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Combination of Geothermal Heat Pumps and Photovoltaics

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ABSTRACT

How great can the coverage of self-generated PV electricity be for the generation of buildings heat? In order to become more independent of energy suppliers and fossil fuels, an increasing number of people are making use of the energy that their own property can provide. Soil and groundwater supply enough thermal energy, even in the deepest winter, to heat a building. Such energy is rendered usable by means of a heat pump. It extracts heat from the soil with the help of electrical energy and "pumps" it up to a higher temperature level. The electrical energy or a portion thereof can also be generated using a photovoltaic installation on one's own property.

Generating solar power on one's own roof and consuming it in the house, may be more economical today than feeding it into the grid. The more electricity one can use oneself, the better. A heat pump and a photovoltaic installation perfectly complement each other. The photovoltaic installation supplies inexpensive electricity for the heat pump and thus reduces heating costs. In return, the heat pump enhances the economic efficiency of the photovoltaic installation due to the increased use of solar power. The environment also benefits from this combination, because self-generated solar electricity is always 100% renewable, whereas heat pump electricity obtained from the grid is partly renewable and partly conventional.

Viewed over the course of a whole year, electricity is obtained both from the grid and from solar energy. The solar portion will initially depend on the given quantitative relations, which include the electricity consumption of the heat pump and the yield of the photovoltaic installation. For a well-insulated single-family home, this can be about 30 to 50%. A further crucial factor is the extent to which the two systems are coupled with one another. Using the simplest of methods, it is now possible for a heat pump to switch itself on automatically whenever there is a surplus of electricity from the solar panels.

This paper provides an overview of the subject of a combined geothermal heat pump and photovoltaic installation and is intended to communicate and highlight a basic understanding of the combination of these two technologies. Using a calculation tool, different modes of operation, including storage technologies, can be simulated to ensure that the heat pump can be primarily operated using self-generated electricity. The presentation will be supplemented by best practice projects, which provide a full overview of the various possible uses and technologies.

1. INTRODUCTION

The energy transition can only be successfully implemented if the heating transition plays an important role in it. The generation of green electricity alone is not enough to make successful progress with the heating transition. Geothermal energy will make its contribution and Germany offers excellent conditions for tapping into this potential.

In order to become more independent of energy suppliers and fossil fuels, an increasing number of people are making use of the energy that their own property can provide. Soil and groundwater supply enough thermal energy, even in the deepest winter, to heat a building. Such energy is rendered usable by means of a heat pump. It extracts heat from the soil with the help of electrical energy and "pumps" it up to a higher temperature level. The electrical energy or a portion thereof can also be generated using a photovoltaic installation on one's own property.

Generating solar power on one's own roof and consuming it in the house, may be more economical today than feeding it into the grid. The more electricity one can use oneself, the better. A heat pump and a photovoltaic installation perfectly complement each other. The photovoltaic installation supplies inexpensive electricity for the heat pump and thus reduces heating costs. In return, the heat pump enhances the economic efficiency of the photovoltaic installation due to the increased use of solar power. The environment also benefits from this combination, because self-generated solar electricity is always 100% renewable, whereas heat pump electricity obtained from the grid is partly renewable and partly conventional.

Of course, the heat pump cannot be operated 100% with solar power. On the one hand, other devices in the building also use solar power and, on the other hand, heating is also needed at night when no solar power is available. In the winter, the performance of the photovoltaic system during the day is often not sufficient to enable the heat pump to run independently with solar power.

Viewed over the course of a whole year, electricity is obtained both from the grid and from solar energy. The solar portion will initially depend on the given quantitative relations, which include the electricity consumption of the heat pump and the yield of the photovoltaic installation. For a well-insulated single-family home, this can be about 30 to 50%. A further crucial factor is the extent to which the two systems are coupled with one another. Using the simplest of methods, it is now possible for a heat pump to switch itself on automatically whenever there is a surplus of electricity from the solar panels.

The heat pump converts the solar electricity into heat and stores it in the hot water and buffer tank. The temperatures in the storage tanks are raised above the normal level so that more heat is produced than is actually needed at the time. In the evening hours, the heating and hot water requirements can initially be covered using the overloaded storage tanks. The heat pump pauses during this time and there is no need to buy electricity from the grid.

This paper provides an overview of the subject of a combined geothermal heat pump and photovoltaic installation and is intended to communicate and highlight a basic understanding of the combination of these two technologies. Using a calculation tool, different modes of operation, including storage technologies, can be simulated to ensure that the heat pump can be primarily operated using self-generated electricity. The presentation will be supplemented by best practice projects, which provide a full overview of the various possible uses and technologies.

