# The optimal combination of energy storages, photovoltaic systems and wind turbines at local level

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**This report examines the optimal combination of wind-turbines, photovoltaic-plants and battery-storage at local level. The combination of wind-turbines and photovoltaic-systems induce synergy effects. Aims are: That a commune, can be supplied by themselves with energy to 100%, with help of a battery-storage. And to find the optimal combination of installed capacity between wind-power and photovoltaic. And to find an optimal storage placement within the MV-power-plant of the community.**
**The result: To get 100% self-sufficient supply, there is the need of a very big storage of 973.42MWh. The optimal combination of installed capacity is 71.35% wind-power and 28.65% photovoltaic. A storage may be placed at the generation plants.**

## I. INDRODUCTION AND MOTIVATION

According to the renewable energy law, which was amended in 2012, the share of renewable energy in electricity production has to be increased at least until 2050 successively to 80% [3].
But how can that be done? And what problems will occur there?
Due the deregulation process, there is already a change in the European energy market.
Due this liberalization of the electricity energy market, the trend towards decentralized power generation and supply is enhanced. At the moment, it is for the producer of local renewable energy, as well as for the existing grids, the best option to consume as much as possible of the produced energy on site. Thus, losses are minimized and the electrical grid is less loaded. In addition, it is becoming increasingly attractive to consume the generated energy by yourself, cause of the in the "renewable energy law" agreed a continue fall of monthly feed-in tariffs. Thru these energy storage are required because the need of energy is not simultaneously to the production. So the energy storage can decoupled them from each other. Thru this measure more decentralized renewable energy generators can be installed without a major electrical grid network expansion.
With the use of PV-systems and wind-turbines on a local level it is important to note that a PV-system had a daily repetitive behaviour with a peak at midday, in turn a wind-turbine shows a repetitive behaviour of one within several weeks.
According to that, to storage all energy, for a wind- turbine a one-week-storage and for a PV a daily-storage is needed. When both techniques are combined, there is synergy effect, which can be used for the storage and to get an increasing of the degree of self-sufficiency.
The knowledge gained of this publication amounts specifically for the optimal combination of installed capacity of wind-turbines and photovoltaic systems under the application of a battery storage.

## II. STATE OF THE ART AND SCIENCE

The Reiner Lemoine Institute and the Engineering Department of the solar practice were part of a master's thesis, examine the combination of photovoltaic and wind power as an integrated power plant on the same area. The result is that wind power and photovoltaic complement each other due to their low simultaneity. Today there are barely any systems where wind power and photovoltaic are combined in form of a park or at the local level. They are almost built separately and sometimes even seen as competition. However, this is according to the results of the work a mistake, because the shading caused by the rotor blades and towers of the wind- turbines only pulls losses for the energy production of one to two percent. In addition, through the synergy effects (cap. III), the power supply cable is less loaded than would be the case when both technologies would be considered separately. If the extremely rare event occurs that both power plants deliver their full power, the flow of energy can be limited to 60% of the peak performance. Nevertheless, only yield losses of three to four percent occur. In addition, the power supply cable must not be dimensioned higher. The losses dependents on the ratio of installed capacity. If there is a 1:2 ratio of wind power to solar, it comes to the losses above. If there is a ratio of 1:8, the losses are only 10% [11].

