Development of an integral climate-neutral energy concept for the village of Rodder

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***Abstract* — In the project, different integral climate-neutral energy concepts for the village of Rodder are presented. The aim of the project is to analyse possible climate-neutral energy supply concepts in order to decarbonise the electricity, traffic and heat sectors. The project has shown that a significant expansion of photovoltaics in the distribution grid is only possible with battery storage. In addition, an photovoltaic ground mounted system or a wind power plant with coupled battery storage is needed to achieve a autarky rate of 100%. For a climate-neutral supply of the heating sector, a combination of solar heating, a wood chip heating plant and buffer storage is a possible solution.**

1 Introduction

In order to advance the climate-neutral transformation of the energy system and the associated decarbonisation, renewable technologies must be used. According to the requirements of the Federal Climate Change Act, Germany should be climate neutral by 2045 [1]. This requires the significant expansion of renewable energies and storage capacities.

Using the village of Rodder as an example, the project shows how the energy transition can succeed in the electricity, transport and heating sectors. For this purpose, various climate-neutral energy supply concepts are presented. These can contribute to creating climate-neutral alternatives for the reconstruction of the energy infrastructure destroyed by the flood disaster.

2 Village of Rodder

The village of Rodder is geographically located in the Eifel in the district of Ahrweiler and belongs to the municipality of Adenau. The village of Rodder is rural and surrounded by fields and forests. The area of the municipality is 6.38 km². In 2021, the population was 237. Rodder is predominantly characterised by single-family houses. There is also a carpenter's workshop, a restaurant and two farms. There are no other large industrial enterprises. [2]

Currently, 19 photovoltaic (PV) systems are installed on house roofs in Rodder [2]. The total annual electricity consumption is not known. The heat supply of Rodder is currently largely generated by decentralised heat generators on a fossil basis (oil & liquid gas). Sustainable heat generators such as heat pumps or wood heating systems exist in isolated cases. A heat infrastructure, such as gas pipelines or connection to a district heating network, does not exist. [3]

3 Methodological procedure

The project examines how the electricity, transport and heat sectors in Rodder can be decarbonised and how a possible climate-neutral supply can succeed. The methodological procedure for the analysis of the individual sectors is presented below.

As part of the project, an on-site visit to Rodder was organised, followed by a meeting with the local mayor, Mr Jüngling. Contact was also made with the distribution grid operator Westnetz and the engineering office ibs Energie GmbH.

3.1 Electricity sector (incl. electromobility)

For the analysis of the electricity sector, 20 different load profiles with different consumption behaviour were created with the LoadProfileGenerator of the Chemnitz University of Technology [4]. Charging profiles for electromobility are integrated into the created load profiles. The electricity consumption by electromobility is taken into consideration in the created load profiles. Two different energy behaviours (energy intensive and energy saving) are assumed. For the project, an electrification of private mobility through electromobility was assumed. Other possible climate-neutral forms of propulsion such as the hydrogen-based fuel cell were not taken into consideration.

The annual electricity consumption of Rodder resulting from the created load profiles is 597 MWh. This corresponds to an average electricity consumption of a household of 5,000 kWh per year (including electric mobility). The annual electricity consumption resulting from the load profiles can be found in the attached report.

The analysis of a climate-neutral supply of the electricity sector is carried out in two steps. First, the distribution grid (400 V) and then the medium-voltage grid (20 kV) are examined. In a first step, the possible expansion of photovoltaic systems on the roofs of houses is considered in the distribution grid. In this context, the resulting effects on the electricity grid with regard to voltage deviation and line and transformer utilisation are examined. In addition, various scenarios and operating modes of battery storage for photovoltaic systems are presented.

In a second step, it is examined how Rodder can be supplied with climate-neutral energy at every hour of the year. Based on the analysis of the possible expansion of PV on the house roofs in the distribution grid, possible energy supply concepts are finally presented. In the process, the addition of a PV ground-mounted system and a wind power plant in combination with a coupled battery storage system in the medium-voltage grid is investigated.

The starting point for the analysis of the distribution grid is the electricity grid plan of Rodder, which was provided by the distribution grid operator Westnetz. The electricity grid in Rodder is an open ring grid with three transformers (0.25 MVA) and mainly overhead lines.

The effects of the expansion of photovoltaics on the distribution grid are simulated with the python-based open source tool PandaPower. Three different PV generation profiles with different nominal powers and alignments were used for this purpose. In addition, an Excel tool was created to simulate the different operating modes of the battery storage systems.

A Python-based energy system model was developed in PyPSA for the analysis of the PV ground mounted plant and the wind power plant in the medium-voltage grid. The model can be used to simulate the required plant capacity of the renewable energies and the storage capacities depending on the annual autarky rate.

An explanation of the detailed procedure, the representation of the power grid, the load and generator profiles used, the structure of the Excel tool and the Python code for PandaPower and PyPSA can be found in the attached report.

3.2 *Heating sector*

For the analysis and concept development of the climate-neutral heating sector in Rodder, the heat consumption was determined. In order to cover the thermal consumption, two climate-neutral heat supply concepts were developed. In these, a local heating grid in Rodder is considered, to which every consumer in the village is connected:

1. Scenario: Solar heating + seasonal storage

2. Scenario: Solar heating (base load supply) in combination with a wood chip heating plant (peak load) and a buffer storage.

The heat consumption was determined on the basis of a survey sent to the municipality by the mayor in cooperation with an engineering office, in which the heat generator and the corresponding fuel consumption had to be specified. Using the average outdoor temperatures from weather data, the heating limit temperature and the diurnal variation of heat loads according to VDI 2067, sheet 7, a heat load profile for Rodder is created in Excel. [5, 6]

The future transmission heat losses of the transport pipes of the local heating grid are also determined. These are distributed equally over the heat load profile of the village. Standing losses are determined for the heat storage and used as a factor in the calculations.