2. FRAMEWORK CONDITIONS AND TECHNOLOGGY

The energy transition in Germany not only requires regenerative power generation as an important building block, but also regenerative heat generation. A significant part of final energy consumption in Germany is used to heat buildings. In fact, this makes up about 70% of the final energy consumption for the household sector according to figures published by the Federal Ministry for Economic Affairs and Energy, BMWi, (2018). Consequently, one of the ambitious goals of the energy transition is the expansion and increased use of geothermal energy. The base load capacity of geothermal energy is a great advantage in this regard.

2.1 Renewable energy in Germany

In 2018, the share of renewable energy in Germany's gross electricity consumption rose to 37.8 percent (2017: 36 percent). In total, around 226 billion kilowatt hours (billion kWh) of electricity were generated from sun, wind, water and biomass, which is around 4 percent above the level of the previous year (216 billion kWh) according to figures published by BMWi, BMWi (2019).

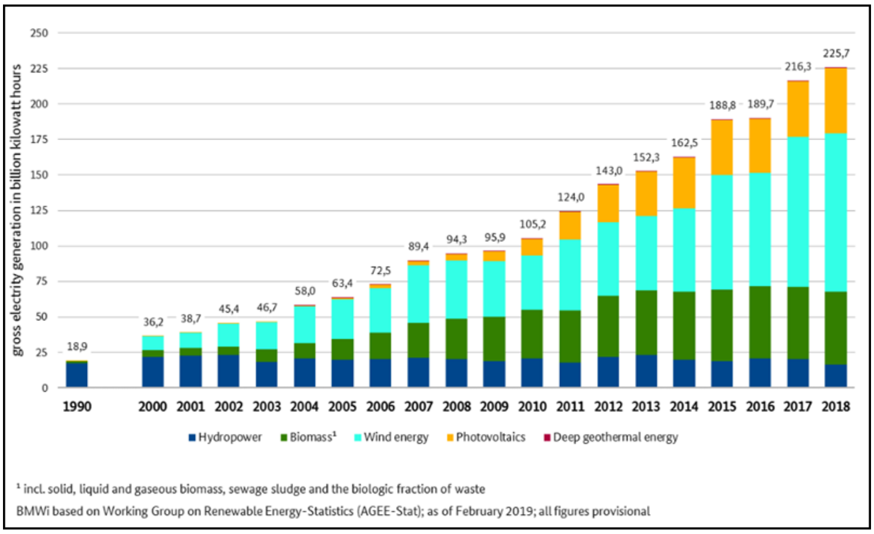

Figure 1: Development of power generation from renewable energy sources in Germany, BMWi (2019)

Final energy consumption for **heat** from renewable energy sources in 2018 remained at the previous year's level of around 171 billion kilowatt hours total. Thus, the share of renewable energy in the total final energy consumption for heating and cooling in 2018 was 13.9 percent according to figures published by BMWi, BMWi (2019).

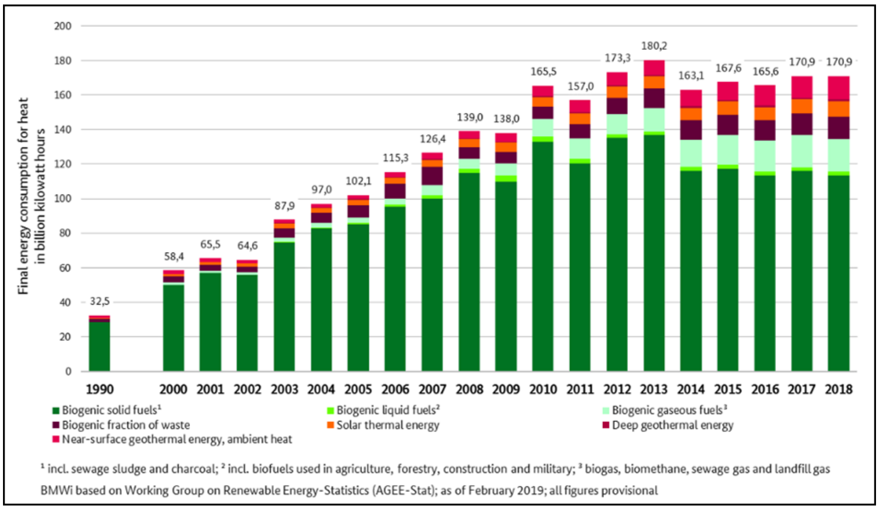

Figure 2: Development of heat consumption from renewable energy sources in Germany, BMWi (2019)

Heat pumps in Germany

The heat pump market is also developing positively in Germany. In 2018, sales of heat pumps totalled approximately 84,000 systems. Heat pumps are already being installed in every third new building in Germany and increasingly in existing buildings as well, Sabel (2019). They have long been regarded as mature, low-maintenance building technology and are appreciated for their particularly efficient heating.