## III. SYNERGIEEFFECTS AT THE COMBINATION OF WIND AND PHOTOVOLTAIC

By the combination of wind-turbines and PV-systems, the generation can be made more uniform due the low simultaneity of the production of energy of both technologies. In Figure 1 (top) the generation of a PV-system and a wind- turbine, as well as their combination (bottom) are plotted in the frequency domain (the frequency converted equivalent in days to get a better description). The producer profiles were subjected to a Fourier analysis. So the most striking behaviour of the both technologies can be determined and graphically displayed. When you install a photovoltaic system, the solar radiation repeats with a daily peak at midday (see above Figure 1, mark No. 2 green plot), so you need a daily-storage to save the total produced energy. And so the lulls at times without irradiation, mostly at night, are bridged. The cyclical behaviour of a wind power plant in northern Germany exhibit significant differences compared to a photovoltaic-system. It dominates an all 33 days recur behaviour (Figure 1, mark No.4, above, black plot), followed by a weekly recur behaviour (Figure 1, mark No.3, above, black plot), which is typical for the presence of a low pressure area. When both technologies (Figure 1 bottom) combined in equal parts, especially the wind power profile can be abraded. The all 33 days recurring dominant cycle could be abraded by the superposition of the photovoltaic system (Figure 1, mark No.4, below, black plot). The now dominant behaviour is that of a daily-storage. Nonetheless, trends for a weekly-storage (Figure 1, mark No. 3, bottom, black plot) are still given, albeit in much lesser extent. The behaviour can be further improved by optimal distribution of production between PV and wind- power. This effect is discussed in Chapter V on a concrete example.

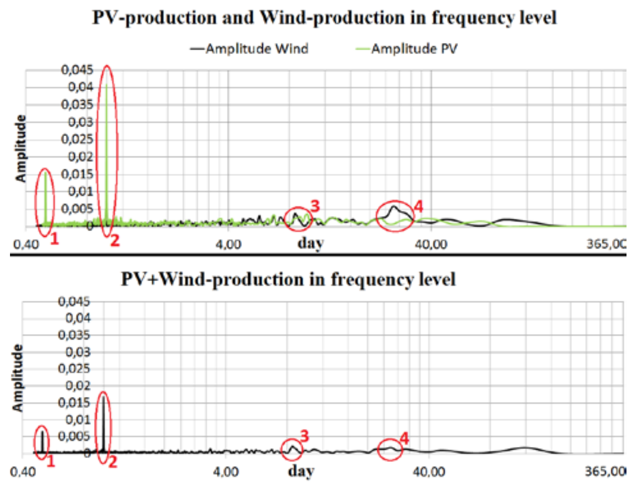


*Figure 1: Cyclic behaviour of a wind-turbine, photovoltaic-system and theirs combination, accrue by a Fourier transformation of the producer profiles*

In addition the production behaviour can be represented by the degree of self-sufficiency of two example systems with respectively summarily same consumption as production and a 100% generation by photovoltaic or under the use of a 100% generation by wind-power. The self-sufficiency is shown in Figure 2, on the top: 100% generation by PV and the lower part: 100% generation by wind-power. Figure 2 shows a waterfall chart, on the x-axis the day of the relevant year is shown, the y-axis indicates the corresponding time and the colour scale indicates the current level of self-sufficiency.

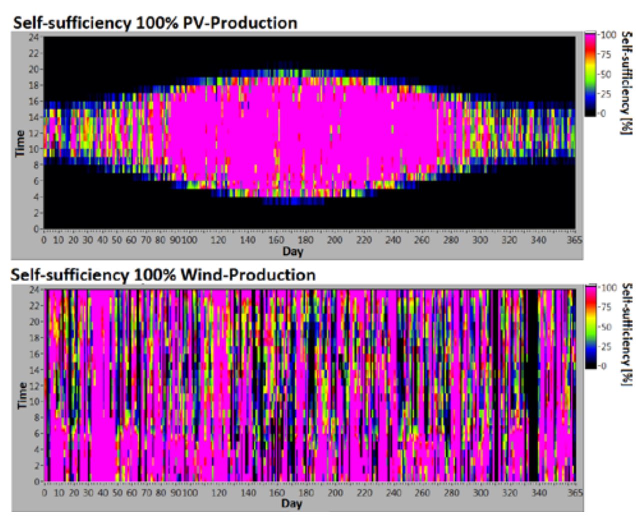


*Figure 2: Self-sufficiency in form of a waterfall diagram, above a 100% generation by PV, below 100% generation by wind-power, created by a simulation*

In the case of 100% generation by PV, the diagram clearly shows, that the self-sufficiency falters seasonal. At times without sun (black area) the self-sufficiency is zero. In the case of generation by100% wind, a cyclical behaviour, with repetitive spikes where a 100% self-sufficiency can be achieved, occur. In addition, the production is relatively seasonal independent. In the area of day 335 occur, a longer period with a self-sufficiency rate of 0%, cause of the to insufficient wind speeds, so that wind turbines could not generate energy.