With the help of a self-created Excel tool, the generator load profile of an solar heating ground mounted system is determined. For this purpose, the solar insolation data in Rheinland-Pfalz is imported and calculated with the efficiency of a vacuum tube collector (designed for heating grids). For the heating grid, 75°C and 50°C are assumed as the average flow and return temperatures, resulting in a constant temperature difference of 25°C as an annual average.

A Python-based energy system model is being developed in PyPSA for the scenario analysis of the open-space solar thermal system in combination with a seasonal storage system. The model can be used to simulate the required system power of the heat generators and the storage capacities depending on the annual autarky rate.

An energy system model is developed in Excel for the second scenario solar heating ground mounted system with daily storage and wood chip heating plant. The model can be used to simulate the required system power of the wood chip heating plant after specifying the solar heating power and the storage size.

The detailed procedure for creating the heat load profiles and generator load profiles, as well as the structure of the Python code for PyPSA and the Excel model can be found in the attached report.

4 Result electricity sector (with electromobility)

4.1 *Simulation in PandaPower (distribution grid)*

As explained in chapter 3.1, the aim of the simulation with PandaPower is to investigate the maximum possible expansion of photovoltaic systems on the roofs of houses and the influence of electromobility without causing a local grid overload. Three different scenarios are analysed and evaluated.

In the first scenario, it is assumed that there is no battery storage for photovoltaic systems in the houses. There is a PV surplus feed-in.

In the second scenario, battery storage with conventional operation is considered. If there is PV overproduction and self-consumption is covered, the storage is charged. When the storage is full, grid feed-in takes place.

In the third scenario, the operating mode of the battery storage is adapted to optimise the grid. Here, the maximum feed-in of the PV system is limited and the battery storage is only charged when this limit is reached. Finally, both storage modes are compared with each other and a recommendation is given.

In each scenario, reactive power management of the photovoltaic systems is taken into account. With Q(U) regulation, either inductive and capacitive reactive power is provided depending on the grid voltage.

Whether a critical grid condition exists is determined using reference values. In the further course, it is assumed that the voltage of ± 6% must be observed. A utilisation of 70% or rather 50% in normal operation is aimed at for the transformer and the electricity lines. A detailed explanation of the reference values can be found in the attached report. [7, 8]

4.1.1 *Scenario 1 (no battery storage)*

The simulation with PandaPower shows that in the first scenario without battery storage, photovoltaic systems (~540 kWp) can be installed on 50% of the house roofs in the distribution grid without causing a grid overload. Figure 1 shows the voltage over the year for each grid bus. It can be seen that even taking electromobility into consideration, the voltage deviation downwards can mostly be observed. On one point, the grid voltage drops below the critical value of -6% (red circle) due to a high load.

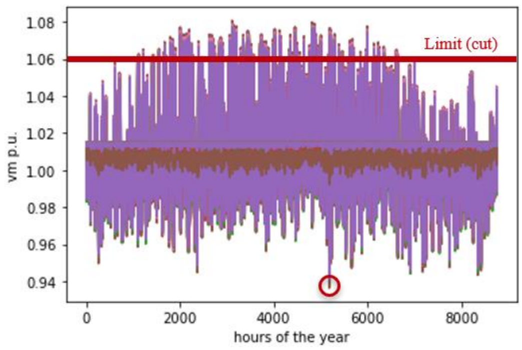

Figure 1: Voltage band without battery storage. Due to curtailment, 18.9 MWh are lost annually. [own illustration]

In the future, however, demand response could shift peak loads and prevent excessive voltage reduction. In principle, it can be stated that the use of electric mobility does not overload the low-voltage grid. This is due to the load profiles used with the different charging behaviour.

The voltage deviation upwards, due to PV generation, puts a strain on the power grid, especially in summer. The grid voltage is regularly above the critical value of +6%. Since no battery storage is taken into account in this scenario, the PV systems must be regulated when the voltage limit is exceeded (red line). Due to the curtailment of the PV plants, 18.9 MWh per year are lost. This corresponds to 2.85% of the annual production. The energy losses due to curtailment could be reduced by demand response if flexible consumers such as washing machines or charging e-cars are used during times of high PV production.

The maximum load of the transformer is 110%. Since the power grid is an open ring network, if one transformer is overloaded, the circuit breaker can be opened and the second transformer can take over the load for a short time. The maximum utilisation of the electricity lines is 68%. The values for the transformer and electricity line utilisation refer to when the PV systems are not regulated. It can be assumed that the utilisation will decrease with corresponding deregulation. The result diagrams for the transformer and the electricity line can be found in the attached report.

4.1.2 *Scenario 2 (conventional battery storage)*

In this scenario, battery storage for photovoltaic systems with a simple and conventional mode of operation is considered.

Figure 2 illustrates the operating mode of a storage with a capacity of 5 kWh for an example day. As soon as there is PV overproduction and consumption is covered, the storage is charged (between 6 and 9 a.m.). When the storage is full, a PV grid feed-in takes place (from 9 am). This operating mode aims to maximize self-consumption and autarky. This operating mode does not relieve the load on the electricity grid, since at maximum PV generation (12 o'clock) the storage is already fully charged. The feed-in peak continues to burden the electricity grid. In the evening, when consumption is greater than PV generation, the storage is discharged again (from 5 pm).

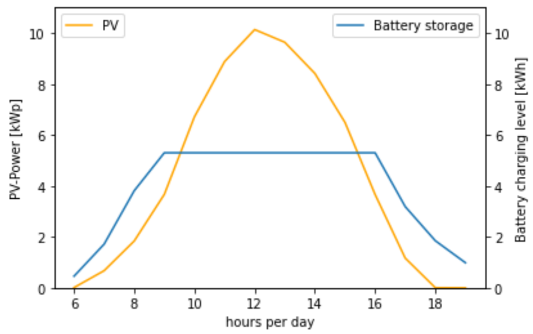

Figure 2: Conventional operation of a battery storage system for a sample day. The storage unit does not relieve the electricity grid. [own illustration]

For the simulation in PandaPower, battery storage with a capacity of 5, 8 and 12 kWh were assumed. In addition, it was assumed that every house with a PV system also has a battery storage system. The detailed allocation of the synthetic load profiles used to the PV generation profiles and the respective storage capacities can be found in the attached report.