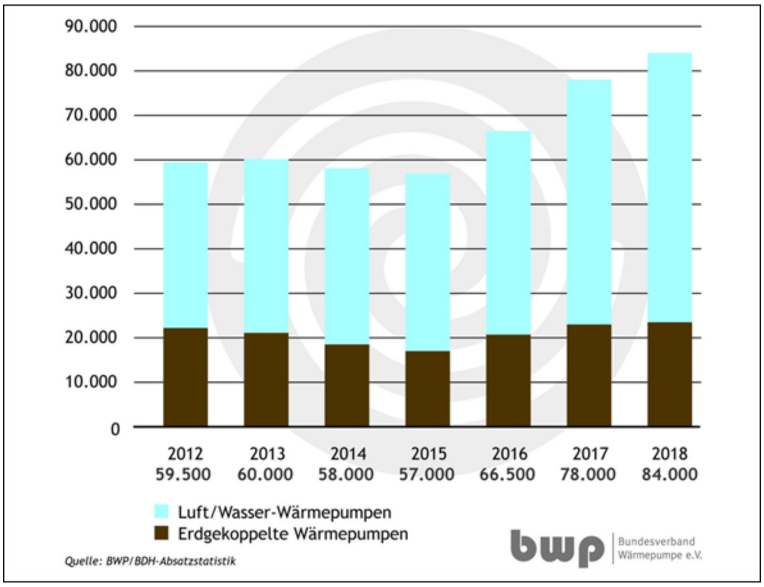

Figure 3: Sales figures for heat pumps in Germany from 2012 to 2018, German Heat Pump Association (2019)

2.2 Function of the heat pumps

Since their widespread market launch at the end of the 1970s, heat pumps have developed into increasingly efficient heating systems. The coefficient of performance (COP) has improved considerably over the years and today more than four kilowatt hours of heat can be generated from one kilowatt hour of electricity. The principle of how additional free energy from the environment is generated by heat pumps has remained unchanged.

A refrigerant (now free of ozone-depleting CFCs) circulates in a closed circuit within the heat pump. This essentially consists of two heat exchangers, a compressor and an electronic expansion valve. Heat is extracted from the environment (air, geothermal energy or groundwater) and fed into the building. The thermal energy generated by the electrical operating power supplied to the compressor can also be used.

2.3 Inverter technology

Until just a few years ago, heat pumps only had compressors that ran at a constant speed. As with any older oil or gas heating system, the heat output generated is always greater than that actually required in the building. The flow temperature is regulated by switching the heat generator on and off.

Heating is performed at full power for a few minutes followed by idle time. This type of stop-and-go operation involves heat losses, as the system is constantly heating up and cooling down. It is advantageous not only for a heat pump's efficiency, but also for its longevity if it can work as long as possible after starting.

In addition to these on/off heat pumps, those that adapt their heating output to the actual heat requirements have been on the market for a few years now. They permanently and continuously regulate the speed of the compressor to achieve this. This is referred to as inverter technology or modulating heat pumps. As a positive side effect, the heat pump works more effectively in the partial load range than under full load! For example, the field trial "Heat pumps in the existing building stock" conducted by Fraunhofer ISE confirmed that participating heat pumps equipped with inverter technology had above-average annual performance figures compared with on/off devices, Fraunhofer ISE (2014).

Especially in combination with a photovoltaic system, variable speed technology offers a further decisive advantage, as reduced speeds require less electrical power consumption. The following graphic illustrates an example of this.

A fixed-speed heat pump draws its connected load of 3,000 watts in spurts. When the heat pump is idle, a large part of the solar power is fed into the grid. When the heat pump is running, most of the electricity then has to be bought back from the energy supplier.