## IV. DESCRIPTION OF THE INVESTIGATION AND EVALUATION

### A. *Description of the studied commune*

In the existing commune in northern Germany, wind-turbines and photovoltaic-systems are installed. The distribution is in Table 1.

*Table 1: Installed capacity, annual energy yield and specific yield*

| Technologie | installed power [MW] | annual energy generation [MWh/a] | specific yield [MWh/MW] |
|---|---|---|---|
| Windpower | 42.53 | 84,252.24 | 1,9812 |
| Photovoltaic | 6667 | 6,315.6 | 9,4730 |

The total installed capacity amounts to 49.2MW. Here, 86.4% accounted on wind power (42.53 MW) and 13.6% (6.67 MW) on photovoltaic. There are producer profiles available from the year 2009. The consumption can be assumed to 35,000MWh/a.

### B. *Economic-paramters*

For the economic investigation of the various system variants, a static economic calculation is conducted, this refers to an investment term of 20 years and based on the same behaviour for the producer and consumer files over the time period. Table 2 shows the inputs for the economical investigation.

*Table 2: Parameters for the economical investigation*

| plant component | sort | | unit of measurement |
|---|---|---|---|
| wind-turbine | investment costs | 1384 [4] | €/kW |
| photovoltaik-plat | investment costs | 1000 [5] | €/$kW_p$ |
| inveter | investment costs | 99 [1] | €/$kW_p$ |
| storage | investment costs | 440 [6] | €/kWh |
| storage-aid | Förderungssumme proz. | 0.3 [7] | p.n. |
| max storage-aid | Förderungssumme | 600 [7] | €/kWh |
| operational costs photovoltaic | running costs | 10 [9] | €/kW |
| operational costs wind | running costs | 25.45 [10] | ct./kW |
| operational costs storage | running costs | 0 | €/kWh |
| electricity costs | running costs | 29 [8] | ct. |
| feed-in photovoltaic | running income | 9.19 [3] | ct. |
| feed-in wind | running income | 8.87 [2] | ct. |
| calendar endurance storag | solid | 20 [6] | a |
| numbers of circle storage | solid | 5000 [6] | - |
| investment term | solid | 20 | a |

## V. SIMULATION AND EVALUATION

This chapter includes all realized simulations and the evaluation of their results. For this, the chapter is divided into several sub-chapters.

- Simulation of the existing system
- Existing system extended by a storage
- Existing system self-sufficiency optimization by optimal distribution between installed wind-power and PV
- Existing system self-sufficiency optimization by optimal distribution between installed wind-power and PV under the influence of a storage
- Simulation of the optimal storage placement within the commune

### A. *Simulation of the existing system*

In this chapter, the existing plant with its parameters from the Caper IV A. simulated. There is still no battery storage. Figure 3 shows the current self-sufficiency of the community. The Figure is coined by the behaviour of the wind-turbines, there are repetitive peaks and dips aroused by the corresponding cyclically occurring low pressure areas (see Chapter III.) which can explained by the corresponding intensity of the wind. The behaviour of the PV-systems (see Figure 3) is also clearly visible, towards summer there is an increase of self-sufficiency and towards the winter there is a decrease (yellow area in the centre of the figure). The average self-sufficiency based on the year is 77.55%. Energy must only be consumed from the parent HV-grid in the case of that the generated energy at the time of the energy demand is insufficient

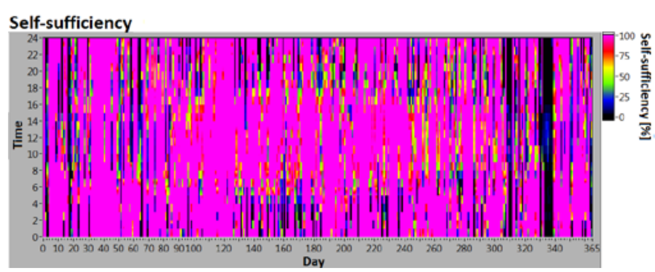


*Figure 3: Self-sufficiency of the existing plant based of a simulation. On the y-axis the time in hours is plotted, and on the x-axis the day of the year. The colour scale indicates in each case the height of the current self-sufficiency level*

The balance of the costs and benefits of the system is shown in Table 3. The largest income in the balance sheet is saving of costs in the demand of energy. This specification refers of an investment term of 20 years. Electricity production costs added up to 6.17 cents/kWh.