The simulation with PandaPower shows that in the second scenario with conventional battery storage, as in scenario 1 without storage, photovoltaic systems (~540 kWp) can also be installed on 50% of the house roofs in the distribution grid without causing a grid overload. Figure 3 shows the voltage over the year for each grid bus. It can be seen that the voltage drop can be reduced by the storage systems and that no critical grid state with a voltage of -6% occurs.

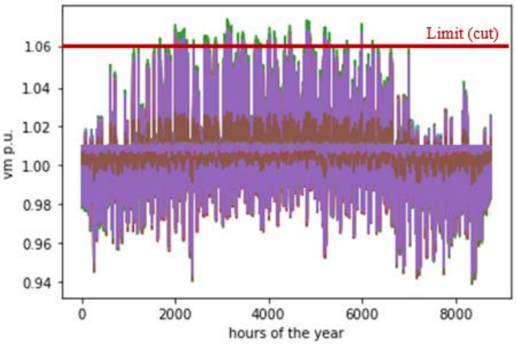

Figure 3: Voltage band with conventional battery storage. The voltage drop can be reduced by storage. Grid relief does not take place with PV feed-in. 12.7 MWh are lost annually due to regulation. [own illustration]

As already explained, the grid is not relieved by the conventional operation of the storage facilities. The feed-in peaks at midday continue to exist. This causes the grid voltage to rise to over +6%, especially in summer. Despite the inclusion of battery storage, the photovoltaic systems must be regulated when the voltage limit is exceeded (red line). Due to the regulation of the PV systems, 12.7 MWh are lost per year. This corresponds to 1.91% of the annual generation. The energy losses due to regulation could be reduced by demand response if flexible consumers are used during times of high PV generation.

The maximum utilisation of the transformer is 105%. The maximum load of the power lines is 65%. The values for the utilisation of the transformer and the power lines refer to when the PV systems are not regulated. It can be assumed that the utilisation will decrease with corresponding regulation. The result diagrams for the transformer and the electricity line can be found in the attached report.

4.1.3 Scenario 3 (grid-serving battery storage)

In this scenario, the battery storage systems are considered with a grid-serving mode of operation. Figure 4 illustrates the grid-serving mode of operation of a battery storage system for an example day.

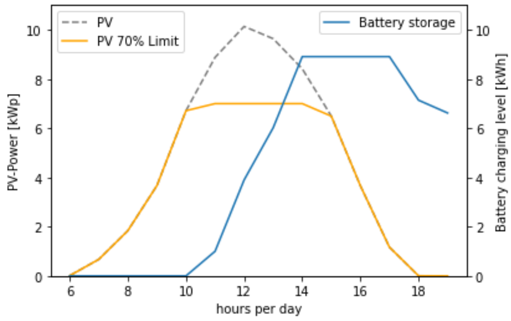

Figure 4: Grid-serving operation of a battery storage system for a sample day. The storage system relieves the grid. [own illustration]

The maximum feed-in power of the photovoltaic system is limited to 70% of the nominal power (P_{Peak}) (yellow curve). The battery storage is only charged when the power of the photovoltaic system reaches the maximum feed-in power. Figure 4 shows that the battery storage is charged between 10 a.m. and 2 p.m. when the feed-in power of the photovoltaic system is at its maximum. As soon as the power of the photovoltaic system drops below the maximum feed-in power of 70% P_{Peak}, grid feeding takes place and the storage unit is no longer charged (from 2 pm). The storage level remains constant until consumption can no longer be covered by the photovoltaic system and the storage is discharged (from 5 pm).

For the simulation in PandaPower, it is assumed that every house with a PV system also has a battery storage system. The detailed assignment of the synthetic load profiles used to the PV generation profiles can be found in the attached report.

The simulation with PandaPower shows that in the third scenario, with a grid-serving mode of operation of battery storage, more photovoltaic systems can be installed on the house roofs in the distribution grid. Due to the grid-serving operation of the battery storage systems, a photovoltaic system can be installed on 75% of the house roofs without overloading the grid. Due to the grid-serving operation of the battery storage systems, 25% more photovoltaic systems can be installed on the rooftops in Rodder compared to scenarios 1 and 2. The installable photovoltaic capacity increases from ~540 kWp (Scenario 1 & 2) to ~810 kWp.

In the simulation with PandaPower, no storage capacities were specified. With the help of an Excel tool, the maximum necessary storage capacity was determined for each consumer load profile in order to limit the maximum feed-in power of photovoltaics to 70% of P_{Peak}. The procedure and structure of the Excel tool can be found in the attached report. Depending on the load profile and generation profile of the photovoltaics, the battery storage must have a capacity of between 5 and 21 kWh in order to limit the power of the photovoltaics to 70% of P_{Peak}.

Figure 5 shows the voltage over the year for each grid node. It can be seen that the grid is relieved by the grid-serving operation of the storage. There is no critical condition with a voltage deviation of ± 6%. The battery storage systems cap the feed-in peaks of the photovoltaic systems. As in the first two scenarios, electromobility does not lead to an overload of the electricity grid. In principle, however, demand response could also relieve the electricity grid by using flexible consumers (e.g. e-mobility) at times when PV generation is high.

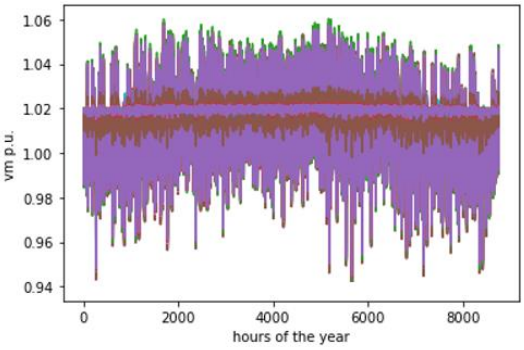

Figure 5: Voltage band with grid-serving battery storage. The storage systems relieve the power grid and no critical grid condition occurs due to e-mobility or photovoltaics. [own illustration]

As already explained in chapter 3.1, reference values are used to assess whether a critical grid condition exists. In addition to the voltage deviation, the line and transformer utilisation is also determined in the simulation carried out with PandaPower. Figure 6 shows the utilisation of the transformers. Transformers 0 and 1 are located in Rodder. Transformer 2 only supplies a farm outside the village.