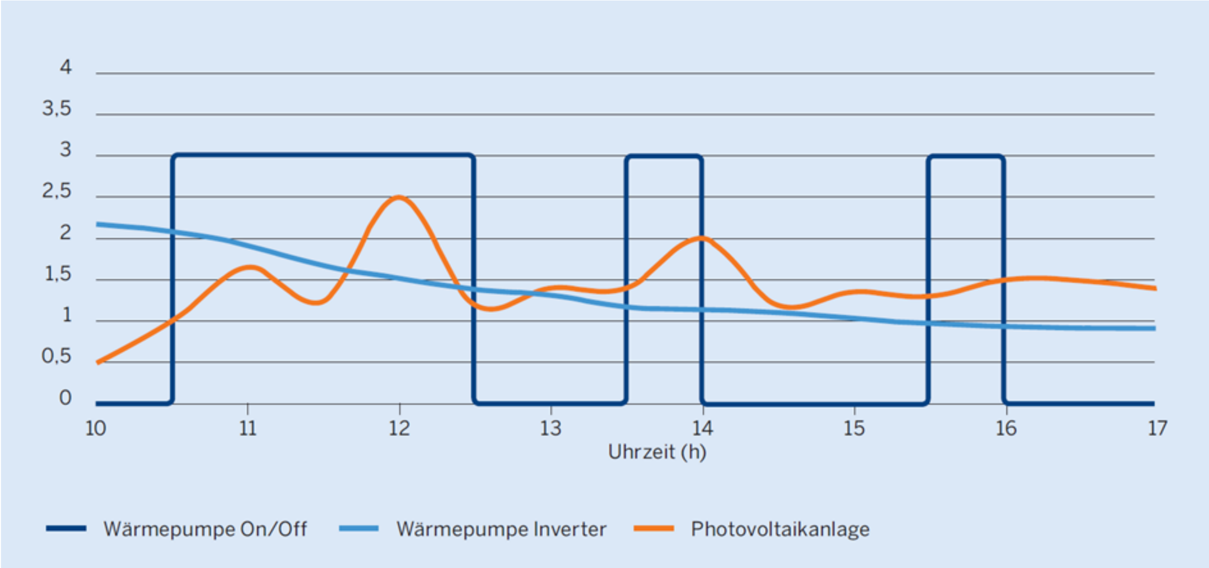

Figure 4: Comparison of heat pump performance curves (in kW) with and without inverter technology, EnergieAgentur.NRW (2017)

The inverter device with the same maximum output runs continuously and consumes an average of about 1,800 watts. This performance can be largely covered by the PV system so that only little electricity needs to be drawn from the grid. Inverter technology thus permits increased self-consumption and a higher level of self-sufficiency.

2.4 Photovoltaic systems and heat pumps

A photovoltaic system essentially consists of solar modules, one or more inverters and electricity meters. The solar modules generate electrical direct current from solar radiation, which the inverters convert into grid-compatible, 400/230-Volt, 50-Hertz, alternating current.

In the age of full feed-in, the largest possible photovoltaic system was also the most lucrative. This has no longer been the case since personal consumption has gained importance. If a heat pump is added to the household's usual electricity consumption, it must be taken into account in the design of the PV system, as it significantly increases own consumption. Many factors play a role here, such as the heat pump's electricity consumption, the size of the buffer and hot water tanks and, above all, the user behaviour with regard to household electricity. The ideal system size with an intelligently integrated heat pump is always larger than is the case when only electricity consumers in the household are supplied. Dimensioning the photovoltaic system to be as large as possible has proven itself in practice. Heat pumps require the most electricity in the winter. The sun is very low in the sky during the winter months and therefore south-facing modules offer the most advantageous angle to the sun and can better supply the heat pump. An East-West system is also economical, but contributes slightly less electricity to the heat pump.

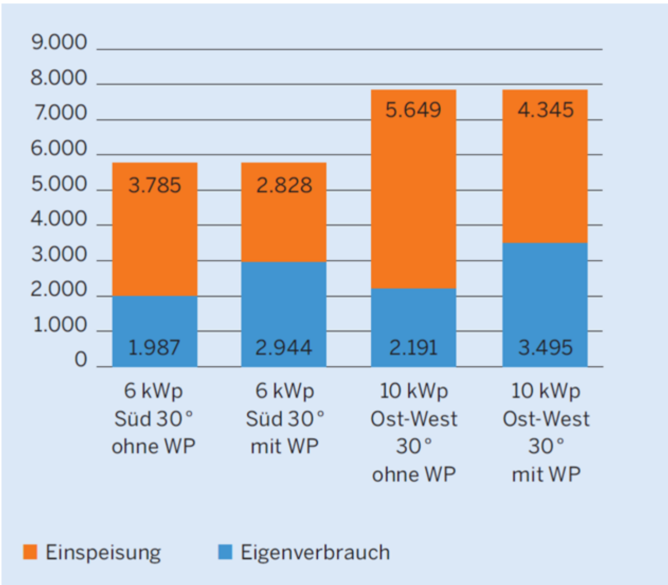

Figure 5: Increase in own consumption (in kWh) due to heat pump with 4,000 kWh electricity consumption and optimised hot water preparation, EnergieAgentur.NRW (2017)

3.0 COMBINING HEAT PUMPS AND PHOTOVOLTAICS

The heat pump converts the solar electricity into heat and stores it in the hot water and buffer tank. The temperatures in the storage tanks can be raised above the normal level so that more heat is produced than is actually needed. In the evening hours, the heating and hot water requirements can initially be covered using the "overloaded" storage tanks. The heat pump pauses during this time and there is no need to buy electricity from the grid.

