenarios are not economically beneficial. Their overall earnings partially don't reach half of their investment costs at all. Hence, under the circumstances of this research project, it is economically more beneficial, to operate the energy cell without a battery storage.

IV. Adjusting Hybrid-Optimal battery storage on economic profitability

Like seen in Figure 1 the project Hybrid-Optimal with the realized size of the HBSS and the boundary conditions doesn't get profitable. Even if the LIB is sold on the primary control reserve market, the NPV stays negative. To analyse if this is a general result or just an effect of the boundary conditions of the Hybrid-Optimal project, the battery storage is adjusted on economic profitability.

Therefore, the dependency of the self-consumption on the battery storage capacity is taken into account (see at III.B in [3]). According to Figure 4 and Figure 11 in [3] the self-consumption level reaches it biggest increase until a capacity of roughly 50 kWh. For higher energy capacities, the gradient of the self-consumption level decreases, because of seasonal effects.

As a result of this observation, hereafter the battery storage system in the demonstration project is assumed to consist only of the LIB. Additionally, the capacity of the LIB is varied to find the break-even-point, where the NPV gets positive.

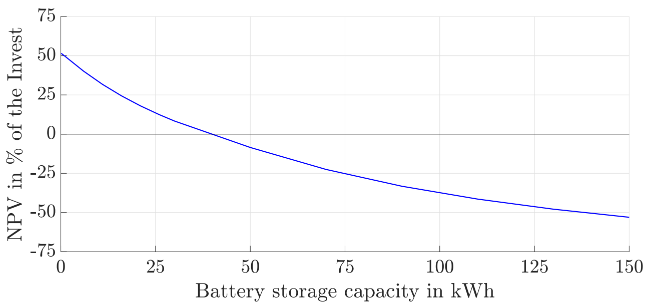

Fig. 2. NPV depending on the battery storage capacity, Scenario 2

In Figure 2, the dependency of the NPV (Scenario 2) on the size of the battery storage is presented. With increasing capacity the NPV decreases. Around 39.3 kWh capacity the NPV turns negative. To analyse the influence of the generation-load-ratio or the size of the energy cell, the capacity of the LIB is set to 86.7 % of the installed PV power. Hence, the capacity in the demonstration project gets 39 kWh. In addition, the Scenarios 5 - 7 are modified, so that just 80 % of the LIB capacity is sold on the control reserve markets. To simplify the calculation, it is assumed that the LIB has the same power than capacity (39 kW / 39 kWh).

In Figure 3 it can be seen, that with a reduced capacity (101 kWh HBSS to 39 kWh LIB) more scenarios get economic profitable. The Scenarios 5 and 6, which include selling 80 % of the capacity on the control reserve markets,

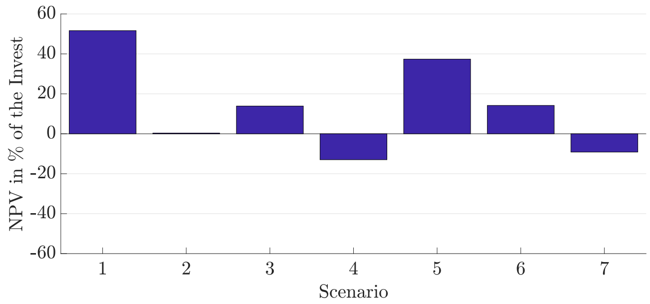

Fig. 3. Comparison of different market opportunities; Hybrid-Optimal with 39 kWh LIB capacity

get a positive NPV, and the NPV of Scenario 2 gets close to zero. Therefore the paper focus on the Scenarios 1, 2, 5 and 6 in its further course.

As a result it can be concluded that using battery storages to develop grid sections to energy cells just gets profitable at all, if either the regulatory conditions are changed so that these batteries can take part in the control reserve markets or the technical circumstances require investments, that are even higher than the losses due to the use of the battery storage. Therefore, each project which uses battery storages in grid sections with high penetration of PV has to be calculated individually.

V. Influence of the generation-load-ratio to the profitability

With the knowledge of section III-B and the reduction of the battery storage to a 39 kW / 39 kWh LIB the influence of the generation-load-ratio is analysed. The data from the project area for the yearly consumption and the yearly PV generation leads to a generation-load-ratio r_{gl}

$$r_{gl} = \frac{E_{PV}}{E_C} = 1.034 \tag{7}$$

For the calculation it is assumed, that the energy generation from the PV system stays continuously by $E_{PV} = 44.132\,MWh$ and the yearly consumption of the energy cell is varied between a r_{gl} of 0.7 and 1.3, which means an intervall from 63.05 MWh to 33.95 MWh for the yearly consumption of the energy cell.