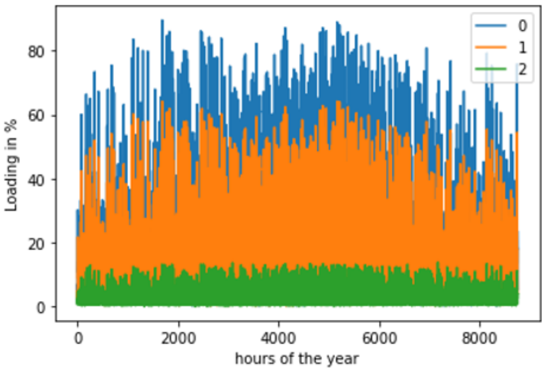

Figure 6: Transformer utilisation with grid-serving storage. The storage reduce the load from PV generation [own illustration]

The load of the transformers is determined by the apparent power. The apparent power is calculated according to Pythagoras from the active power and the reactive power. The reactive power depends on the power factor cos(φ). In the simulation, a cos(φ) between 0.9 and 0.95 was used for all loads. For the photovoltaic systems, an inductive cos(φ) =0.95 was used. In order to determine the apparent power of the transformer, the active power of the lines must be summed from the back to the front. [9]

Figure 6 shows that transformers 0 and 1 are most heavily loaded. According to grid planning restrictions, a transformer should only be utilised to 70% in normal operation to have a buffer for short-term peaks. Transformer 0 is located in the middle of the village and has the highest load. For a short time, transformer 0 is loaded to over 70%. However, this is not a critical grid condition, as the utilisation above 70% occurs at worst-case times and the utilisation does not exceed 100% at any time during the year. Due to the open ring grid, if transformer 0 is overloaded, the circuit breaker can be opened and transformer 1 can take over the load for a short time. Transformer 2 has the lowest load, as it only supplies a farm outside the village and no other loads or generators are connected. It can be stated that in the scenario with grid-serving operation of the battery storage, the transformers are not overloaded and no critical grid condition occurs.

In addition to the voltage deviation and the transformer utilisation, the utilisation of the electricity lines is also taken into account. According to grid planning restrictions, these should not be utilised by more than 50% during normal operation in order to have a buffer for short-term peaks. The electricity lines are designed for the nominal current. Figure 7 shows the utilisation of the electricity lines.

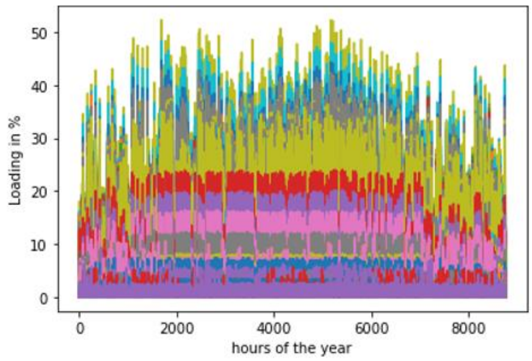

Figure 7: Utilisation of electricity lines with grid-serving storage [own illustration]

It can be seen that the electricity lines are partly utilised to over 50%. However, this is not a critical grid condition, as the utilisation above 50% takes place at the worst case times and the utilisation is not above 100% at any time during the year. The maximum current on the lines is lower than the nominal current for which the cables are designed.

In principle, it can be summarised that the grid-serving mode of operation of the battery storage relieves the electricity grid. Compared to the scenarios without battery storage and with conventional battery storage, 25% more photovoltaic systems can be installed on the roofs of houses in Rodder with the grid-serving mode of operation. The installable photovoltaic capacity increases from ~540 kWp (Scenario 1 & 2) to ~810 kWp.

4.1.4 Comparison of battery storage operating strategy

In the previous chapters, two different operating modes of battery storage in combination with photovoltaics were presented and the effects on the electricity grid were investigated. Especially in rural areas, the full PV potential cannot be used due to shortages in the distribution grid. It has become clear that the conventional mode of operation (scenario 2) does not relieve the electricity grid, as the storage is fully charged when the maximum PV generation is available. However, if the battery storage is charged at times when the maximum PV generation is present, the feed-in peaks can be capped and the electricity grid is relieved. Due to the grid-serving mode of operation, more photovoltaic systems can be installed and grid expansion in rural areas can be avoided or is not necessary until later.

For most homeowners, maximizing self-consumption is most important, as there are economic advantages to using PV electricity for self-consumption. Maximizing self-consumption and increasing autarky is economically advantageous because the grid purchase costs are higher than the feed-in tariff. The study in the project showed that the conventional operation of battery storage and the associated increase in autarky does not relieve the distribution grid.

On the other hand, battery storage can be operated in such a way that the distribution grid is relieved. In this case, however, the increase in autarky is not prioritized. There is therefore a contradiction between the two operating modes. On the one hand, battery storage should increase autarky. On the other hand, battery storage should be operated to serve the grid. Therefore, a combination of the two operation modes would be recommended. In this case, the operator has the benefit of the improving the self-consumption of the PV system and the grid operator benefits from reduced impact on the grid.

Basically, two intelligent hybrid operating modes are possible. The first intelligent operating mode focuses on autarky, but feed-in is also considered. In this operating mode, the storage is kept as full as possible. But the required capacity for the next day's PV generation is fed into the grid by a certain discharge. This mode requires an estimate of the next day's surplus PV generation. The PV generation for the next day is forecast and the required storage capacity is kept free. In this way, the autarky is increased and the PV feed-in peaks are fed into the storage. If the forecast excess PV generation for the next day is not accurate, energy can be lost if there is not enough storage capacity. [10]

The second intelligent operating mode focuses on feed-in, but autarky is also considered. In this operating mode, the storage is discharged as much as possible. But the next day's consumption is left in the storage. This mode requires an estimate of the next day's consumption. The consumption for the next day is predicted and the required consumption is left in the storage. In this way, energy losses are less likely, but autarky may decrease if there is not enough energy in the storage due to a weak forecast. [10]

The first operating mode, where the focus is on autarky, will probably be more relevant for most storage operators and homeowners. Therefore, it is recommended to adapt scenario 3 presented in chapter 4.1.3. The storage facilities will still be used to relieve the grid, but the hybrid operating mode will also take autarky into account.