*Table 3: Balance of costs for the existing system based on the economic parameters in Table 2*

| Balance of costs | exisiting system |
|---|---|
| **cost** (p.a.) | |
| photovoltaic costs | 369.852 € |
| wind costs | 2.943.130 € |
| storage costs | 0 € |
| costs demand of energy | 2.277.771 € |
| **sum costs** | **5.590.753 €** |
| **use** (p.a.) | |
| income PV feed | 382.037 € |
| income wind feed | 5.256.700 € |
| income saving energy demand | 7.872.280 € |
| **sum use** | **13.511.017 €** |
| **profit** | **7.920.264 €** |
| **electrical production costs** | **6,17 ct/kWh** |

From current perspective, compared to the time of construction of the existing systems and to the associated energy costs and feed-in tariffs, the system could still operate economically. The system is still economic, cause of the price for the supply of energy increased continuous and the cost of the components for the production decline steadily [8] [12].

### B. *Existing system extendes by a battery storage*

This examines the impact of a battery storage to the existing system from Chapter V. A. The investigation should show how big a storage must be chosen to make the commune 100% self-sufficient from a network operator. For the investigation a NAS-battery is used, as this has been established for applications over 1MWh on the market. The max. DOD is 100%. The charging losses are 80% [6]. Figure 4 shows the self-sufficiency. On the x-axis the battery capacity is increased. The range in which the battery capacity is examined is zero MWh to a very large storage of one GWh.

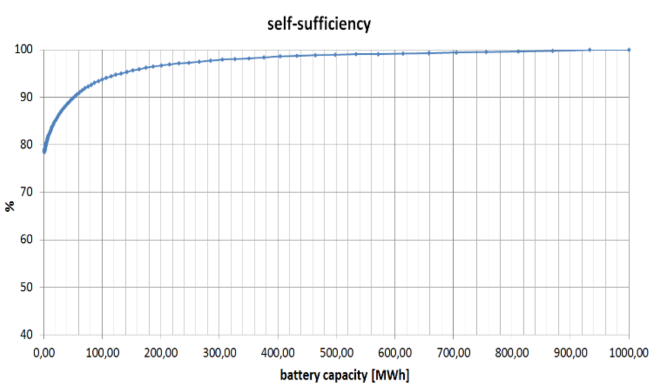


*Figure 4: Self-sufficiency of the existing system extended by a battery storage based of a simulation*

To make the commune independent of a network operator, a battery storage of 973,42MWh is needed. The storage behaviour is shown in Figure 5.

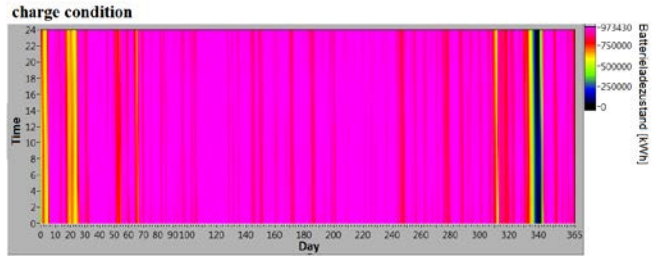


*Figure 5: Charge condition status of the existing plant with a capacity of 973.42MWh resulting from a simulation. On the y-axis the time is plotted, on the x-axis the day of the year is plotted. The colour scale indicates in each case the height of the current level of charge.*

The storage is just as large as necessary to save enough energy to cover the demand of energy at every moment. In this case, the storage must be designed relatively large cause of the much higher installed capacity of wind-.power. Wind-power produced energy in relatively large intervals and the battery has to bridge these gaps. The storage is also often fully charged and can not absorb any more excess energy. A 100% isolation from a parent HV-grid is not ecologically worthwhile. Because significantly more energy is produced than is needed, so even with a self-sufficiency of 100%, there is an overrun on energy. In addition, the utilization of any possible numbers of full cycles (225 per year) is, with an occupancy rate of 10.24 cycles in the simulation period of one year, significantly too low. A corresponding balance costs is presented in Table 4.