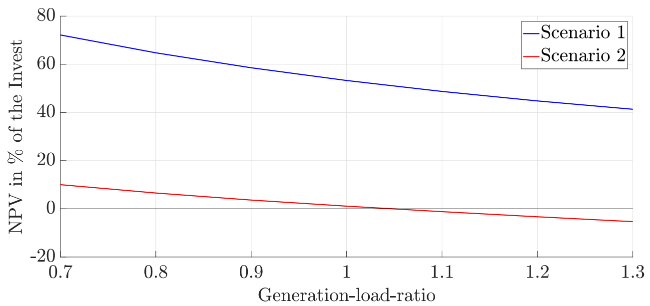

Fig. 4. NPV depending on generation-load-ratio

The profitability of the energy cell is strongly dependent on the generation-load-ratio, like it can be seen in Figure

4. As long as the household load-profiles stay the same[3], a decreasing r_{gl} leads to an increasing self-consumption level (SCL). Therefore, it can be assumed, that the SCL is proportional to the inverse of r_{gl} (see Figure 5). As the NPV is proportionate to the SCL, this directly leads to higher earnings, and therefore a better profitability and a higher NPV.

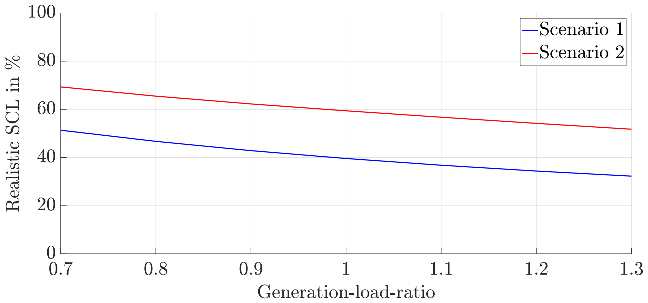

Fig. 5. SCL depending on generation-load-ratio

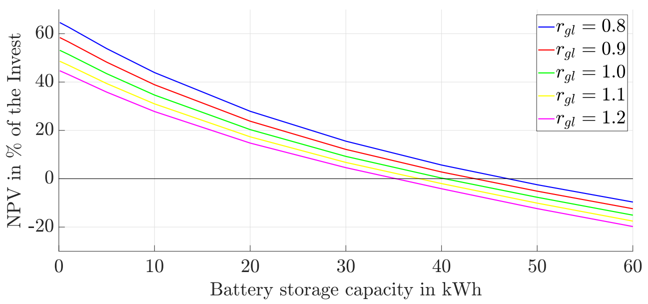

Fig. 6. NPV depending on generation-load-ratio and LIB capacity, Scenario 2

As seen in Figure 6, different generation-load-ratios also lead to different battery storage capacities Cap_B, which are profitable. Over all it can be concluded, that a higher consumption, which leads to a smaller generation-load-ratio makes bigger battery storage capacities also economically beneficial.

To generalize these dependencies the ratio between generation and load r_{gl} and the ratio between battery storage capacity and installed PV power r_{BPV} is analysed.

$$r_{BPV} = \frac{Battery\ storage\ capacity\ in\ kWh}{installed\ PV\ power\ in\ kW} \tag{8}$$

To compare the ratios, for different generation-load-ratios the corresponding battery storage capacity Cap_B is calculated, which results in a

$$NPV < \pm 0.001\%. \tag{9}$$

The product of the two ratios k_{Batt} is defined as

$$k_{Batt} = r_{gl} \cdot r_{BPV} = r_{gl} \cdot \frac{Cap_B}{P_{PV}} \tag{10}$$

and has the unit kWh/kWp.

[3]Because the self-consumption-level strongly depends on the single household load-profiles, this is a necessary assumption to compare different generation-load-ratios. Therefore, the used standardized household profiles are multiplied with the varied yearly consumption. This leads to a comparable self-consumption-level and NPV.

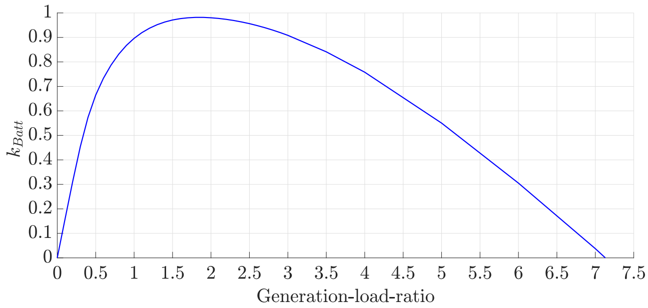

Fig. 7. k_{Batt} depending on generation-load-ratio

In Figure 7 the dependency from k_{Batt} on the generation-load-ratio can be seen.

