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OPtimising Hybrid Energy grids

for smart citieS

WP3 Monitoring and System Analysis

Deliverable 3.2

Analysis of physical coupling nodes of Hybrid Energy Grids

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Deliverable Description

Abstract: This report gives a short introduction to the different energy grids and an overview about available technologies which are necessary for hybridization between the different energy grids. Furthermore, the nominal and dynamic parameters for the technologies are explained.
The main objective of this report is to give an overview about the range of the several technologies and the required parameters for the realization of dynamic simulation models.

Key Words: ICT, smart cities, hybrid energy grid, energy saving, demonstrations, smart grid, energy control, monitoring

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Dissemination Level

Dissemination Level		
PU	Public	**X**
PP	Restricted to other program participants (including the Commission Services)	
RE	Restricted to a group specified by the Consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Executive Summary

The OrPHEuS project elaborates a hybrid energy network control system for Smart Cities. Within this system novel cooperative local grid and inter-grid control strategies for the optimal interactions between multiple energy grids has to be implemented. This is done by enabling simultaneous optimization for individual response requirements, energy efficiencies and energy savings as well as coupled operational, economic and social impacts. Starting from existing system setups in two cities, enhanced operational scenarios are demonstrated for today's market setup, as well as for future market visions.

In fact of the changes in the electrical grid with increasing decentralized feed-in, it is recommended to implement hybridization between the several energy grids in order to avoid high costs for the development of the electrical grid. For this it is important to know the structure and functioning of several grids as well as the various energy system coupling systems.

The main scope of the Deliverable D3.2 (Task 3.2) is the analysis of physical coupling nodes of Hybrid Energy Grids. First, an overview about the different energy grids is given. Next, a description of several nominal and dynamic parameters is outlined. Subsequently an explanation of the different coupling systems between the energy grids and their nominal parameters is included. Finally, an overview of different options to avoid reinforcement costs for electrical distribution grids are given.

Administrative Overview

Task Description

For hybrid energy networks in Smart Cities the transformation of energy from one system into another and vice versa is necessary. The transformation can be done through physical coupling points connecting different energy grids. The transformation process could be unidirectional or bidirectional and transform one energy from into one or more others.

In this task the various physical coupling points like block heat and power plants, heat pumps and power to gas systems will be investigated in terms of standards, regulations and technical constraints. A further investigation focuses on the coupling point monitoring and model description for the mapping into simulation and system algorithms as well as the needed measurement values. The results will give an overview on the characteristic curves, response times, system efficiency, sensible and stress avoiding operation modes and operation costs.

Relation to the Scientific and Technological Objectives

The task 3.2 is related to the STO2 – Adaptation of the existing monitoring systems for the fine granulated energy network control operations. Based on the given information in this task it is possible to assess which monitoring systems are necessary for realizing a working connection between the several energy grids.

Following coupling notes were analyzed in this report:

- CHP 512 types
- Electric Boilers 70 types
- Gas Boilers 124 types
- Power-to-gas 18 projects
- Heat Pumps 1772 types

Relations to activities in the Project

The input for this task comes from task 2.2 and 2.3 focusing on development of a framework for future smart energy network operations and the definition of use case studies in the demo sites.

The information and results of the task 3.2 will contribute to work package 4 which engages in the simulation of the different energy grids and several physical coupling points of the demo sites. This work will be done by AIT.

Terminologies

Abbreviations

MS	Milestone
STO	Scientific & Technological Objective
E_{PH}	Energy of the photon
c	velocity of the light
h	Planck's constant
λ	Wavelength
E_g	Band Gap Energy
V_{OC}	Open circuit voltage
MPP	Maximum power point
I_{SC}	short current
R_S	serial resistor
R_P	parallel resistor
I_{PH}	photocurrent
η_{module}	module efficiency
P_{STC}	power under standard test conditions
A_{module}	area of the module
Y	Final Yield
E_{AC}	Produced AC energy
P_{nom}	nominal power
PR	Performance Ratio
IER	Institute for Energy Economic and rational energy application
PtG	Power-to-Gas
PtH	Power-to-Hydrogen
HP	Heat Pump
COP	Coefficient of performance
CHP	Combined Heat and Power System
F-I	Feed-In
MV	Medium voltage
LV	Low voltage
nT	Normal Transformer
rT	Regulated Transformer

Table of Contents

1. Introduction

This report gives a short introduction and overview of physical coupling points between the different energy systems to solve problems with increasing feed-in of renewable energy in the demo sites of the OrPHEuS project. Due to political targets, like the reduction of CO_2 production, the electrical power supply in Europe will change in future. The integration of decentralized renewable energy systems into the present low and medium voltage electrical grid is challenging and brings along plenty of problems. In future, with the existing control strategies and systems from centralized energy supply, it will not be possible to guarantee a secure power supply.

The integration of fluctuating feed-in power from volatile decentralized power systems e.g. with photovoltaic (PV) and wind plants is a new challenge for electric distribution grids. In fact, there is excess energy available as well as a high demand by low production. The high overproduction leads to voltage band violations, overload of grid infrastructure and decreasing prices at the spot market, also to negative prices. Furthermore, the installation of energy storages into the grids is a requirement to shift the surplus into times of demand. Today there is no connection between the different energy grids, but in future it will be essential to implement this and to use the synergies between the different grids. One option is the transformation of the power surplus, with power-to-gas-systems, into hydrogen or methane. In this way it is possible to store the energy for a long period of time. Furthermore, the power surplus could also be used for heating and thermal storages with a capacity of several hours are state-of-the-art.

The main objective of this report is to give an overview of analysis results of physical coupling points of hybrid energy grids in the demo sites performed in several studies. This is the basis for the adaptation of the existing monitoring systems to the fine-granulated energy network control operations (STO 2). It is important to know which dynamic parameters exist in order to be able to set up a common control strategy. Furthermore, the report describes which systems can be used for hybridization. Therefore, an overview of existing devices and the range of the available parameters are given. The report investigates more than 1,700 different types of heat pumps, 66 gas turbines, 425 Otto engines for combined heat and power systems and around 180 boilers. Moreover, an overview of existing and planned power-to-gas-projects in Germany is illustrated. Some of them are already developed and ready for use, some are at the research stage, but they seem to be necessary for the future market. This information is required in work package 4 which simulates the different grids and their connections.

This report is organized as following:

- Chapter 2 gives a short overview on the state-of-the-art and contemporary structure of several grids.
- Chapter 3 shows the important parameters which seem necessary for a simulation of hybrid energy grids and for the connection between the different energy systems.
- Chapter 4 describes the different systems which can be used for a hybridization of the power grids. In addition, it gives an overview of already existing hardware.
- The appendix includes the possibilities for regulation and development of the electrical grid without hybridization between the grids as well as an overview of power-to-gas projects.

2 Overview

Today's electrical power generation is characterized by central power plants mainly using nuclear or fossil fuels. The structure of the electrical grid is technically oriented towards those central power plants. Historically, the load flow runs from these central power plants via the different grid levels to the customers. [1] The highest load is used as benchmark for the dimension of the transformers and cables. The high overproduction of the renewable energy systems change the well-known system and the load flow is no longer in one direction. Nowadays the feed-in from the distribution network to the overlain levels could happen, if the decentralized production exceeds the local demand. The feed-in power from the renewables can be several times higher than the load [2]. In fact, the cables and transformers can be overloaded. Therefore, it is necessary to develop the existing grid. Moreover, the voltage range could be violated by the feed-in of the renewable energies. Nowadays the distribution grid operators only increase the capacity of the grid in overload situation. This results in very high costs, but it is not the only possible way [3].

The gas grid is realized comparably to the electrical grid. The gas grid is divided in a high, medium and low pressure level like the electric voltage levels. Furthermore, there are central feed-in points, where the gas is transported to the customers. Large storage capacities are included in the grid to avoid also seasonal supply defiles [3, 4]. This storage potential and the now available infrastructure makes the gas grid interesting for hybridization measures with the electrical grid [5, 6]. The approach for the future is to transform the overproductions from the electrical grid into gas by power-to-gas systems. Thus it will be possible to use the gas directly or re-transform it into electrical power.

The district heating grid is also interesting for hybridization and the use of overproduction in the electrical grid. It is provided by combined heat and power systems, which are located in the cities [3]. Due to energy loss from the pipes, district heating systems are island systems for cities. The overproduction in the electrical grid can be transformed into heat power and be directly used. Thermal storages are also available, which makes it possible to store the energy. The problem are the losses of these thermal storages, which makes a seasonal storage inefficient today. However, researches are done to develop new storage systems with smaller losses.

Today the different energy grids are operated separately and usually there are no couplings between them. A solution to handle the fluctuating feed-in of renewable energies will be hybridization. One advantage of hybridization is the possibility to reduce the power excess in the electrical grid and use the energy locally. However, concerning this problem there are also some other opportunities available and a comparison of their economic values is necessary. Furthermore, hybridization can assist in the regulation of the fluctuating feed-in power of the renewable energies. Therefore, it is possible to use different systems for positive and negative regulation power. The possibility of seasonable energy storage in the gas grid makes the hybridization between the grids even more essential.

3 Identified parameters

This chapter gives an overview of the important parameters for the different systems. It is subdivided in nominal and dynamic parameters. They are necessary for the creation and function of the simulation models, which are implemented in work package 4.