4.2 Energy system model in PyPSA

The photovoltaic systems on the roofs of the houses only generate enough electricity in theory to supply Rodder with climate-neutral electricity all year round. Sufficient electricity from renewable energies must be available at all times of the year. Therefore, this chapter presents possible solutions for a climate-neutral supply of the electricity sector.

The results presented in the following are based on the scenario presented in chapter 4.1.3 (~810 kWp PV on the roofs and grid-serving operation of the storage). This storage operation mode does not prioritize autarky. If the hybrid storage operation mode explained in chapter 4.1.4 were assumed, the results would probably be different.

The annual electricity consumption of Rodder assumed in this project, including the use of electric mobility, is 597 MWh (chapter 3.1). From the difference between consumption and PV generation and the charging profiles of the battery storage, the load that cannot be covered by PV on the house roofs can be determined at every hour of the year (Figure 8).

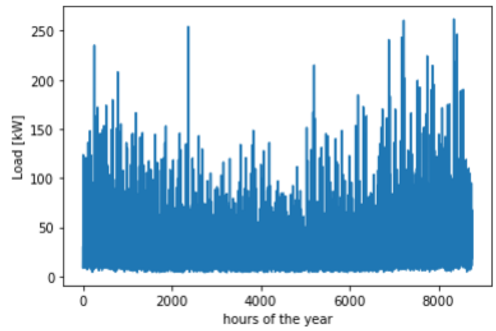

Figure 8: Consumption that can't be provided by rooftop PV and must be served by other renewable producers. Especially in winter, a higher amount of electricity needs to be produced. [own illustration]

Subtracting the PV generation on the house roofs, 329 MWh must be provided annually from other renewable generation so that Rodder is supplied climate-neutrally at every hour of the year. More electricity must be produced, especially in winter.

In the following, various options are presented as to how Rodder can be supplied in a climate-neutral way at any hour of the year. First, an PV ground mounted system is coupled with a battery storage system. Then a wind power plant is coupled with a battery storage system and it is examined how the required storage capacity changes in comparison to the PV ground-mounted system. For this purpose, a Python-based simulation is carried out with

PyPSA. The techno-economic parameters used for the simulation can be found in the attached report.

The possible locations for the PV ground-mounted system and the wind power plant are not investigated in this project.

4.2.1 Determination of the PV ground-mounted system

In a first step, the required PV power can be determined in a balance sheet to generate the 329 MWh. With a specific yield of 1050 kWh/kwp [5], a 315 kWp PV ground-mounted system would theoretically suffice.

Figure 9 shows the results of the simulation. The figure shows the autarky rate depending of different storage sizes. On the horizontal axis, the storage size is shown in relation to the annual average daily consumption.

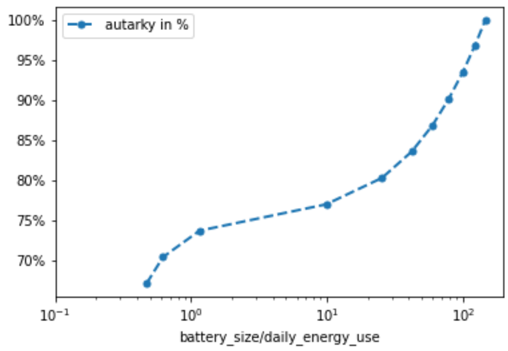

Figure 9: Autarky rate depending of different storage sizes in relation to average daily consumption with a 315 kWp PV system [own illustration]

The autarky rate increases as the storage becomes larger until the storage capacity is approximately equal to that of a day's storage. Afterwards, the autarky rate remains constant as the storage capacity increases. The autarky rate only increases again with a significantly larger storage tank. This effect results from the seasonal variation in PV generation and makes an extremely large seasonal storage unit necessary for 100% autarky. Especially in winter, when there is little PV generation, consumption must be covered from the storage for a longer period of time. To achieve 100% autarky, the battery storage of the PV ground-mounted system must have a capacity 147 times that of the average daily energy consumption. In combination with a 315 kWp PV ground-mounted system, the battery storage must have a capacity of ~ 106 MWh to supply Rodder with climate-neutral energy every hour of the year.

4.2.2 Photovoltaic ground mounted system

In contrast to the previous chapter, no constant PV power is specified in this chapter. The PV ground-mounted system is coupled with a battery storage system.

Figure 10 shows the required PV power and storage capacity depending on the autarky.

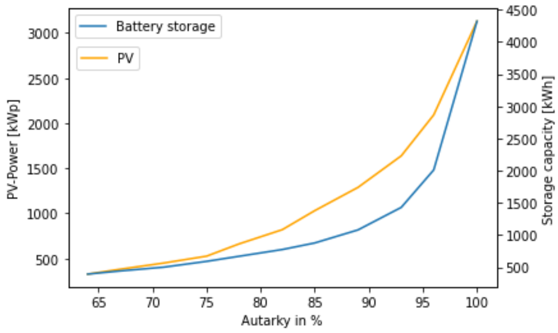

Figure 10: PV power and storage capacity depending on autarky [own illustration]

Figure 10 shows that PV power and storage capacity increase with increasing autarky. Up to an autarky of 75%, the ratio between PV and storage size is approximately one to one. After that, the storage capacity increases faster than the PV power. This is due to the fact that in large-scale projects (> 1 MW) the addition of 1 kWh is cheaper than the addition of 1kWp PV [11]. To achieve 100% autarky, a 3.1 MWp PV ground-mounted system and a 4.3 MWh battery storage system are required. This power and capacity are needed because a climate-neutral supply must also be guaranteed for a longer period of time in winter.