Taking $r_{gl} = 1.034$ of the project Hybrid-Optimal into account, k_{Batt} gets 0.9. With Equation (10) this leads to

$$Cap_B = k_{Batt} \cdot \frac{p_{PV}}{r_{gl}} \tag{11}$$

$$Cap_B = 0.9 \frac{kWh}{kWp} \cdot \frac{45\,kWp}{1.034} = 39.17\,kWh \tag{12}$$

Therefore, it can be shown, that the HBSS in the project Hybrid-Optimal with a capacity smaller $Cap_B < 39.17\,kWh$ gets economic beneficial, what can also be seen in Figure 3.

VI. Influence of the Energy Cell's Size to the Profitability

A. Definition of Different Energy Cells

To analyse the influence of the energy cell's size, three more energy cells are defined.

For all four energy cells a yearly Insolation E_{Ins} of 980.7 kWh/kWp is assumed. Because of the differing P_{PV}, different profits p_{feed} for the statutory feed-in compensation are used. To extend the different grid sections to energy cells in each of them a LIB is integrated. To estimate the capacity of the LIB, the set P_{PV} is used to calculate the resulting r_{gl}. With r_{gl} the corresponding k_{Batt} as seen in Figure 7 is used to calculate Cap_B with Equation (11). For the energy consumption of the scenarios the percentage of different household types from [17] and their average yearly energy consumption from [16] are taken into account.

- **Single-family house**: A single-family house (four-person-household) in the suburb
- **Apartment house**: 6 households in a 3 storey apartment building
- **Residential area**: Demonstration project Hybrid-Optimal, 10 households
- **City district**: 400 private households in a city district

The same scenarios as in chapter IV are analysed. 1000 household profiles from [4] are taken to calculate average

[4]Although [18] rules, that PV systems with $P_{PV} > 100\,kWp$ get a statutory in-feed-compensation lesser than the used 10.61 ct/kWh, which is set over a auction, the paper assumes the same profit p_{feed} for energy that is fed into the electric grid. This seems arguable, because the average discounted deficit over the lifetime of the PV systems is around 10 % of the investment costs and it can be assumed that a quantity discount in the same height is realistic, if 1700 kWp are bought instead of 6 kWp or 45 kWp

TABLE I
OVERVIEW ENERGY CELL DATA

energy cell	E_C	P_{PV}	$c_{PV,op}$
Single-family	4.955 MWh	3.5 kWp	291.88 € /a
Apartment house	19.062 MWh	20 kWp	465.00 € /a
Residential Area	42.674 MWh	45 kWp	884.25 € /a
City district	1270 MWh	1650 kWp [4]	29 267.50 € /a
energy cell	r_{gl}	k_{Batt}	Cap_B
Single-family	0.69	0.79	3 kWh
Apartment house	1.03	0.9	17 kWh
Residential Area	1.03	0.9	39 kWh
City district	1.27	0.945	1223 kWh

energy cell profiles taking the spread of the realistic self-consumption level according to [3] into account. Corresponding to the number of households, the same number of household-profiles is used to calculate average cell-profiles. These profiles are used to calculate an average realistic self-consumption level for each energy cell, according to [3]. The SCL for the four energy cells (time of installation and therefore without degradation) can be found in Table II.

TABLE II
SELF-CONSUMPTION LEVEL SCL FOR DIFFERENT ENERGY CELLS

energy cell	SCL Scenario 1	SCL Scenario 2
Single-family house	44.68 %	66.14 %
Apartment house	38.23 %	58.08 %
Residential Area	38.60 %	58.47 %
City district	33.42 %	51.23 %