3.1 Nominal Parameters

This part of the report describes the different nominal parameters and efficiencies for the electrical and thermal systems. The nominal parameters are given by the manufacturer of the systems and will determine under special test conditions.

3.1.1 Electrical power

The electrical nominal power P_N is measured in Watt. The nominal power of a device gives the output power or usage of any device. The nominal electric power is only given under well-defined operation conditions. For example PV-systems can reach higher and lower power feed-in than the nominal power, depending on the weather conditions.

3.1.2 Thermal power

The thermal power depends on the temperature difference, the temperature coefficient of the fluid or material and the mass flow. The thermal power gives no answer regarding the temperature value of the input and output temperature. But these temperatures have a strong influence on all processes. Therefore, it is necessary to know the temperatures to evaluate the thermal power. E.g. Power plants emit high thermal powers through their cooling towers in the environment, but it is technically not practical to use that power due to the low temperature levels.

3.1.3 Electric efficiency

The electric efficiency describes the ratio of the absorbed power to the power output while the output is always electrical power. For example, the electric efficiency of a photovoltaic system describes the ratio between the solar irradiance as power absorbed and the electric feed-in as power output.

3.1.4 Thermal efficiency

The thermal efficiency is defined analogous to the electric efficiency, but with special consideration of the thermal power, chapter 3.1.2

3.2 Dynamic Parameters in part load operational range

In this part of the report the necessary dynamic parameters are listed. Those are important to realize dynamic simulation models of the different systems. With these parameters it is possible to develop different control strategies.

3.2.1 Operating Times

The operating times are necessary for the definition of the control strategies for each system. Most likely there are some important time parameters for a suitable operation of the coupling points because of technology or system depending limitations.

3.2.1.1 Minimal off-time

The minimal-off-time describes the time span between shut-down and restart of a system to avoid stress or damages to the system. In the case of the optimization it is important to know the minimal time needed between the turn off and turn on of the used system. When the minimal-off-time is not integrated in the control system, the aging effects on the system can increase.

3.2.1.2 Maximal off-time

The maximal-off-time describes the time span between shut-down and restart without an additional maintenance or starting procedure. If the system is not maintained efficiency can decrease, ageing processes can increase or the system could be damaged.

3.2.1.3 Minimal on-Time

The minimal-on-time describes the time span a system has to run after switching it on. The control system has to take care of this parameter in order to maximize the efficiency in this working process. For example, some systems have to reach a working temperature before they reach the operating point. If a system runs for a too short period of time the efficiency of a system can drop or maybe it could cause some serious damages to the system. For example, when some systems always run for a very short time without reaching the operating temperature some sediments can build up and influence the process.

3.2.2 Minimal power

The minimal power is the power a system has to provide to work in a stable process. Below this border the system efficiency can also decrease rapidly.

3.2.3 Maximal power (overload)

The maximal power the system can afford or absorb for a short period of time without decreasing the lifetime of the same, also known as overload. For example, a transformer could operate for several hours with more than 100% of the nominal power without a reduction of lifetime, if it cools afterward.

3.2.4 Maximal power change

The maximal power change is defined as the maximal possible power change per time. It is determined by the system's thermodynamic or electric properties. In future, this is very important for the regulation between generation and load of the electrical grid. For example, conventional power plants with steam turbines have a very small power change of 3-6 % of the nominal power per minute, contrary to this gas turbines have a power change of 20 % of the nominal power per minute and even gas engines 2.5% per second [7], and exactly these gas turbines and engines will play a fundamental part in the future electrical grid. [8]

3.2.5 Maximal power switching frequency

The maximal power switching frequency describes the number of possible power change operations during a time period. It is important for the regulation and operation of the system. With the fluctuating feed-in of some decentralized producers it is very important to be able to react fast.

3.2.6 Switching operations

The switching operation describes the absolute number of switch-on and switch-off operations of systems.

3.2.7 Cold start

It describes the possibility of a system to start after a long period of time without a warm up phase of the system.

3.2.8 Warm start

The warm start is the ability to start the system after a short break.

3.3 General system characteristics

The general system characteristics describe important parameters for the economic and technical side of the operation of a system. They are necessary for the implementation and optimization of the control strategies for each system.

3.3.1 Yearly operation hours

The hours the system runs under full and part load within the period of one year. This parameter is determined by the control strategies and also has an impact on the economical side of the system

3.3.2 Full load hours

The time a system works with nominal power. This is an indicator for economic efficiency and is usually used for systems with fuel requirements like fossil plants and smaller CHP systems. For example a PV-system has approximately 4380 h of irradiance within a year. The full load hours of the system in Germany are around 900 h [8].

3.3.3 Maintenance interval

The maintenance interval usually is the time span between two maintenance procedures. This has an impact on the control strategies especially concerning to the time the maintenance should be done to cause the least non extra break times to the system.

3.3.4 Island Mode

Is the ability of the system to operate without any connection to the electrical grid e.g. like an uninterruptable power supply in a hospital or the CHP in Skellefteå.

3.3.5 Black start ability

This parameter describes the possibility of a system to restart by itself after a shut-down of the electrical grid without receiving electric power from the grid.

3.3.6 Volatile or controllable

This parameter describes the basic functionality of a system. Volatile systems like PV and wind generators are only driven by the weather and are not controllable. It is not possible to control the real energy output of this systems for a certain time. Their power generation can increase or drop down very fast. Controllable means having the ability to control the power output over the whole operation time. For example, conventional power plants or CHP are controllable systems.

4 Coupling points

In this chapter a conclusion of possible coupling points between the different energy grids is given. All the systems transform the input power into another type of power, for example electrical power into heat power. For all systems a high number of available types are considered and analyzed to give an overview on possible configurations.

In chapter 5 the connection between the coupling points, the use cases and the demonstration sides are described.

4.1 Combined heat and power

Combined Heat and Power is the state-of-the-art in today's power plants. It is an opportunity to increase the efficiency of the processes by waste heat recovery. In this way a higher saturation of the used fuel is realized.

4.1.1 Gas turbine

Gas turbines are lucrative for CHP application where very high temperature standards are necessary and less space and high power levels are required. The gas turbine also allows, in combination with systems which use external heat sources (e.g. steam turbines and engines), the achievement of very high electric efficiencies up to 60 %. These are the benchmarks which could be reached with combustion of fuel. Only the fuel cell technology gets similar values. But the fuel cell is not finally developed and not available on large scale on the market. A further advantage of the gas turbine is the availability in a high range of nominal power classifications. Because of this, it is especially interesting for cities where difficult applications are possible.

4.1.1.1 Nominal parameters

A data base of 66 different types is used to find key parameters [9]. The turbines have a nominal power from 0.495 MW_{el} to 274.6 MW_{el}. In Figure 4-1 the results and functions of the data base analysis are represented. All power functions are linked to the right axis while all values with normalized unit are denoted to the left axis. The dots are the real data and the curves are regression lines for the given functions.

All available parameters in the data base:

- Type, electric nominal power — $P_{el,nom.}$ — [kW]
- Fuel nominal power — $P_{th,nom.fuel}$ — [kW]
- Nominal electric efficiency — η_{el} — [%]
- Necessary gas pressure (absolute) — p_{fuel} — [bar]
- Exhausting mass stream — $\dot{m}_{exh.}$ — [kg/s]
- Exhausting temperature — $T_{exh.}$ — [°C]
- Thermal power — P_{th} — [kW]S
- Steam mass stream — $\dot{m}_{steam.}$ — [t/h]
- Thermic efficiency — η_{th} — [%]
- Total efficiency — η_{total} — [%]

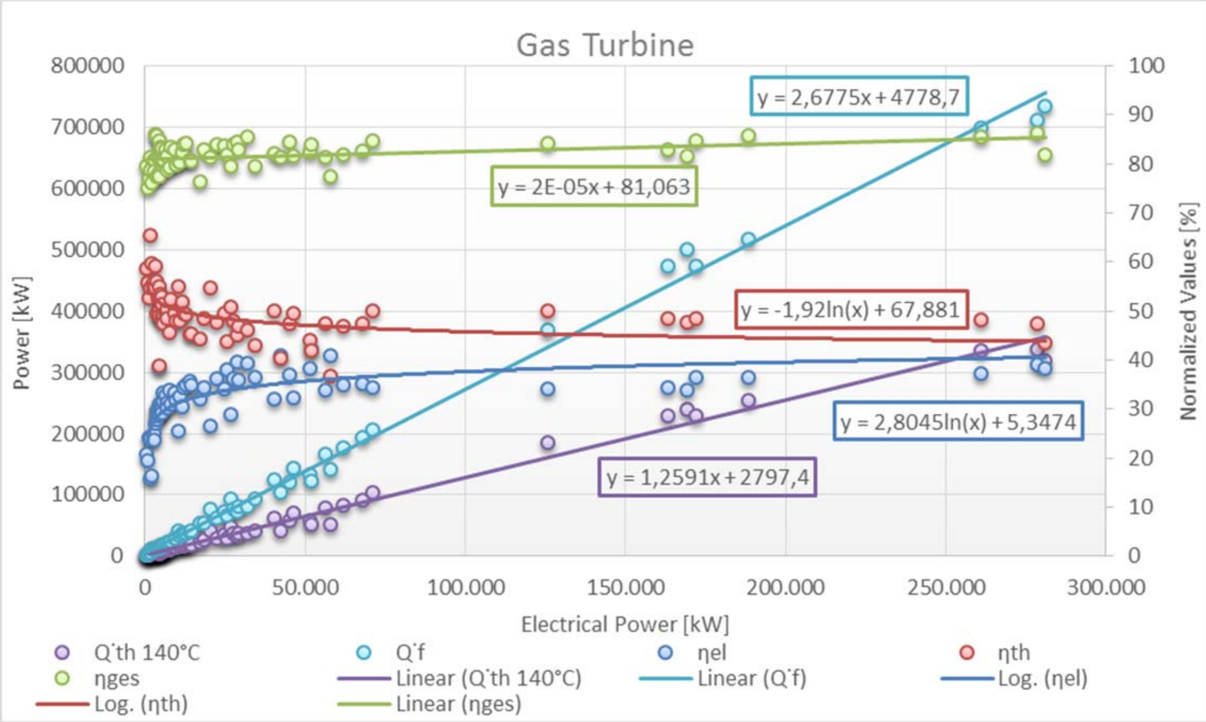


Figure 4-1: Nominal parameters and functions of gas turbines [9]