***Table 4: Balance of costs of the existing system compared to the existing system extended by a battery storage, according to the efficiency parameters from Table 2.***

| Balance of costs | exisiting system | existing system with energy storage |
|---|---|---|
| **cost** (p.a.) | | |
| photovoltaic costs | 369,852 | 369,852 |
| wind costs | 2,943,130 | 2,943,130 |
| storage costs | 0 | 14,990,700 |
| costs demand of energy | 2,277,771 | 0 |
| **sum costs** | **5,590,753** | **18,303,682** |
| **use** (p.a.) | | |
| income PV feed | 382,037 | 281,856 |
| income wind feed | 5,256,700 | 4,229,690 |
| income saving energy demand | 7,872,280 | 10,150,000 |
| **sum use** | **13,511,077** | **14,661,546** |
| **profit** | **7,920,264** | **-3,642,136** |
| **electrical production costs** | **6.17 ct/kWh** | **20.21 ct./kWh** |

Comparing both balance of costs, it can be clearly seen, that from the today's economic perspective an energy storage could not get a system to 100% autonomic. The cost of electricity per kilowatt hour are, compared to the existing system, much larger by a factor of 3.28. This in turn corresponds to an annual loss of approximately € 3.7 million. In order to use a battery storage so that the economy is still given, the breakeven point of the system is determined with a storage. This is shown in Figure 6.

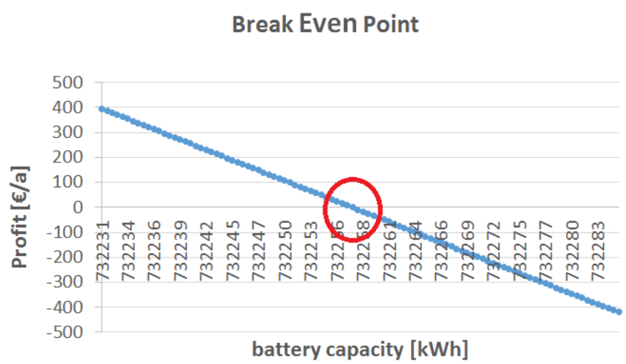


*Figure 6: Break Even Point of the system*

A battery capacity of 732.257MWh could be used. The self-sufficiency would be at the average level of 99.45%, which compared to the higher cost of around € 3.7 million for the storage that brings 100% self-sufficiency, represents a very good result. Such a large storage could prevent the supply of energy from the HV-grid at almost any time. Only in a short period, in which the wind speed is not high enough, so that the wind turbine can generate energy and battery storage is accordingly empty, energy would be obtained.

### *C. Existing system self-sufficiency optimization by the optimal distribution between installed windpower an PV*

This chapter deals with the optimal combination of installed capacity of wind-power to those of photovoltaic. For the simulation all parameters from A. exist. The total installed capacity of 49170kW is maintained and distributed optimally. Specifically, this means that the total installed capacity is distributed to the wind turbines and PV system to get an optimal addition of the production paths. So the production is matched to the energy demand and there is a greater degree of coverage, which brings a higher degree of self-sufficiency. In Figure 7 the self-sufficiency is applied on the relationship between the installed capacity of wind-power (left on the x-axis is equal to zero) and PV (right on the x-axis is equal to zero).