Several technical possibilities for communication between the two systems are already available on the market. With regard to the heat pump, most manufacturers use the same principle. The "SG-ready input" (SG = Smart Grid) serves as an interface for the heat pump so that it can respond to the production of solar electricity. The interface can be controlled in different ways. One simple variant consists of connecting the heat pump directly to the inverter via a pipe. The solar power generated should not only be used by the heat pump, but should also be available for all the other power consumers in the household.

When using solar power for the heat pump, an inverter heat pump should be used if possible. This serves to ensure the heating output is adapted to the actual heat requirement. The compressor speed is continuously regulated.

Whether it is worth combining a heat pump and a photovoltaic system also depends on the building. If it is well insulated and, in the best case, equipped with surface heating, very low flow temperatures suffice. These in turn improve the functioning of the heat pump. This is because heat pumps work more efficiently and economically when the temperature difference between the environmental energy source (air, earth or water) and the heating water is low. A heat pump in combination with photovoltaics is therefore particularly worthwhile in new buildings or those that are being comprehensively renovated to make them more energy efficient.

On average, a photovoltaic system covers about 30 percent of a heat pump's electricity requirements. However, this value varies depending on the building's efficiency standard and increases with the use of an intelligent control system.

4.0 HEAT PUMP OPTIMIZATION FOR A HIGH LEVEL OF SELF-SUFFICIENCY

The extent to which a heat pump can be operated with solar power depends on many factors. Some of these are determined during system planning, whereas others are affected by the settings made during operation. In order for a heat pump and a photovoltaic system to work well together, the following must be observed.

4.1 Heat distribution and storage system

The heat pump will work more efficiently, the smaller the temperature difference is between the heat source and the heating flow temperature. Especially when combined with a photovoltaic system, this means that the heat pump can be supplied more by solar power proportionally. Therefore, the flow temperature of the heating circuits and the temperature in the hot water tank are important variables.

The **flow temperature** required by the heating system to heat a building enough in winter depends largely on the insulation of the outer shell as well as the size and type of heating surface. If less energy escapes through a well insulated outer shell, then less energy has to be introduced via the heating surfaces. In addition to the obvious advantage that less energy is required overall, there is a second advantage: less energy input means less output from the heating surfaces, which means lower flow temperatures. In addition to the temperature, the size of a heating surface naturally determines its output. Generously dimensioned panel radiators are advantageous and underfloor or wall heating is ideal.

As a rule, a **buffer tank** is integrated for hydraulic decoupling of the heat pump and heating circuits. The amount of heat that can be stored increases with its size. The available space and accessibility of the installation room naturally limit this. In addition to the size, however, the flow temperature of the heating circuits is also decisive in this regard, as the heat pump can heat the storage tank to a maximum of 60 °C to 65 °C. The greater the difference between the required and the maximum possible flow temperature, the more energy can be stored when solar power is available. In combination with floor and wall heating systems, no buffer tank is needed if the piping alone provides sufficient water volume and a minimum volume flow is ensured. This is indispensable for the efficient operation of the heat pump and can be achieved, for example, by having some heating circuits constantly open, usually in the living area.

One large free heat accumulator is the building itself. Large quantities of energy can be stored simply by increasing the **room temperature** by a few degrees during forced operation. The air itself offers only little potential due to its low specific heat capacity. However, since it heats everything in the building including the interior walls, ceilings and floors, furniture, etc., there is a huge storage mass that can absorb more energy, the greater the temperature difference between the normal and the increased room temperature is. If you have heated your building up from 20 °C to 23 °C in the afternoon using solar power, for example, then the heat pump will have less to do in the evening hours.

4.2 Dimensioning the heat pump

At the standard design temperature in your place of residence (e.g. - 10 °C), the heat pump must generate enough heat to maintain an internal room temperature of 20 °C. In other words, the heat output of the heat pump must correspond to your building's heating load. For efficient operation, it is necessary to design the system so that it is exactly aligned with this value. Approximate dimensions with typical, specific values (e.g. 100 watts per square metre) are very inaccurate. Calculations pertaining to the consumption of the old gas or oil heating, which assume full load hours, also allow only for approximation of the actual heating load. A "reserve surcharge" is often added and the heat pump is designed to be too large in most cases.