4.1.1.2 Dynamic Parameters in part load operational range

The minimal run power is 20% of the nominal power [10a]. Furthermore, there are different opportunities to raise the power to the maximal run power, but they are accompanied by negative effects on the life span of the gas turbine. This will be explained in chapter 4.1.1.3. An increase of the turbine entry temperature allows raising the power up to 5-10 % of the nominal power. Water and steam injection increase the nominal power to 18 % [10b]. The Figure 4-2 approximately describes the relative electric efficiency in part load operational range [10a].

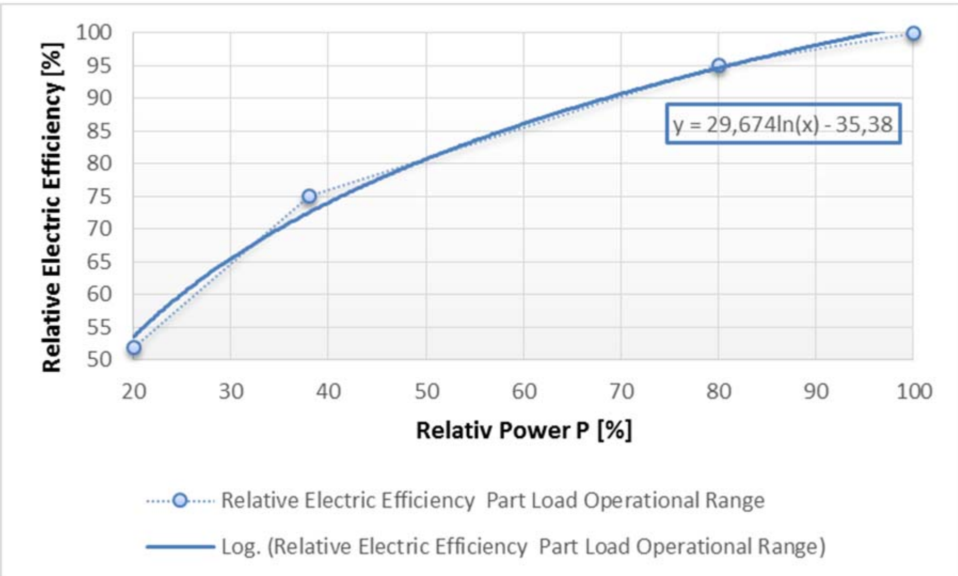


Figure 4-2: Function of the relative electric efficiency of a gas turbine [10]

The gas turbine owns the ability to change the actual power output by a ramp of 10 % of the nominal power per 10s, which is useful for grid regulation [10c]. After a break of 6-8 hours the gas turbine can reach nominal power after 35 minutes. The important figure for the launch is the temperature of the gas turbine. In the case of a cold start it takes around 3h to reach nominal power [10d].

4.1.1.3 General system characteristics

The operating and full load hours depend on the operating method. In general, black start ability is possible but it is not common for gas turbines.

Maintenance intervals are very important for a safe and sustainable operation of the gas turbine. Minor inspection includes a stop for 2-4 days, being necessary after approximately 8,000 operating hours. The major inspection consists of a comprehensive deconstruction and a detailed visual check, including e.g. hot-gas-path inspection after 24,000-41,000 operating hours [10].

After 10.000 operating hours the ageing of the gas turbine causes a loss of 2–4% of the nominal power and a loss of 1–3% of efficiency [10e]. A detailed description of the impact of ageing is given in the ISO 3977-9 [10f]. Operating the turbine with over load can increase its ageing process tenfold [10b].

The hybrid link to other grid elements is given to steam engine, steam turbine, Sterling engine and Organic Rankine Circling (ORC), as the gas turbine can be a heat source for these machines. Furthermore, the power-to-gas (PtG) and the power-to-hydrogen (PtH) could become important techniques.

4.1.2 Combined heat and power systems (CHP)

Block heat power systems are available in different power classes. They can be used in family houses as well as for supplying the district heating grids in cities. Typically CHP are mainly used for the production of heat, but it is also possible to mainly generate electricity with them. The operating method is influenced by economics.

4.1.2.1 Nominal Parameters

The analysis is based on a data base of 425 types of Otto engine CHP [11]. The Otto circle is the common circle of gas fired engines. In the data base there are also 14 types of pilot injection engines available using bio gas, four types of Diesel gas CHP and three engines which run with extern heat source like process heat or exhaust heat from a gas turbine. The nominal power ranges go from 5 kW_{el} to 18,300 kW_{el}.

All available parameters in the database:

- Manufacturer
- Type, engine
- Nominal electric Power $P_{el,nom}$ [kW]
- Nominal thermic Power $P_{th,nom.}$ [kW],
- Nominal fuel Power $P_{th,fuel,nom.}$ [kW]
- Nominal electric efficiency η_{el} [%],
- Nominal thermic efficiency η_{th} [%],
- Nominal total efficiency η_{total} [%],
- Medium eff. pressure [bar],
- NOX in the exhaust [mg/Nm3]
- CO in the exhaust [mg/Nm3]
- Acoustic noise 1 m [dB(A)]
- Length [mm]
- Width [mm]
- Height [mm]
- Mass [kg]

Figure 4-3 displays the different functions resulting from the data base of the nominal parameters. The setting in this figure is analogous to Figure 4-2.

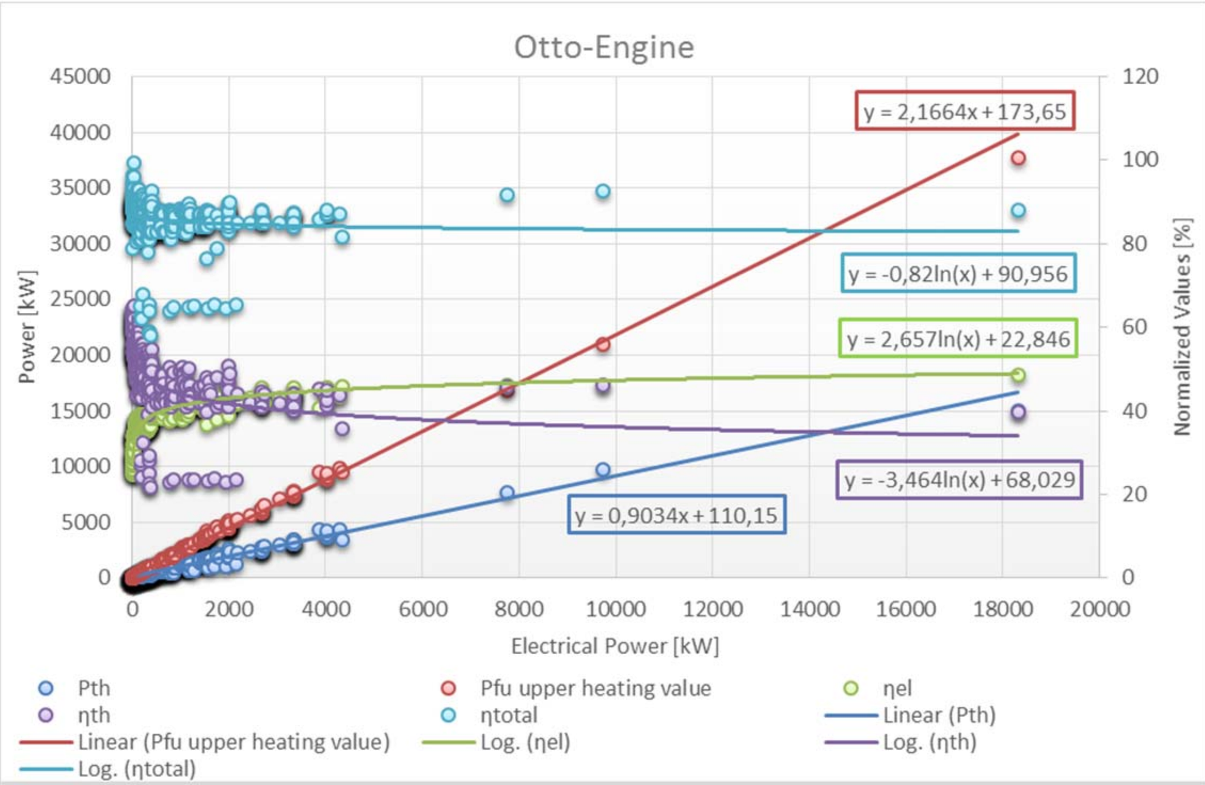


Figure 4-3: Nominal parameters and functions of Otto-Engines [11]

4.1.2.2 Dynamic Parameters in part load operational range

Gas CHP can reduce their power to around 40% of the nominal power with a ramp of e.g. 2.5% per second [7]. The dynamic parameters for power and electric efficiency from one single gas engine power plant are to be found in appendix 5.3.