B. Comparison of the Profitability of Different Energy Cells

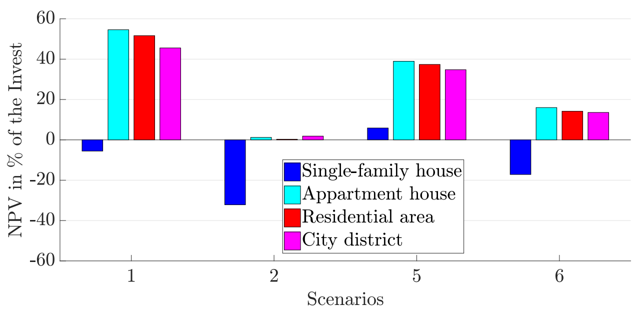

Fig. 8. Comparison of economic profitability for different energy cells

In Figure 8 it can be seen, that the energy cells Apartment house, Residential area and City district produce comparable results. The NPV stays positive in all scenarios, in Scenario 2 it also is nearly zero, which validates the capacity-estimation with Equation (11) and Figure 7, at least for bigger energy cells. For Scenario 5 the NPV varies between 34.76 % and 38.93 %, for Scenario 6 between 13.57 % and 15.99 %.

But it can also be seen, that the Single-family house has a different NPV profile in the scenarios. It is the only one, which generates a negative NPV in Scenarios 2 and 6 and even in Scenario 1. Therefore, it seems, that the influence of the size of the energy cells doesn't matter that much, as long as the energy cell is bigger than a minimal size. If the size is falling below this minimal size, the energy cell doesnt get economically beneficial. The main reason are the operational costs $c_{PV,op}$ for the PV system, especially the cost components, which for $P_{PV} < 10\,kW_p$ are independent from the installed power (see Equation (1)), such as maintenance, insurances and electric meter rent.

C. Calculation of a Minimal Energy Cell Size for Economic Profitability

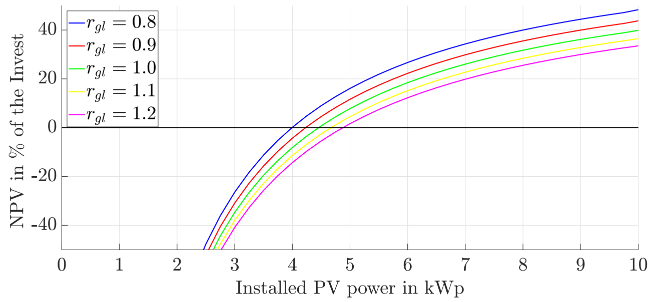

Fig. 9. NPV over the installed PV power with different load ratios, Scenario 1

In Figure 9 it can be seen, that the minimal size of the energy cell depends on the installed power of the PV system and the generation-load-ratio. Corresponding to the results in chapter V, r_{gl} influences the realistic self-consumption level of the energy cell, and therefore determines the possible earnings and the NPV. It can be assumed that $P_{PV,min}$ is proportional to r_{gl}, what also can be seen in Figure 9. A higher generation-load-ratio results in a lower self-consumption level and therefore the installed PV power has to be higher to reach a positive NPV.

As a result of Figure 9, it can be assumed, that with the given boundary conditions an energy cell with a generation-load-ratio r_{gl} of one is economic beneficial, if there is installed a PV system with an installed power higher than 4.5 kWp.

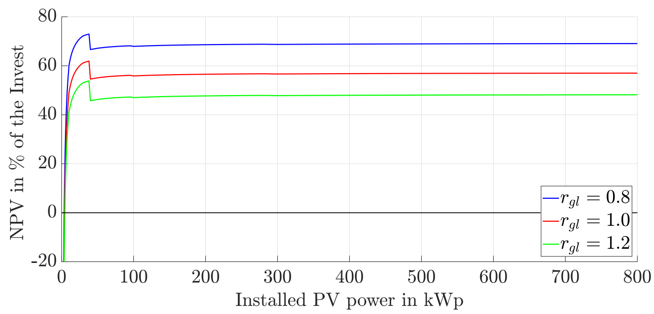

Fig. 10. NPV over the installed PV power with different load ratios, Scenario 1 for high installed power in City district

In Figure 10 the NPV over a long power-range is shown for the energy cell City district. The leap in the NPV at $P_{PV} = 40\,kWp$ results from the lower statutory feed-in compensation for PV systems with more then 40 kWp. It can be seen, that there seems to be an upper boundary for the maximum reachable positive NPV between 45 % and

70 % of the investment costs in Scenario 1, depending on r_{gl} and the corresponding SCL. Compared with Figure 8 this assumption seems reliable, the NPV in Scenario 1 is for all four energy cells between 45 % and 55 %.

Overall it can be seen, that reaching sustainable profits with a PV energy cell depends on the generation-load-ratio and also on the installed PV power, with NPV is proportional to $1/r_{gl}$ from chapter V and NPV is proportional to $log\,(P_{PV})$ from Figure 10. To reach sustainable profits (defined as 20 % of the investment costs) energy cells with $P_{PV-min} > 5\,kWp - 7\,kWp$ minimum installed PV power are necessary. PV systems with less than $P_{PV} \approx 4\,kWp$ mostly aren't profitable at all.