Figure 11 shows the autarky rate for different storage sizes. The following figure shows the different PV powers and storage capacities according to the autarky rate shown in Figure 10.

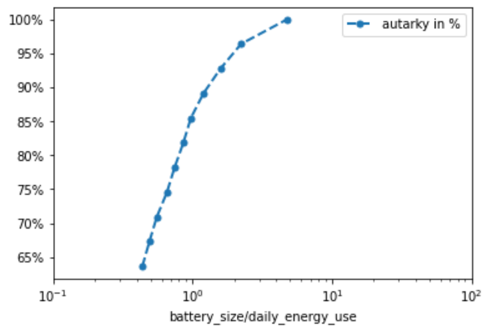

Figure 11: Autarky rate depending on different storage sizes in relation to average daily consumption. The values consider different PV powers and storage capacities [own illustration]

The figure shows that with 3.1 MWp PV and an autarky of 100%, about 5 times the storage capacity is required in relation to the average daily energy consumption. With an autarky of 85%, for example, the storage size corresponds to that of a daily storage.

4.2.3 Wind power plant

In contrast to the previous chapter, this chapter couples a wind power plant with a battery storage system. The effects of operating a wind power plant on the storage capacity required to supply Rodder in a climate-neutral way every hour of the year are shown.

For the simulation, a generation profile of an Enercon E-115 with a capacity of 4.5 MW and a hub height of 120 m is used. The annual energy yield is 8.7 GWh. [12]

If only the consumption shown in Figure 8 (329 MWh) is to be covered, which cannot be covered by PV on the house roofs, a storage facility with a capacity of 540 kWh is necessary to supply Rodder in a climate-neutral way at every hour of the year. Most of the energy generated by the wind power plant is fed into the grid.

The wind power plant generates significantly more electricity than is consumed annually in Rodder. Therefore, the next step is to investigate the necessary storage capacity if no PV is installed on the house roofs and the wind power plant is the only renewable electricity producer. The goal is for the wind power plant to be able to supply Rodder with climate-neutral electricity at any hour of the year without photovoltaics.

If the entire annual consumption (597 MWh) of Rodder is to be covered by the wind power plant, a storage facility with a capacity of 890 kWh and with 340 kW is necessary. Figure 12 shows the autarky rate depending on different storage sizes. On the horizontal axis, the storage size is shown in relation to the annual average daily consumption.

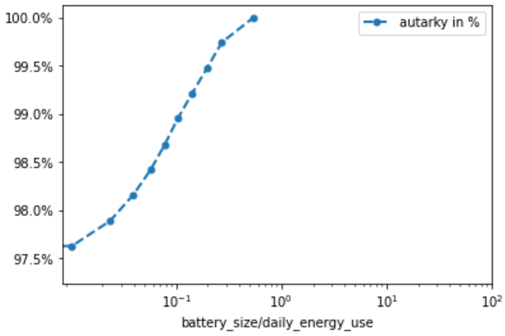

Figure 12: Autarky rate depending on different storage sizes in relation to average daily consumption with a 4.5 MW wind power plant [own illustration]

The figure shows that the wind power plant achieves a high autarky even with very small storage sizes. This is because the wind power plant produces significantly more electricity than is consumed in Rodder. Most of the energy generated by the wind power plant is fed into the grid. To achieve a autarky rate of 100%, the storage coupled to the wind power plant must have a capacity of half a day's storage (Figure 12).

4.2.4 Comparison of the energy system models

This chapter summarises the most important results from the previous chapters. Table 1 shows the required plant capacities and storage capacities to achieve 100% autarky and to supply Rodder with climate-neutral energy every hour of the year.

TABLE 1: REQUIRED POWER AND STORAGE CAPACITIES

Scenario	**Power EE [MW]**	**Storage capacity [MWh]**
PV ground mounted system	0.315	106
PV ground mounted system	3.1	4.3
Wind power plant*	4.5	0.89

* refers to the supply of the total annual consumption (597 MWh) of Rodder

The following figure 13 shows the autarky rate of Rodder for different renewable plant capacities depending on different storage sizes. On the horizontal axis, the storage size is shown in relation to the annual average daily consumption.

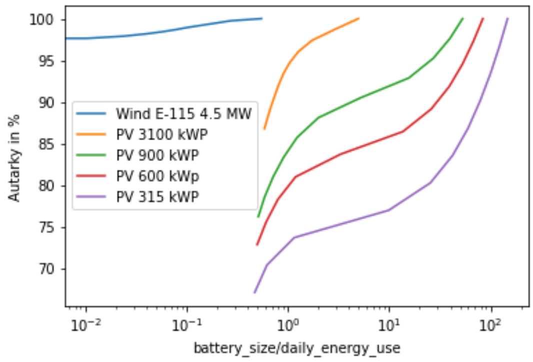

Figure 13: Autarky rate as a function of different storage sizes in relation to average daily consumption for different renewable plant capacities [own illustration]

With increasing renewable system power, the required storage size becomes smaller. For example, for a autarky rate of 100% with 315 kWp PV, a storage with a 147-fold capacity in relation to the average daily energy consumption is required. With 3.1 MW PV, on the other hand, a storage with a 5-fold storage capacity in relation to the average daily energy consumption is required to achieve 100% autarky. The figure also shows that a high level of autarky can be achieved with a wind power plant, even with very small storage capacities. Increasing the storage capacity only leads to a marginal increase in autarky. This is due to the fact that the wind power plant produces significantly more electricity than is consumed in Rodder. Most of the energy generated by the wind power plant is fed into the grid.

5 RESULT HEATING SECTOR

In 2021, a total of 1,760 MWh of heating energy was consumed in the village of Rodder. Based on the determined transmission heat losses in the planned local heating grid, this will increase to 1,977 MWh. Figure 14 shows the concept of the climate-neutral local heating grid developed in the project.