4.1.2.3 General system characteristics

A major inspection is the cylinder head change, which is necessary after 15,000-35,000 operating hours. A general overhaul is necessary after 35,000 to 60,000 operating hours [12a].

A hybrid-link to other grid elements is given to Sterling engine and Organic Rankine Circling (ORC), as the CHP turbine can be a heat source for this machines. Furthermore, PtG and the PtH can become important technologies because of the gas fuel.

4.2 Electric Boiler

Electrical boilers are known for their high efficiency in energy conversion from electricity to thermal energy. As to this study they are suitable for an efficient conversion of energy caused by peak-shaving operation. They can be used small-scale as well as large-scale units.

4.2.1 Large scale electrical Boiler

For the large-scale electrical boilers some projects of grid operators for providing negative secondary control power exists, for example the one built and used in Munich. They have an installed power of 10 MW, which are provided by 4x2.5 MW electrical heaters. This system has to provide its full power to the grid within less than 5 minutes because of the requirements of secondary control power systems. The system has the following specifications [13]:

- Power: 10 MW_{el}
- Input voltage: 690 V
- Incoming Temperature: 55-62°C
- Outgoing Temperature: 90-150°C
- Nominal Pressure: 25 bar at 20°C
- Power Level: 40 switches with steps of 250 kW

To provide negative secondary control power the system has to fulfill the specifications shown in Figure 4-4.

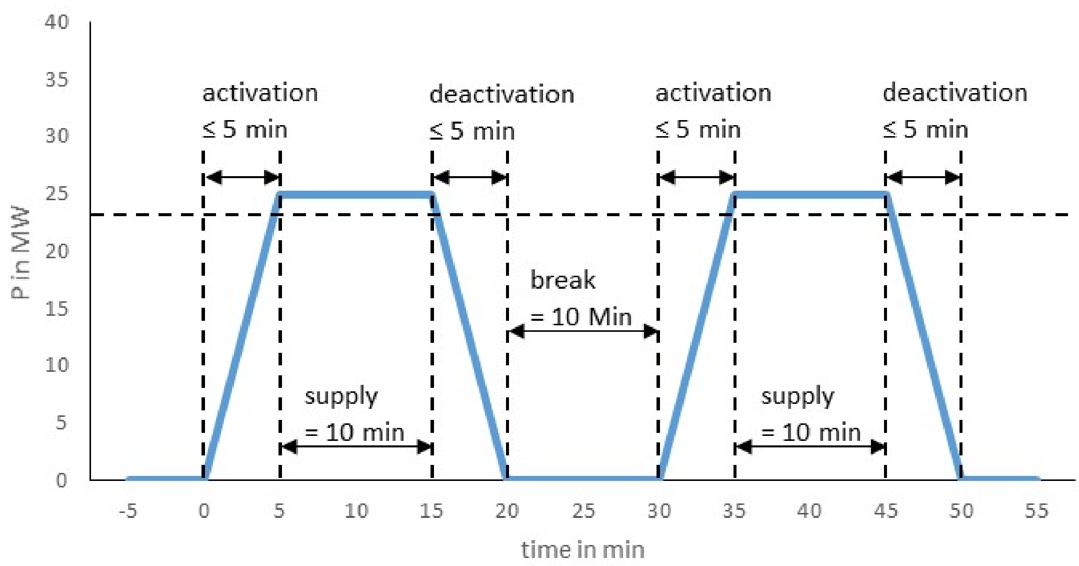


Figure 4-4: Specification for providing negative secondary control power

The system has to provide its full power within less than 5 minutes and it has to shut down in less than 5 minutes, too. For the test it has to supply the negative secondary control power for a period of time of 10 min. A break of 10 min is scheduled between the deactivation and the activation. For such a big scale boiler the high amount of energy consumption could be problematic for the grid and has to be considered in the definition of the connection point. Otherwise, additional costs could arise due to utilization of the power lines and the transformer.

4.2.2 Small scale electrical Boiler

The small scale boiler can provide warm water and supply the heating systems in households. There are many electrical boilers available for this application with efficiency of nearly 100%. Such systems could be used for peak shaving and for the transformation from electrical energy to thermal energy. The electrical boilers can consume almost their full electrical power immediately after switching on. The full thermal power can be delivered after a heating up period. Those systems have quite a fast response. The data base of this statistic overview contains 66 electrical boilers of a nominal electrical and thermal power output between 1.1 and 350 kW. Their flow temperature is between 32 and 350 °C. The thermal power shows a linear dependence on the electrical power. The dependence on the electrical power is shown in Figure 4-5.

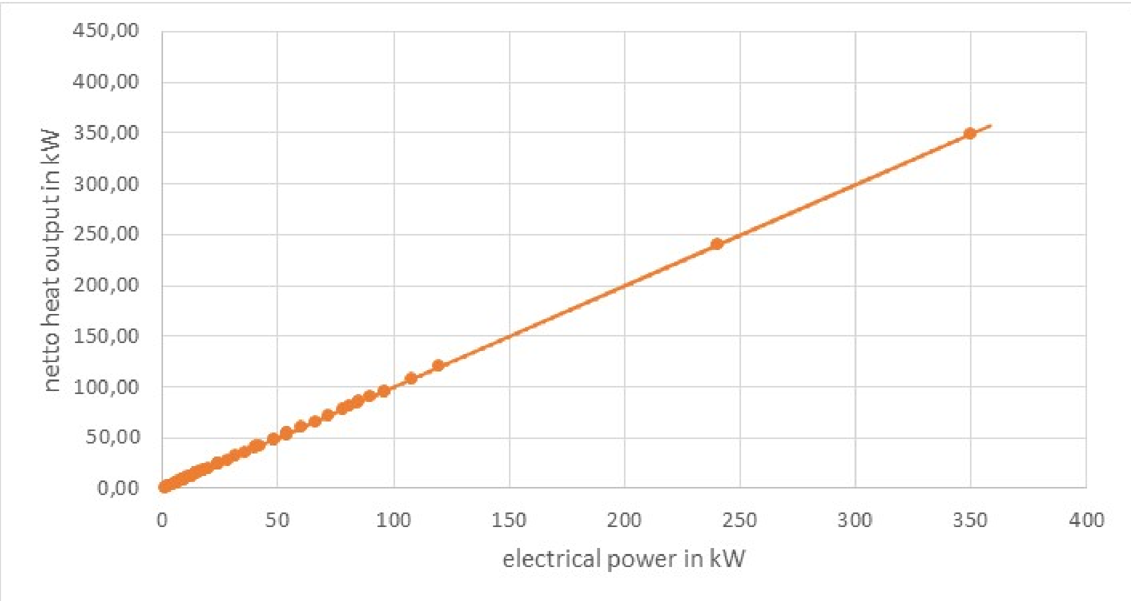


Figure 4-5: Dependence of electrical and thermal power

The connection between the thermal and the electrical power can be illustrated by a linear function. This is due to the efficiency of energy conversion of almost 100% with only a small variation. This is achieved through the use of constant temperature and a specific minimum flow rate per minute. The comparison between the thermal output and the flow rate is shown in Figure 4-6.

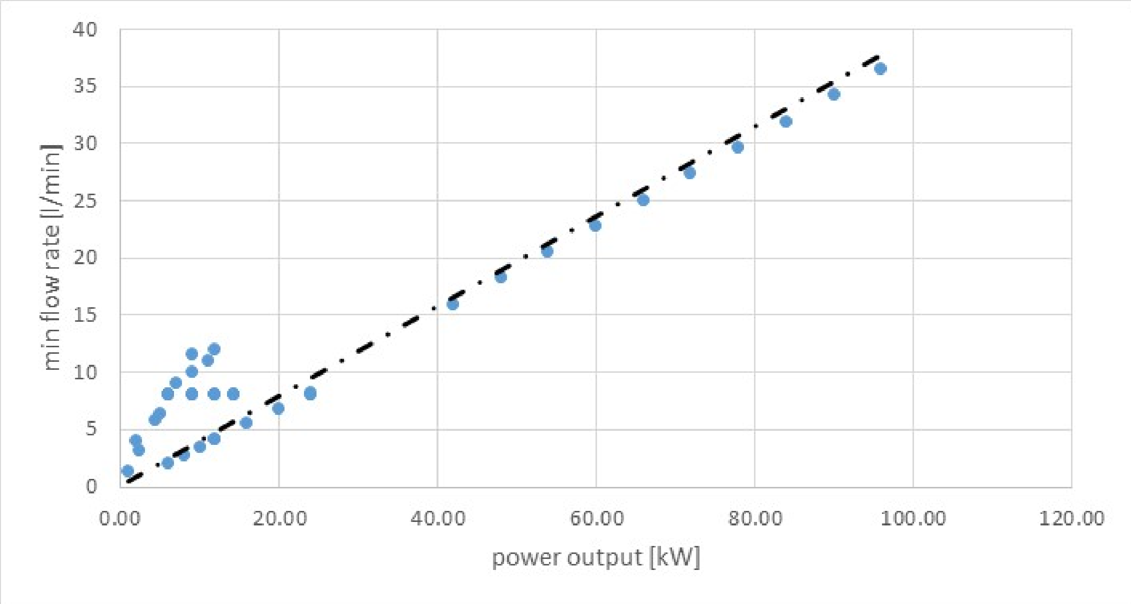


Figure 4-6: Min flow rate against power output

The single flow rates can also be connected with a linear function. The coefficient of determination is calculated as 0.8423. This figure implies that the linear regression is quite good, especially for the bigger electrical boilers. Boilers with less than 20kW show a maximum in variation.