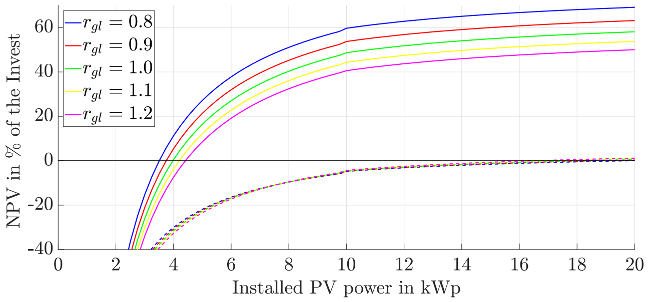

Fig. 11. NPV over the installed PV power with different load ratios for Scenario 1 (pulled through lines) and Scenario 2 (dashed lines)

As also seen in Figure 11 the energy cell must have a minimum size to make the installation of a battery storage, calculated with equation (11) and Figure 7, economically beneficial. Taking Figure 8 and Figure 11 into account, it can be assumed, that the minimal size mostly depends on the installed PV power, and that for energy cells with $P_{PV} > 20\,kWp$ the use of equation (11) and Figure 7 is valid. With a look to Figure 12 the variable k_{Batt} has to be reduced for energy cells with less installed power.

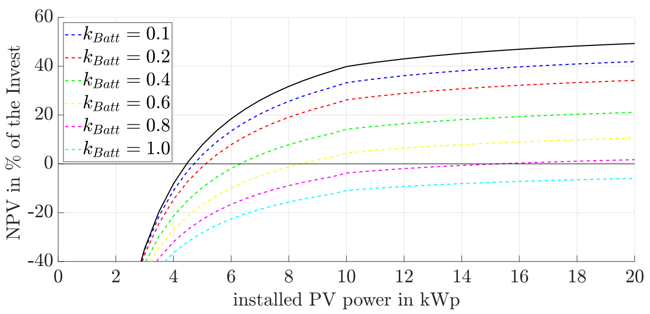

Fig. 12. NPV over the installed PV power with different K_{Batt} and $r_{gl} = 1$ for Scenario 1 (black line) and Scenario 2 (dashed lines)

For smaller energy cells, which consist only of a single household it is advisable to calculate a specific k_{Batt} or Cap_B. This results from a strong dependency of the NPV from the SCL and r_{gl}, which both are highly individual for a single household and can't be generalized. For bigger energy cells with more households, what results in a smaller spread of the real SCL, the above calculations are a reliable estimation for a profitable development of an energy cell through the installation of a battery storage system.

VII. Conclusion

In this paper the economic situation of the demonstration project Hybrid-Optimal has been calculated. It was shown, that the energy cell with the installed HBSS isn't economic beneficial at all, as long as the technical circumstances aren't taken into account. This results from the capacity of the HBSS, which is to big to lead to an economic beneficial situation. If the HBSS is reduced to a 39 kW/39 kWh LIB, it gets profitable to use the battery storage for the self-consumption of the generated PV energy and feed in the surplus on energy for the statutory feed-in compensation.

It was also shown, that there is an economic potential for selling battery storages on the primary and secondary control reserve markets. Therefore it is necessary to adjust the regulatory and legal conditions of installing, operating and offering battery storages on the control reserve markets, especially for distribution system operators (DSO).

Additionally, it was shown, that the profitability of energy cells depends on the generation-load-ratio r_{gl} of the energy cell. This results from the dependency of the self-consumption level from r_{gl} with SCL is proportional to $1/r_{gl}$. It also was shown, that it is possible to estimate an economic beneficial capacity for an energy cell, depending on the installed PV power P_{PV} and the generation-load-ratio, for energy cells with $P_{PV} \geq 20\,kWp$.

Finally, the influence of the energy cell's size to the economic profitability was analysed. It was shown, that the economic benefit of an energy cell is proportional to $log\,(P_{PV})$. Therefore there is a minimal size of the energy cell to achieve substantial profits, depending on the generation-load-ratio and the installed PV power. This also leads to the result, that there is an upper boundary for the profit (NPV of approximately 70 % of the investment), which depends on the generation-load-ratio and the realistic self-consumption level. These parameters depend on the energy cells load profile and therefore the number of households in the energy cell.

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