The effects are as follows:

- The next larger heat pump is more expensive

- In brine/water appliances, the heat source is also designed too large and therefore more expensive
- Heat pumps with on/off operation have short running times and many starting processes
- Inverter heat pumps cannot make full use of their advantages
- It may be necessary to install an oversized hot water tank, as the surface of the tube heat exchanger will not otherwise
- be able to transfer the heat pump's heat output
- The electrical power consumption of the heat pump is unnecessarily high and therefore a lower percentage of energy can be supplied by the PV system and more energy is required from energy suppliers

Many heat pump models are offered by the manufacturers with various levels of performance. But what is to be done if the heating load lies exactly between two available performance levels? The smaller device should be chosen in this case and not the larger one, because the heating load is based on the worst case. This occurs very rarely and when it does, it is usually at night when a slight drop in the room temperature to 18 °C, for example, can be tolerated.

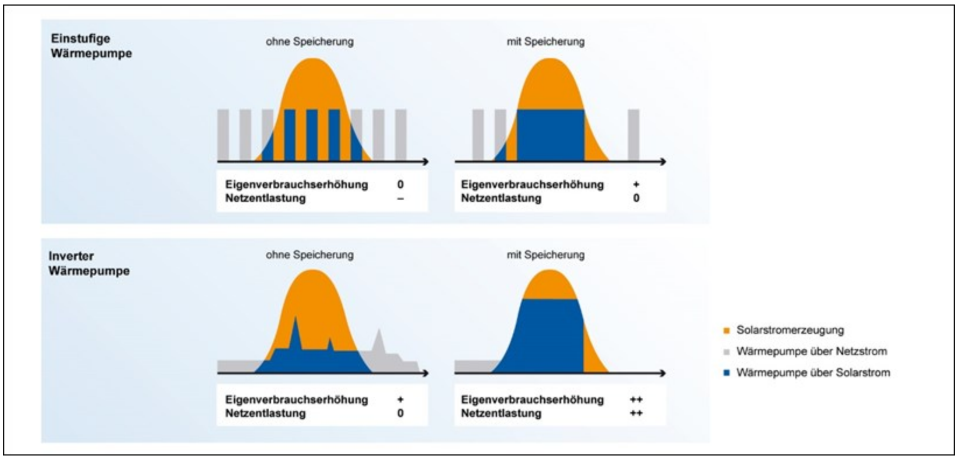

Figure 6: Time variation curve for heat pump and photovoltaics. Comparison of single-speed inverter heat pump with and without storage, EnergieAgentur.NRW, 2017 according to Quaschning (2013)

4.3 Electrical energy storage

An energy storage unit stores excess power for later use. In conjunction with a photovoltaic system, this allows solar power to be used even when the sun is not shining. By using an energy storage unit, more self-generated solar electricity can be consumed. The electricity is not fed into the power grid, but can instead be used later if necessary. The increased share of self-generated energy achieved using energy storage reduces household electricity costs.

Photovoltaic systems without storage units produce solar electricity that must be used immediately. Since solar power is primarily generated during the day and the electricity requirements of most households are low during this time, a lot of electricity is fed into the grid around noon. As a general rule, the demand for electricity increases significantly in the evening hours. Using energy storage, you can store the solar power you do not need during the day and then use it in the evening hours.

The positive characteristics of energy storage are a follows, EnergieAgentur.NRW (2017):
- Storage of PV yield surpluses,
- An increase in self-generated electricity from 30% to more than 50% (sometimes over 70%),
- Reducing strain on the local power grids,
- Current high cost of energy storage
- Price range for the installed storage between €1,000 and €1,500 (price as 12/2016)

Gebäude	Wärme-bedarf	Heizlast	PV-Anlage	Strom-speicher	Autarkie Wärmepumpe
Niedrig-energiehaus 140 m²	10.000 kWh	8 kW	6 kWp	6 kWh	38+10=48%
Neubau 140 m²	15.000 kWh	10 kW	6 kWp	6 kWh	27+10=37%
Altbau 140 m²	25.000 kWh	14 kW	6 kWp	6 kWh	15+10=25%
Altbau 140 m²	25.000 kWh	14 kW	10 kWp	10 kWh	32+13=45%

Sole/Wasser-Wärmepumpe, Lithium-Stromspeicher, 250 W Solarmodule Süd-Dach 30°

Figure 7: Level of self-sufficiency of residential buildings with PV, without and with energy storage units, EnergieAgentur.NRW (2017)

5.0 EXAMPLES

In this section, various possible applications are described based on concrete examples. The first example is a simulation performed using a program created by EnergieAgentur.NRW and the second example is an actual residence in Duisburg, Germany.