4.3 Heat pump

The electric driven heat pump (HP) can switch electric power into thermal. But this gives the opportunity to mount electric power away from the grid if e.g. PV systems feed-in more power as the electric demand needs. The building mass or thermal storages allows to buffer the short time energy's from the electric grid. In Germany 1.5 GW nominal electric power from HP are installed in 2011. Another parameter for the flexibility of the HP is the question to comfort of the customers. A higher temperature band in the rooms allows more flexibility [14a].

4.3.1.1 Nominal parameters

The nominal parameters of the heat pump are given for one single operating point, with the exception of the air-water-HP. There are three operating points available in the data base. This is highly relevant for the efficiency in other operating points, as the HP usually runs in different operating points. Table 4-1 gives an overview of the different available figures. The degree of quality describes how close to the Carnot-Efficiency the efficiency of the HP is. These values are important for the dynamic characteristic of the HP (Chapter 4.1.1.2).

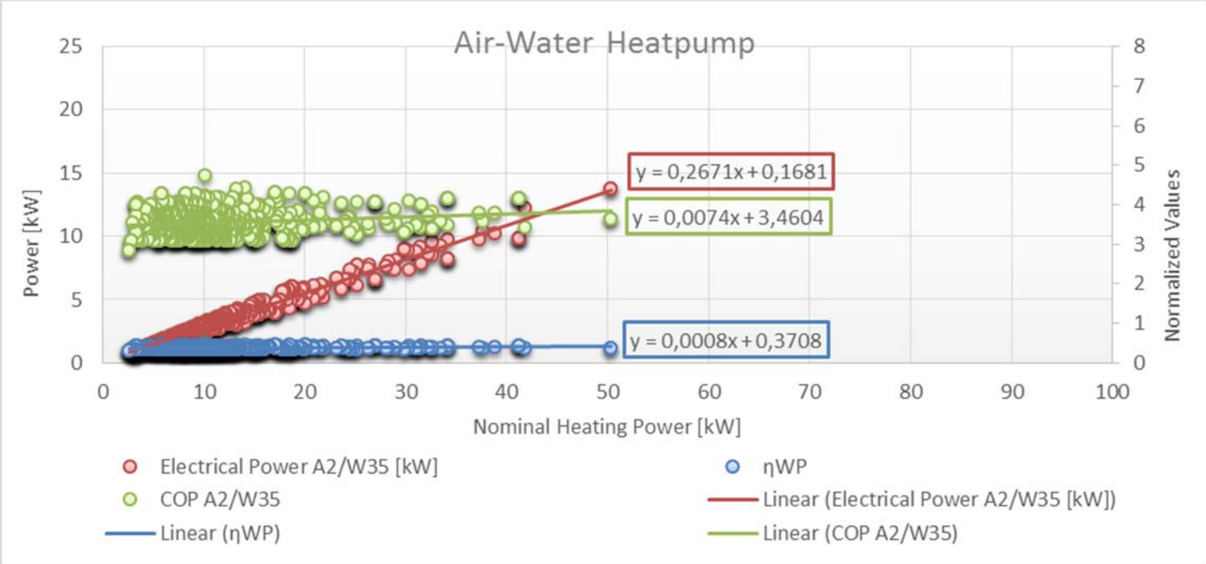
Table 4-1: Overview of the data base of the HP [15]

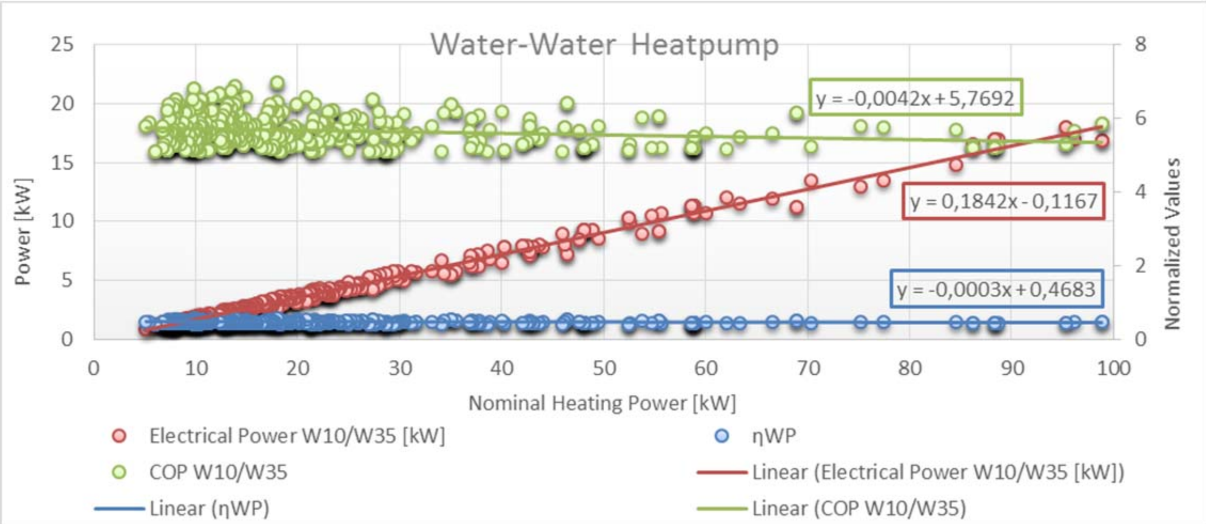
	Number of HP types	**Nominal heating power [kW]**	**Nominal electrical power [kW]**	**Degree of quality η_{WP} [-]**	**Temperature conditions in data base [°C]**	**Delta T in the data base [K]**
Air-Water HP	598	2.58 – 50.32	0.81 – 13.75	0,38	A-7/W35; A2/W35; A10/W35	42, 33, 25
Water-Water HP	458	5.1 – 98.86	18.0- 0.88	0,46	W10/W35	25
Brine-Water HP	716	90.3 – 3.7	0.82 – 21.2	0,52	B0/W35	35

Further available parameters in the data base:

- Manufacturer
- Type
- Coefficient of performance (COP)

The Figure 4-7 shows the functions for the air-water, the water-water and the brine-water HP, which results from the data base. The axis description is analogous to the description in chapter 4.1.1.1.





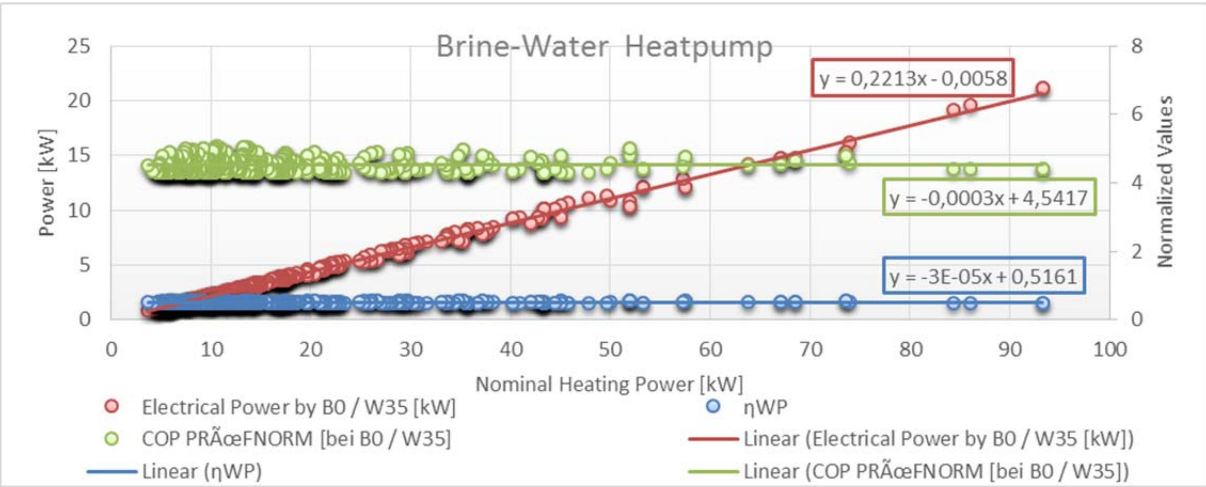


Figure 4-7: Nominal parameters and functions of Air-Water, Water-Water and Bine-Water HP

4.3.1.2 Dynamic Parameters in part load operational range

The COP of HP has a strong dependence on the change of input and output temperature. The temperature is highly affected by the environmental conditions. Especially air-water-HP is strongly influenced by the ambient temperature.