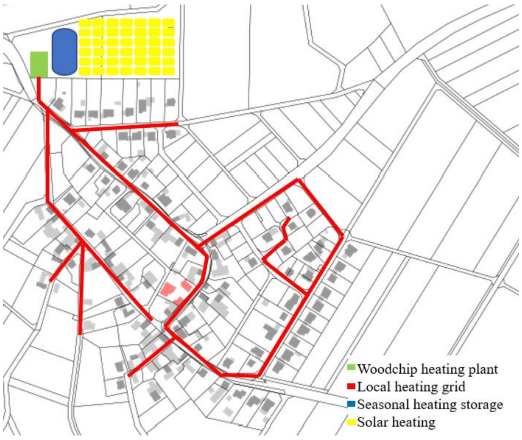

Figure 14: Exemplary illustration of the local heating grid Rodder with Woodchip heating plant, solar heating and the seasonal/ daily heating storage. [own illustration]

The following two scenarios are used to cover the thermal consumption of Rodder in a climate-neutral way at any time of the year:

1. Scenario: Solar heating + seasonal storage
2. Scenario: Solar heating (base load supply) in combination with a wood chip heating plant (peak load) and a buffer storage.

5.1 Solar heating and seasonal storage

In the following, the required power of a solar heating and the volume of a seasonal hot water storage are shown to make the heat supply in Rodder climate neutral.

Figure 15 shows the required solar heating power and storage capacity depending on the level of autarky.

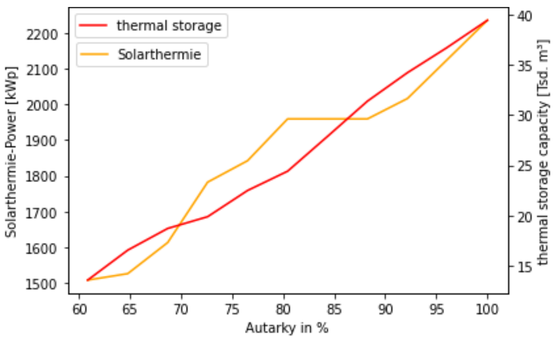

Figure 15: Solarthermie power and saisonal thermal storage capacity depending on autarky [own illustration]

The figure shows that the solar heating power and the storage capacity increase with increasing autarky. With increasing autarky, the volume of the seasonal storage increases significantly more than the solar heating power. This is due to the low specific investment costs of seasonal hot water storage at approx. 2€/kWh [13]. The addition of 1kWh is cheaper than the addition of 1 kWp solar heating [13]. To achieve 100% autarky, a 2.2 MWp solar heating system and a seasonal hot water storage tank of 40,000 m³ are necessary. This corresponds to a usable thermal energy capacity of 1,152 MWh.

The largest seasonal hot water storage tanks in Germany have a volume of 5,000 to 10,00 m³ [13]. The large seasonal storage tank (40,000 m³) is needed because in this scenario only solar heating is considered as a heat generator and the thermal consumption of Rodder must also be supplied from the seasonal storage in winter.

The following figure 16 shows the autarky rate depending on different seasonal storage sizes. The different solar heating powers in Figure 15 are considered here. On the horizontal axis, the storage size is shown in relation to the annual average daily consumption.

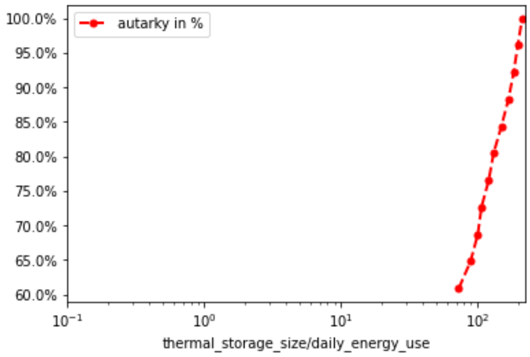

Figure 16: Autarky Rate as a function of different storage sizes relative to average daily consumption. The values consider different solar heating powers and storage capacities [own illustration]

Figure 16 shows that even at a low autarky rate of 60%, a seasonal heat storage system is required, which has a 73 times higher storage capacity in relation to the average daily consumption. With increasing autarky, the storage capacity increases.

This effect results from the seasonally different solar heating generation and makes an extremely large seasonal storage necessary for 100% autarky. Especially in winter, with low solar heating generation over a longer period of time, the consumption has to be covered by the storage. To achieve 100% autarky, the seasonal hot water storage tank must have 213 times the capacity relative to average daily heat consumption.

5.2 Solar heating & wood chip heating plant & thermal storage system

In the following, the required powers of a solar heating plant and a wood chip heating plant as well as the volume of a buffer storage are determined. In this context, it is investigated how the use of a wood chip heating plant affects the required capacity of the solar heating system and the storage size compared to scenario 1 in order to achieve 100% autarky.

For the simulation, the thermal storage was set to a volume of 100 m³ with a usable thermal capacity of 2,910 kWh. This results from the temperature difference of supply and return and the storage volume. The volume was determined on the basis of selected reference projects, in which comparable villages like Rodder are also supplied by solar heating energy and wood chip heating. [14]

The simulation shows that a 700 kW solar heating plant and an 835 kW wood chip heating plant are necessary to supply the thermal consumption in Rodder climate neutrally over the year.

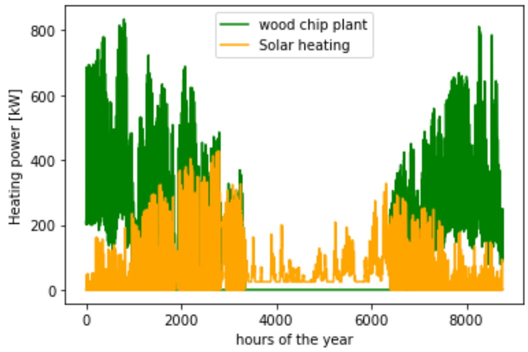

Figure 17: Heating load of Rodder covered by Solar thermal, day storage and wood chips plant [own illustration]

Figure 17 shows the heating load profile of Rodder, which is covered by the generation profiles of the wood chip heating plant as well as the solar heating system and the 100 m³ buffer storage. The generation capacity of the solar heating plant does not exceed 430 kW, which is due to the fact that the heating load profile of Rodder is shown here. In summer, when the solar heating plant would reach the 700 kW peak power, this heating power is not needed by the village and is therefore not shown in the figure.