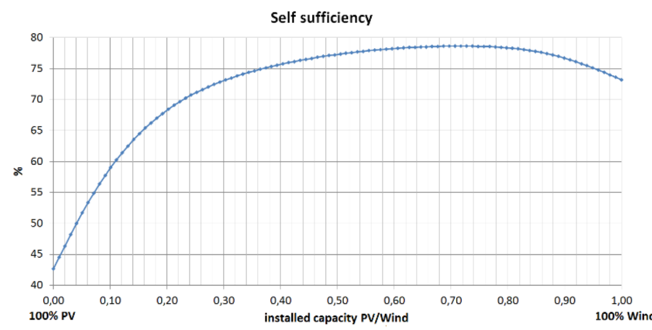


*Figure7: Self-sufficiency applied on the relationship between the installed capacity of wind-power (left on the x-axis is equal to zero) and PV (right on the x-axis is equal to zero).*

The ratio of the installed capacity between wind-power and PV, at the existing system, is already relative well, so there is only a small increase in the degree of self-sufficiency possible. The degree of self-sufficiency would increase to a value of 78.66% (absolute increase 1.12 percentage points), if the installed capacity would redistributed on a level of 71.35% wind-power and 28.65% PV. So the annual energy yield is distributed in 16.1% PV energy and 83.9% energy by wind-power. This corresponds to annual energy yields of 69,499,017MWh/a for the installed wind-power and 13,340,583MWh/a for the installed PV systems. The total annual energy yield would fall to around 8.5% to 82,839,6 MWh/a. The annual energy yield increased because of the higher installed capacity of PV, because the specific yield is lower than the specific yield of wind power. The annual energy yield falls, because of the higher installed capacity of PV, the specific yield of PV is lower than the specific yield of wind power. Associated with this, there is also a decrease in the feed into the grid and thus to the profit. The corresponding balance of costs is plotted below.

***Table 5 : Balance of the existing system and of the existing system with optimized distribution between wind-generation and generation by PV, according to the efficiency parameters from Table 2.***

| Balance of costs | exisiting system | existing system with optimal distribution |
|---|---|---|
| **cost** (p.a.) | | |
| photovoltaic costs | 369,852 | 781,136 € |
| wind costs | 2,943,130 | 2,427,770 |
| storage costs | 0 | 0 € |
| costs demand of energy | 2,277,771 | 2,165,290 |
| **sum costs** | **5,590,753** | **5,374,196** |
| **use** (p.a.) | | |
| income PV feed | 382,037 | 905,865 € |
| income wind feed | 5,256,700 | 4,031,330 |
| income saving energy demand | 7,872,280 | 7,984,710 |
| **sum use** | **13,511,077** | **12,921,905** |
| **profit** | **7,920,264** | **7,547,709** |
| **electrical production costs** | **6.17 ct/kWh** | **6.48 ct./kWh** |

The profit would be reduced by € 372,555 compared to the existing plant. Such an insignificant increase in the degree of self-sufficiency makes for economic reasons rather no sense.

*D. Existing system self-sufficiency optimization by optimal distribution between installed wind-power and PV under the use of a battery storage*

This chapter also deals with the optimal combination of installed capacity between wind-power and photovoltaic systems under the use of a battery storage similar to the size in B. The aim is, through a redistribution of the ratio between the installed capacity of wind-power and PV, to get a better level of self-sufficiency and so a smaller battery is needed. In Figure 8, the self-sufficiency level is plotted over the battery capacity, the individual plots gives the ratio between the installed capacity of wind-power and PV.

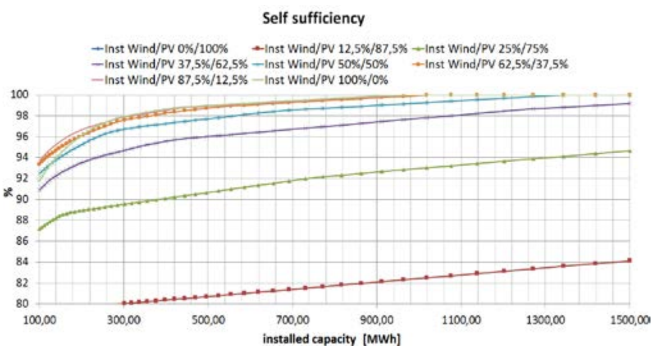


*Figure 8: Self-sufficiency of the existing system with optimal distribution between wind generation and generation by PV, connected to a battery storage, based on a simulation*

Figure 8 shows that the battery storage could be reduced to 946.51MWh when a full supply from wind-power prevails. Thus, a significant shift of the optimum ratio between wind and PV can be seen under the use of a battery storage. The main reason for this, is that the specific yield of wind turbines at the location is round about 2.1 higher than that of the PV- systems and so the battery storage could be better utilized. Without a battery storage the optimal ratio (see C.) was at a level of 71.35% installed capacity by wind-power and 28.65% by PV.