The data base for air-water-HP includes three operating points. This gives the possibility to evaluate the characteristics of the Carnot-Circle in comparison to the function of air-water-HP. The Carnot-Circle is depending on the input and output temperature only. Therefore, it is necessary to multiply the function of the Carnot-Circle by a certain factor. This factor is the degree of quality (η_{WP}). Figure 4-7 shows that the degree of quality is constant for all power levels of the HP. The resulting function is quoted below. Figure 4-8 shows the deviation within a 100 K temperature area.

$$COP = \frac{T_1}{T_1 - T_2} \cdot \eta_{WP}$$
$$T_1 = high\ temperature\ [K]$$
$$T_2 = low\ temperature\ [K]$$

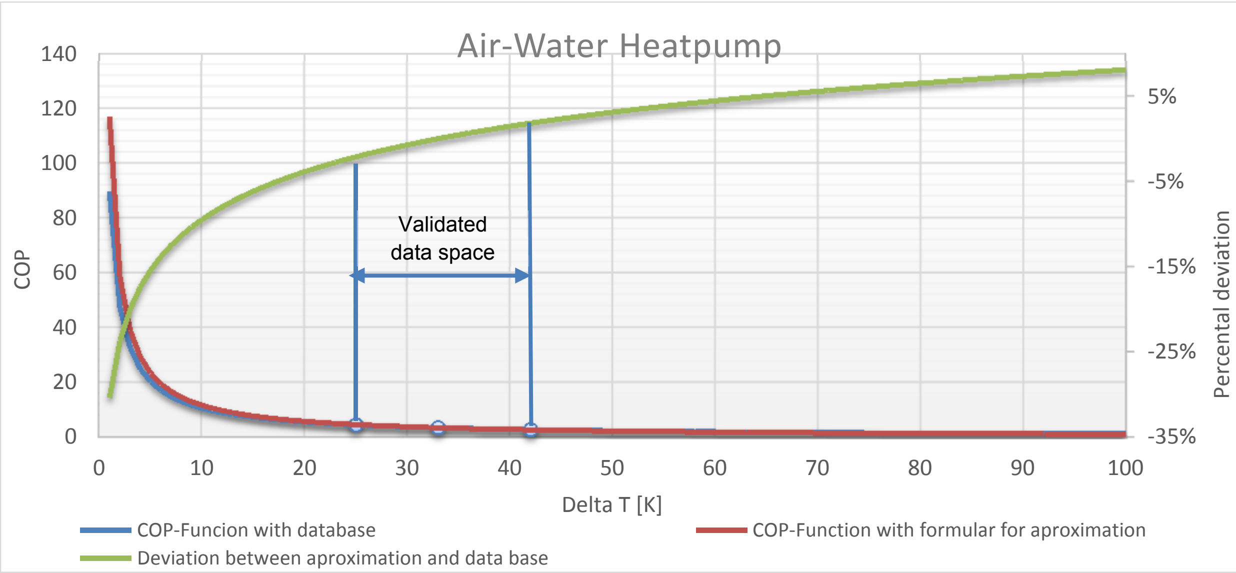


Figure 4-8: Validation of a function of approach on the example of the Air-Water HP

4.3.1.3 General system characteristics

Maintenance is necessary once in a year. The maintenance includes cleaning, measurement and function control of the system components.

The HP has a link to technologies like PV with fluctuating electrical power characteristics, because of the possibility to transfer and feed-in the produced electric power into the heat demand of buildings or district heating grids. The HP is also useful for applications where a constant heat source is available, e.g. back flow of a district heating grid. In this situation the HP can work with a high efficiency over the whole year.

4.4 Roof mounted PV-systems

Beside solar radiation the PV module technology has a big impact on the feed-in power of a solar system. This chapter gives a short overview on the physical process of the transformation of solar radiation into electric energy and highlight why knowledge about meteorological values is important.

4.4.1 Physics of solar cells

It is important to have a look at the physics behind the energy transformation of a solar cell and at the energy of a photon (E_{PH}) to describe a PV module. The following formula shows the physical expression of the energy of a photon at a certain wavelength.

$$E_{PH} = \frac{h \cdot c}{\lambda}$$

In this formula λ represents the wavelength, c is the velocity of the light and h is Planck's constant. The wavelength is influenced by clouds as well as by the path the sunlight takes through the atmosphere, which again depends on the sun elevation angle. On the contrary c and h are invariant constants. When an electron is hit by a photon it changes its energy level and moves from the valence band to the conduction band. This process is shown in Figure 4-9 for a Si-semiconductor [16].

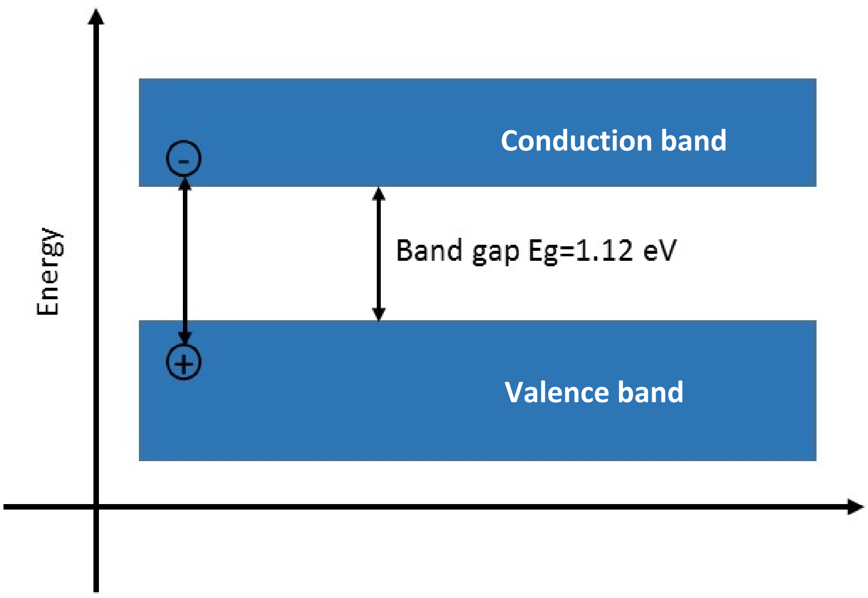


Figure 4-9: Visualization of the Generation of a negative and positive charge in the semiconductor

The energy of a photon has to be higher than the energy of the band gap in order to be absorbed. When the photon is absorbed, the semiconductor generates a positive and negative mobile charge. By doping the semiconductor the conductivity can be increased. When joining n- and p-doping semiconductors a space charged region is obtained. Within this region an electric field is generated by separation of positive and negative fixed charges [16].

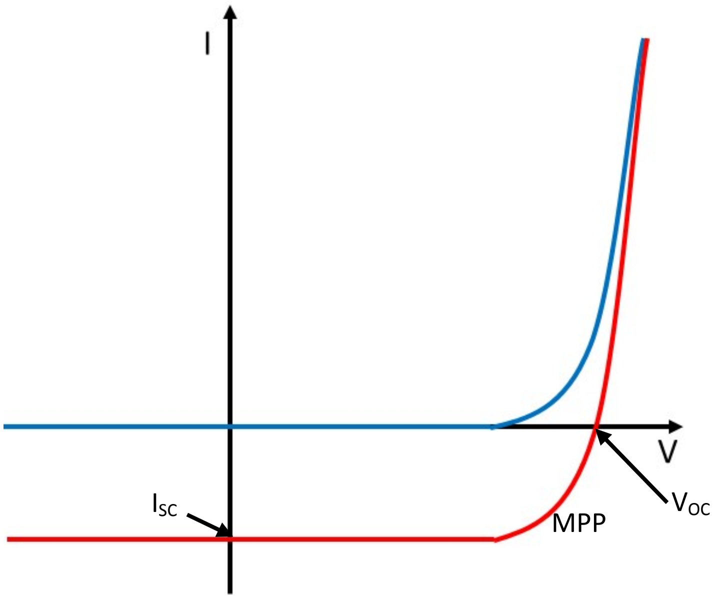


Figure 4-10: Qualified I-V characteristic of a solar cell.

Figure 4-10 shows the I-V-characteristics for dark and positive bias (blue) and for illumination (red). It can be easily understood, that the current increases with irradiance. Furthermore, efficiency of irradiance usage depends also on the spectrum and the used semiconductor material. Important values for describing a solar cell are open circuit Voltage (V_{OC}), short circuit current (I_{sc}) and the maximum power point (MPP). A solar cell can be described in an equivalent electrical circuit, which is shown in Figure 4-11.

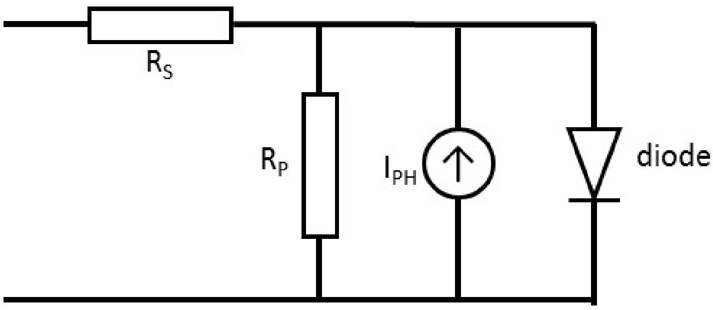


Figure 4-11: Electrical equivalent circuit of a solar cell

The equivalent circuit consists of a diode for the dark current, an antiparallel current source for the photocurrent (I_{PH}), the series resistance (R_S), which includes the resistance of the contacts, the layers and the interconnects, and the parallel resistance (R_p), which depends on the used technology and has an impact on the performance of the device [17]. A solar cell can be set up e.g. as polycrystalline or mono-crystalline silicon or by using thin film techniques. The used cell technology has a big impact on the module efficiency and influence to the electric grid [18]. The efficiency of the modules can also be improved with several techniques shown in the Table 4-2.