5.1 Tool to calculate a building's level of self-sufficiency using a heat pump, photovoltaics and battery storage

Using a combination of a heat pump, a photovoltaic system and an energy storage unit is becoming increasingly popular. But how much electricity can I produce myself for my heat pump and how large should the energy storage unit be? In order to answer these questions, EnergieAgentur.NRW has developed a calculation engine for this tool that simulates the entire year at a resolution of 15 minutes to provide sufficient accuracy.

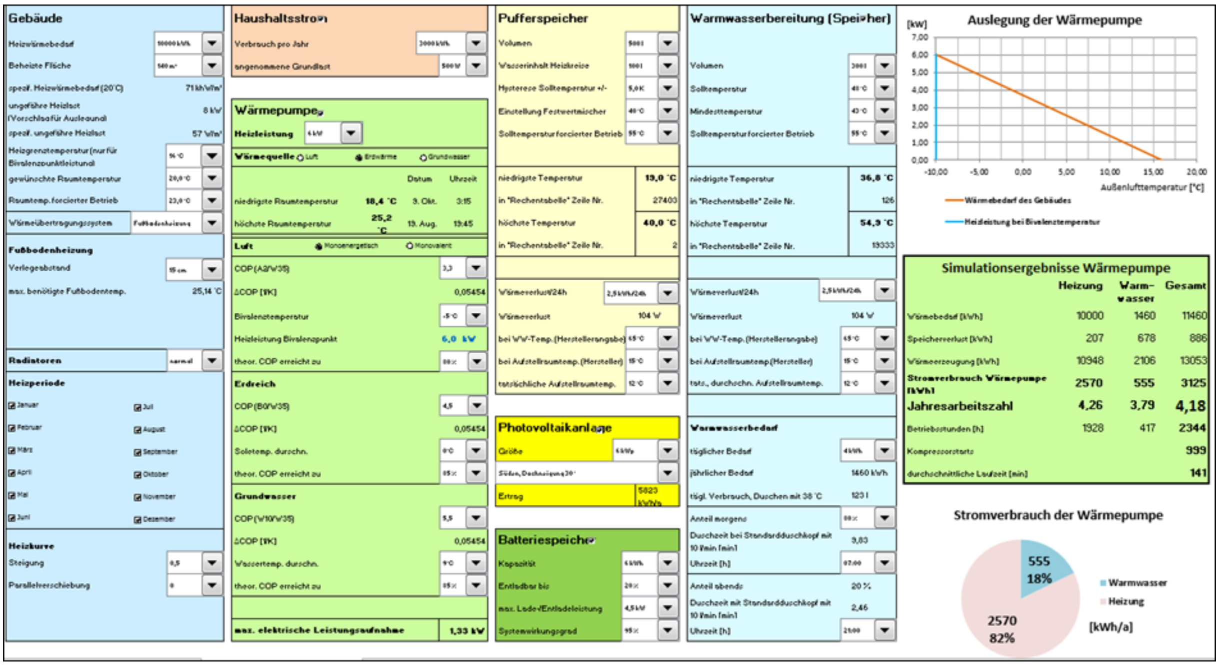

Figure 8: Input screen of the tool used to calculate levels of self-sufficiency, Kersten (2016)

As can be seen in Figure 8, the components can be estimated and roughly dimensioned by entering just a few values, which is very helpful when it comes to making decisions.

The following building data has been entered here to explain how the tool works:

- Heated area: 180 sqm
- Heat requirement: 15,000 kWh
- Heating: 9 kW heat pump
- Heat distribution system: underfloor heating
- Heat source: geothermal probes
- Buffer tank: 500 L
- Hot water tank: 300 L
- Photovoltaic system: 7 kWp, south orientation, 30° inclination
- Battery storage: 11 kWh