*E. Storage placement within the commune*

This chapter deals with the optimal storage placement within a commune. For the study the commune in the north of Germany from A. is used as a basis. Three scenarios were investigate.

- Storage placement at the distribution station
- Storage placement at the producers
- Storage placement at the consumers

The investigated grid is a 20kV medium-voltage network, which is fed by four distribution station from the higher-110kV HV-network. There are wind-turbines, PV-systems, as well as consumer in according to Chapter IV A. The aim of an optimal placement is to keep the losses on the cables and wires as small as possible and to optimize the load flow. The capacity of the storage is just as large as necessary that it theoretically should not come to a demand of energy.

In Figure 9 the individual scenarios are compared. There are investigated the feed into the grid, the demand from the grid and the average load of the utilities.

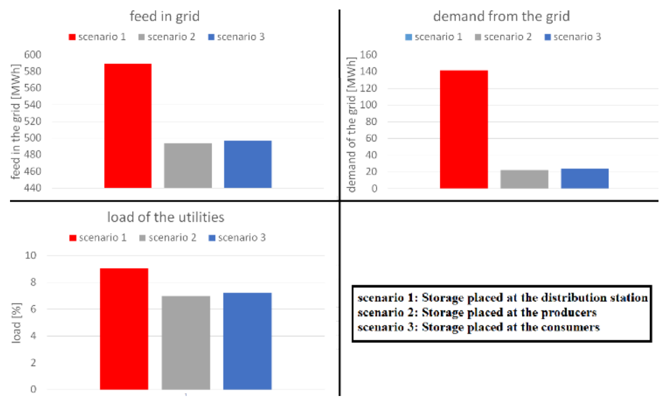


*Figure 9: The feed into the grid, the demand from the grid and the average load of the utilities*

A storage placement at the producers is connected with the lowest losses and the uniform load flow. The demand flank is the smallest of all scenarios, which is close-by the desired aim of a 100% self-sufficient. For this scenario the load flow is optimized. The battery capacity must adapted to the effective power the producer.

## VI. SUMMARY

If a battery storage should be used, the best option is to use a sodium-sulfur battery. For use in areas >1 MWh Sodium-sulfur batteries have become established and proven. To achieve a 100% self-contained power supply, a battery storage with capacity of 973.42MWh would be required. From the economic point is such a large storage very inefficient. In addition the commune never could be completely independent from the network operator, due to its three times larger production in relation to their consumption. To use the remaining excess energy, the energy should be fed in the parent HS network. Under the use of a cheaper battery storage, so that economic viability is given, hath an average self-sufficiency of 99.4% and a capacity of 732.25MWh. This corresponds to a battery capacity of 97.76kWh per household (see Chap. V.B.).
By optimizing the existing system by redistribution of installed capacities between PV and wind, the self-sufficiency of the system could be only minimally increased. A redistribution of installed capacity to 71.35% by wind power and 28.65% by PV could increase the self-

sufficiency by 1.12 percentage points. With this redistribution there is a reduction in the annual energy yield. Such a redistribution would not make sense, especially not from the economic view (see Chap. V. C.).

If the existing plant is extended with a battery storage and then optimal distribution between wind-power and PV is investigated, the optimal ratio of installed capacity shifts to a full supply from wind-power. In addition, the battery capacity can be reduced by 26.9MWh to 946.52MWh, and a 100% self-sufficient supply is still given (see Chap. V.D.).

To ensure the optimal placement of one or more battery storage within the present commune, a placement at the generating facilities would be the best choice. This is partly the case because the excess energy can be directly stored where it is generated, and so the cables and lines are not extra loaded. And so the load transfer at the distribution station would be homogenise because the lines could be used optimally and so the incur of losses is lesser. The load flow would be optimized. The battery capacity must adapted to the effective power of the producers. (see Chap. V.E.).

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