Table 4-2: Limitation of the efficiency and methods to increase the efficiency [16}

Regulated by	Caused by	taken steps Against
reflection and transmission losses	refractive Index low absorption index low optical thickness	anti-reflection layer texturing of the surface back surface reflection layer direct semiconductors
absorption losses	photon energy smaller than band gap	optimization of the band gap multi-junction solar cells
	photon energy bigger than band gap	optimization of the band gap multi-junction solar cells
open circuit voltage	thermodynamics material parameters	semiconductor technology passivation
resistors	resistor of the semiconductor resistor of contact fingers resistor of serial interconnection material defects	buried Contacts process optimization

The connection of many solar cells in series or in parallel creates a PV module. A serial connection increases the voltage while a parallel connection increases the current. This is shown in Figure 4-12.

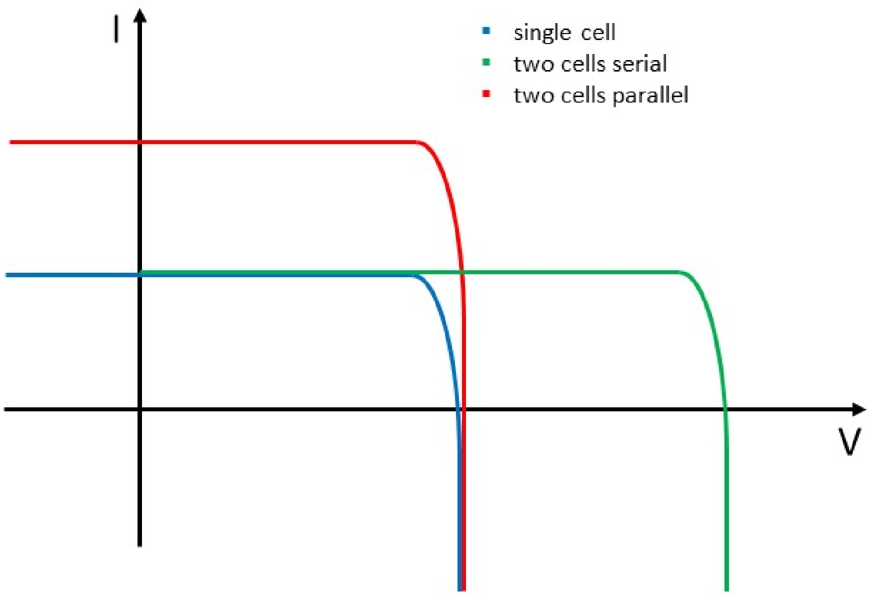


Figure 4-12: Influence of the kind of connection of solar cells

Annual energy output of a PV-system

The planning of a PV-system includes a calculation of the annual electrical output. There are many ways to get the annual yield of a PV-system, e.g. by using the PVGIS application provided by the JRC

[19] using long-term satellite data or other online resources [20]. It is also possible to calculate the annual yield with the following formulas.

$$\eta_{module} = \frac{P_{stc}}{1000\frac{W}{m^2} \cdot A_{modul}}$$

$$Y = \frac{E_{AC}}{P_{nen}}$$

$$PR = \frac{E_{AC}}{E_{module} \cdot A_{module} \cdot \eta_{module}}$$

In these formulas η_{module} represents the module efficiency, P_{STC} the power of the module under standard test conditions, A_{module} the module area. Y is the final yield, E_{AC} is the annual yield of the PV-system, P_{nom} is the installed power of the PV-system and PR is the performance ratio of the PV-system [12]. The annual yield of the grid integrated PV-Systems is a first indicator for the grid situation [21]. The difference of the feed-in PV-energy and the consumed electrical energy gives a first insight into the energy flow through the transformer. At a ratio of 1 the area can supply itself from an annual point-of-view. However, the analysis of time series shows overproduction and underproduction during the year where the consumption has to be suffered by the electric grid. This is the reason why a close look on the grid is necessary.

4.4.2 Impact of the PV-module technology to the grid

With the development of more efficient PV modules there is an impact on the electrical grid like the voltage and the loading of the grid elements. The impact of different technologies and the development of the PV-modules are shown in photovoltaic potential analysis of the test site 1 in Ulm-Einsingen. Further information to this test site is available in D6.1. The used modules are different in the material and/or in the year of production. At a first step is to look on the installable PV-power on the equal roof area. Figure 4-13 shows the different installable power values of the various module technologies. In this case one module technology is used for its whole suitable area.

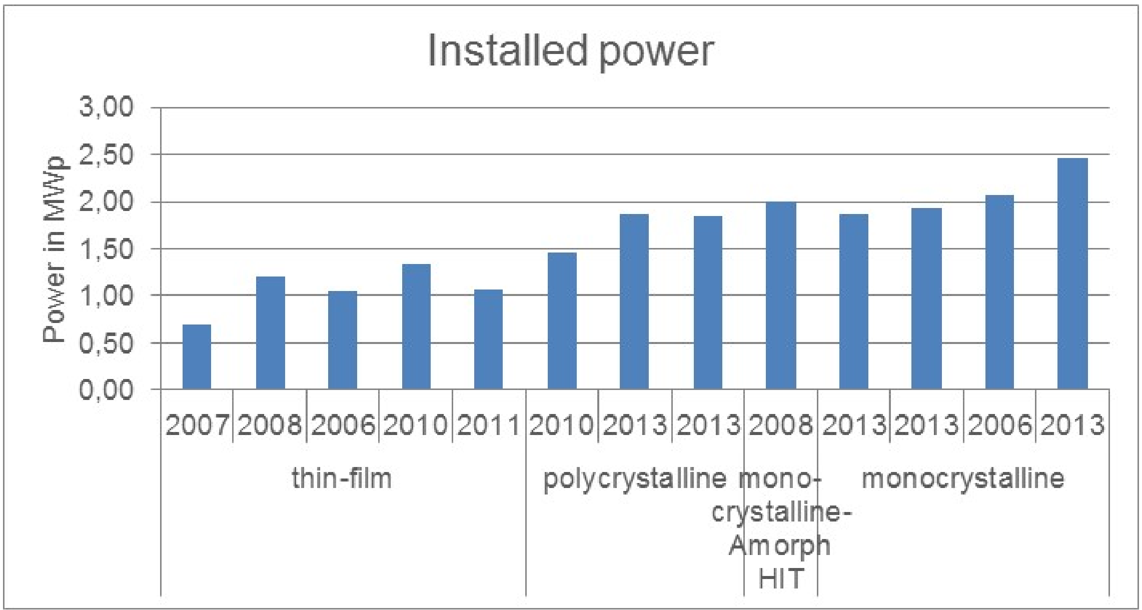


Figure 4-13: Installable power in the Test side 1

Figure 4-13 shows the installable power for the different types of solar modules depending on the year of production. This is the same for all following figures. HIT stands for hetero-junction with intrinsic thin-layer. Depending on the used module a power up to 2.5 MWp can be installed on the roof tops. By the use of thin-film PV-modules only a maximal power of below 1.5 MWp can be installed. This also causes problems for utilization of the transformer. The maximal utilization can increase up to 226%. The maximal utilization of the transformer is shown in Figure 4-14.

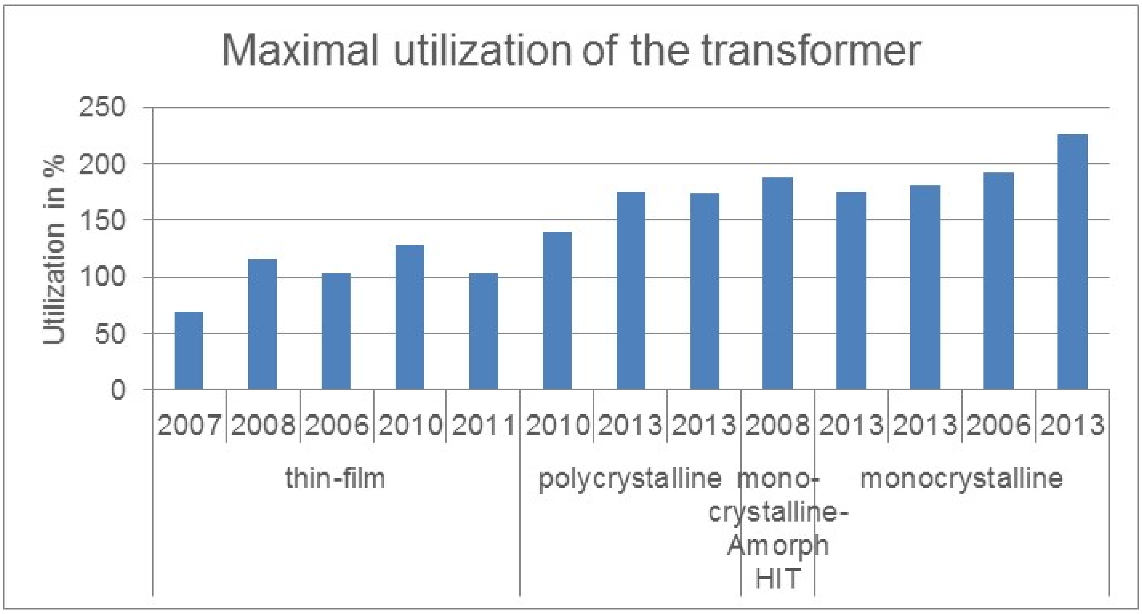


Figure 4-14: Maximal utilization of the transformer depending of the PV-module technology and production year

A maximal utilization above 140% decreases the lifetime of the transformer. The analysis shows an enormous influence of the utilization of the transformer depending on the used solar module technology. For such a high utilization it is necessary to do an analysis of the voltage level in the grid. Figure 4-15 shows the maximum voltages in the grid.