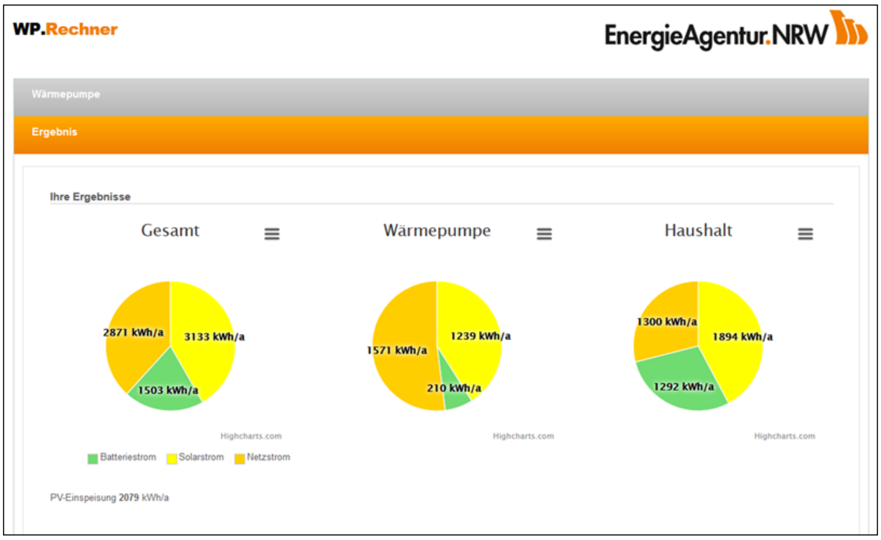

Figure 9: Presentation of results from the calculation tool including total consumption, heat pump consumption and household consumption.

The results of the calculation show levels of self-sufficiency ranging from 48% to 70%. The overall result is PV coverage of approx. 61% for the specified building. The heat pump achieves a PV share of approx. 48% and a level of approx. 70% is achieved for the household.

5.2 An example home that uses a heat pump in combination with photovoltaics

A family from Duisburg, Germany also took advantage of the idea of producing part of the heating energy for their own household themselves and no longer being 100% dependent on the power supplier. They replaced their oil heating with a brine/water heat pump. In order to save costs, a wood-burning stove was also used on a daily basis during the winter months. The annual consumption of wood amounted to approx. 4 m³ per year. The stove is now used only occasionally for cosiness. The 140 m² living space is heated by the heat pump. The monovalent heat pump has an output of 10.9 kW. It obtains 75% of the energy for this from geothermal probes in two 87 m deep boreholes under the lawn and terrace. The remaining 25% consisting of the electrical operating power for the compressor is partly covered by the photovoltaic system. The heat is conveyed via underfloor heating on the ground floor and via radiators on the first floor. The family heats their service water using a hot water heat pump, which at the same time extracts the moist air from the cellar. The roof-integrated PV system includes 28 modules and a total of 7 kWp. It generates energy for the two heat pumps and for the household. The roof is raised to the south and has an inclination of 45°.

According to the users, the heat pumps consumed 4,500 kWh of electricity in 2014, whereas the household consumed 3,500 kWh. The PV system generated 6,400 kWh during the same period. Only electricity that cannot be used in the house itself is fed into the grid.

Figure 10: Family residence in Duisburg with a PV system to produce electricity for the household and the heat pump, EnergieAgentur.NRW (2017)

6.0 SUMMARY

A heat pump in combination with a photovoltaic system is becoming increasingly popular. In order to become less dependent on energy suppliers and fossil fuels, more and more people are taking advantage of the energy that their own property can provide. Soil and groundwater supply enough thermal energy to heat a building, even in the deepest winter. A heat pump can utilize this energy. It uses electrical energy to extract heat from the soil and "pumps" it to a higher temperature level. The required electrical energy can be produced at least partially using a photovoltaic system on one's own property.

Using self-generated solar power to supply a heat pump generally improves amortisation of the PV system if the difference between the feed-in tariff and the heat pump electricity price is less than the difference between the total installation cost of the PV system and the heating electricity tariff for the heat pump. If a new purchase or replacement of the heating system is planned, combining a heat pump with a PV system could be a good choice. However, determining whether it is worth the cost of combining a heat pump and a photovoltaic system also depends on the building. This includes factors such as how the building is insulated and which heating technology is already in use. A heat pump in combination with photovoltaics is therefore particularly worthwhile in new buildings or those that are being comprehensively renovated to make them more energy efficient.

On average, the photovoltaic system covers about 30 percent of a heat pump's electricity requirements (without energy storage). However, this value varies depending on the building's efficiency standard and increases with the use of an intelligent control system.

When using solar power for the heat pump, an inverter heat pump should be used if possible. This serves to ensure the heating output is adapted to the actual heat requirement.

By using an energy storage unit, more self-generated solar electricity can be consumed. The level of self-sufficiency can be as high as 50% (in some cases even up to 70%), but depends on the size of the PV system and the use of an energy storage unit. This also serves to reduce strain on the local power grids.

A calculation tool can be used to simulate the combination of a heat pump with a photovoltaic system and an energy storage unit. The components can be estimated and roughly dimensioned by entering just a few values, which is very helpful when it comes to making decisions. As shown in this paper, however, a 100% supply with solar power cannot be achieved or can only be achieved very rarely. This is especially true in winter, when the output of the PV system is often insufficient to supply a heat pump with 100% solar power.

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