Rodder's heating load is covered by the generation profiles at every hour of the year. The thermal consumption is covered by the solar heating plant, the wood chip heating plant and the buffer storage. It can be seen from the figure 17 that the solar heating plant with a 100 m³ storage covers the complete thermal consumption of Rodder in summer from mid-May to the end of October. Since no thermal energy is required in the summer months except for hot water, the solar heating system has to be shut down at certain times to avoid overheating (when the solar heat is overproduced and when the buffer tank is full).The wood chip heating plant is not needed in the summer months.

The solar coverage rate of the 700 kW solar heating system with 100 m³ storage tank is 22%, which is a common coverage rate for such a system with buffer storage. [14]

Despite the solar heating plant, the power of the wood chip heating plant (835 kW) must be dimensioned for the maximum required heating load of the village. This is because the maximum heating load occurs in winter at a time when the solar heating plant is not generating heat and the 100 m³ storage tank is empty.

Although the peak load of the wood chip heating plant cannot be significantly reduced by increasing the size of the solar heating plant and the day storage tank, the solar coverage rate could be increased and the resulting wood consumption reduced by increasing the size of the plant components. Furthermore, the purpose of increasing the size of the systems must be questioned, since the economic efficiency suffers if the solar heating plant has to be switched off in summer because the storage tank is often already fully charged.

Figure 18 shows an example of the operating mode of the solar heating and the wood chip heating plant for a single day (March 23). Additionally, the thermal load to be covered by Rodder is shown. During this period, the thermal storage is empty.

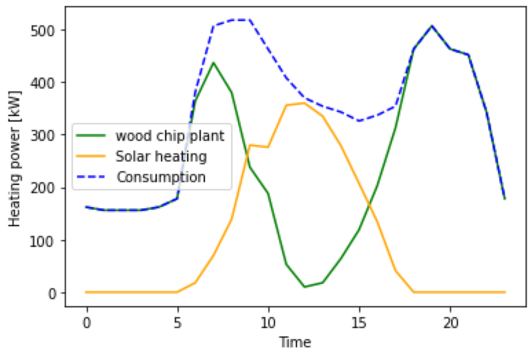

Figure 18: Covered heating load interaction of solar heating and wood chip plant (23. March) [own illustration]

It can be seen how the solar heating system and the wood chip heating plant complement each other to cover the thermal consumption.

Shown in blue is the heating load of the village of Rodder met by the solar heating generation profile and the wood chip heating plant generation profile. The powers of both types of plants together give the required heating power of Roder at any point in time.

To achieve a thermal autarky rate of 100%, in combination with a 700 kW solar heating system, the woodchip heating plant must generate 1,528 MWh annually. This corresponds to a wood consumption of 1,559 bulk cubic meters per year. To provide this amount of wood sustainably, 63 ha of forest are needed, which is about 10% of the total area of Rodder [15]. The village of Rodder owns about 200 ha of forest area [3]. In addition, all forest areas in Rheinland-Pfalz have been certified with the PEFC certificate since the year 2000, which guarantees sustainable forest management [16].

6 SUMMARY

The project has shown that different climate-neutral energy supply concepts are possible to decarbonize the electricity, transport and heat sectors. The table shows the results of the investigated and simulated energy concepts to be able to supply Rodder climate-neutral in the future.

Table 2: possible climate-neutral energy supply concepts for Rodder [own illustration]

Scenario	Power R.E.	Storage capacity
Electricity		
PV ground mounted system	3.1 MW	4.3 MWh
Wind power	4.5 MW	0.89 MWh
Thermal		
Solar heating	2.2 MW	40.000 m³
Solar heating + wood chip plant	0.7 MW (Solar) 0.83 MW (wood)	100 m³

In the analysis of the electricity sector, it has become clear that significant expansion of photovoltaics on rooftops in the distribution grid is only possible if battery storage is coupled with photovoltaics in the future. A conventional operating mode does not lead to any reduction in the utilisation on the grid. An intelligent hybrid operating mode of the storage in which both the autarky rate and the grid relief are considered is one way to drive the expansion of photovoltaics in the distribution grid. In addition, the project work has shown that the use of electric mobility, assuming the load and charging profiles used, does not lead to local grid overload in Rodder. In the future, however, demand response could also contribute to stabilizing the electricity grid.

To be able to cover Rodder's electricity consumption at any hour of the year in a climate-neutral manner, other renewable generators are needed in addition to the PV systems on the house roofs. It has become clear that as renewable plant capacity increases and volatile generation becomes less intense, the required storage capacity becomes smaller. For example, 890 kWh of storage is needed when coupled with a 4.5 MW wind turbine. If, on the other hand, an PV ground mounted system is used, the required storage capacity increases.

The analysis of the heating sector has shown that different renewable supply concepts are possible. In the project, different concepts for a local heating grid were analyzed.

For volatile generation by solar heating, a large thermal seasonal storage with a volume of 40,000 m³ is necessary. Especially in winter, with little solar heating generation over a longer period of time, the consumption must be covered from the storage.

However, a combination of different generation technologies is also possible. Solar heating can contribute to the base load thermal supply and a wood chip heating plant is used to cover the peak load. The simulation showed that the wood chip heating plant (835 kW) must be dimensioned to meet Rodder's peak thermal load. This occurs in winter when no heat generation can be provided by solar heating. Increasing the solar heating power does not reduce the power of the wood chip heating plant.

In conclusion, it can be said that different energy supply concepts are possible to supply Rodder with climate-neutral energy in the future. The project examined how the energy transition can succeed at the local level for Rodder. The knowledge gained can help to drive forward the energy transition in Germany. The climate-neutral transformation of the energy supply can only succeed if the social and political level in Rodder and Germany deal with the energy transition and have the will to live climate-neutral and autark.

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