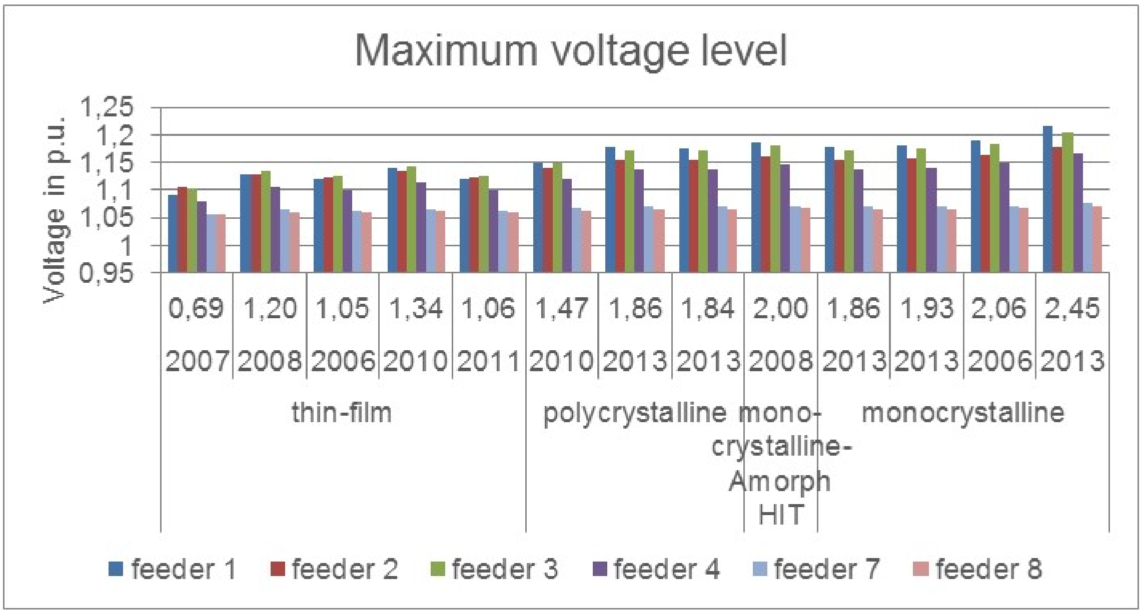


Figure 4-15: Maximum voltage level depending on used solar modules

Figure 4-15 shows a significant rise in the voltage level. The standard DIN EN 50160 defines an allowed voltage range between 0.9 and 1.1 p.u.. The problem with this maximum voltage is the stiff connection between the medium and the low voltage level. As a result of this stiff connection and the circumstance that the last controllable system regularly is between the high and medium voltage level, the maximum voltage for the low-voltage grid is defined at 1.05 p.u., because the allowed 10%-voltage band has to be divided in two parts, one for the low voltage level and one for the medium voltage level. This makes it necessary to analyze the time the voltage is above this border. This result is shown in Figure 4-16.

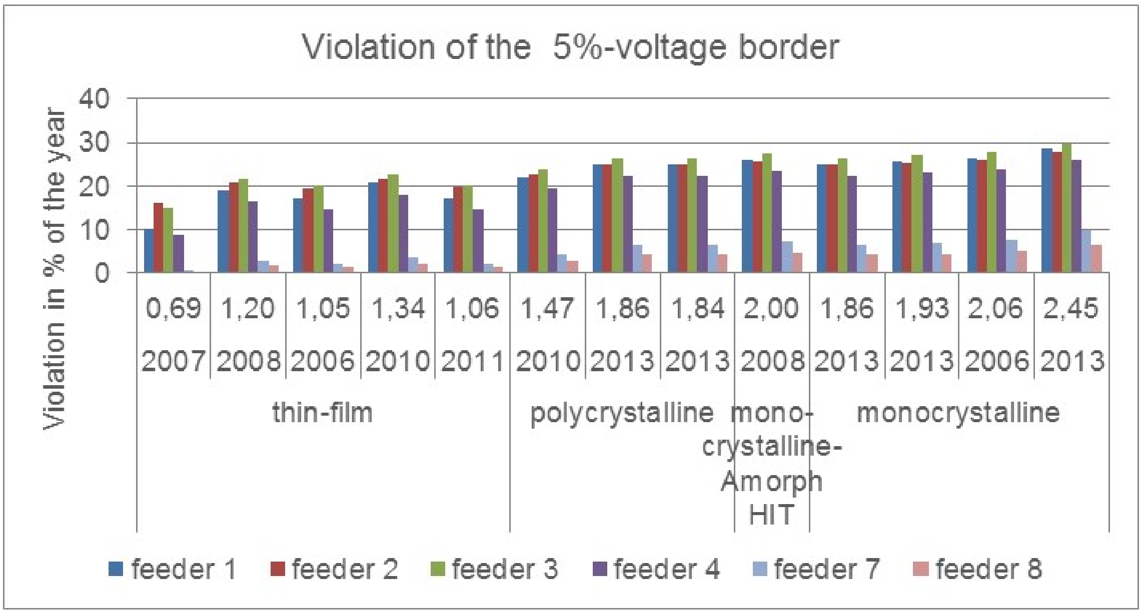


Figure 4-16: Violation of the 5%-voltage border depending on module technology

Figure 4-16 shows a high violation of the 5%-voltage border. Therefore options to stabilize the voltage below this border are necessary. An approach, which could be performed by the PV-systems itself, would be using reactive power. When using reactive power the utilization of the resources has to be below 100% for the transformer and below 80% for the cables. This is due to a rise of the utilization of the resources when using reactive power. Figure 4-17 shows the time the cables are above this limit in per cents of the year.

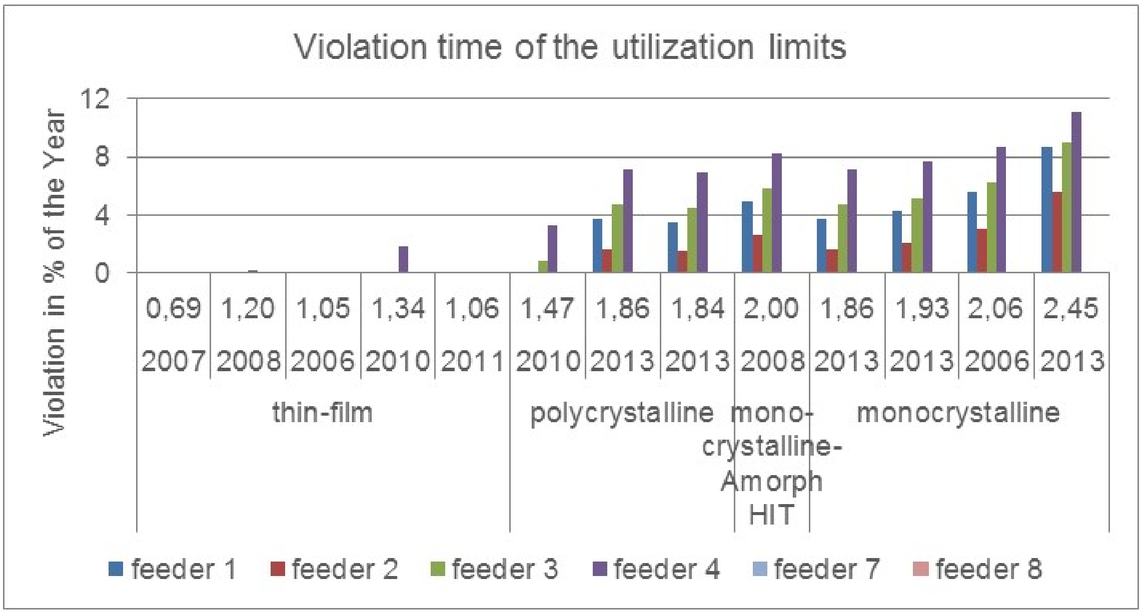


Figure 4-17: Violation time of the cables depending on the used module

For the use of Si-Solar modules the reactive power is no choice for lowering the voltage level in the investigated test site. When using thin-film solar modules there is the possibility to keep the voltage below 1.05 p.u. by using reactive power or by installing low voltage regulation systems or even by using an adjustable transformer for the supply of the low voltage grid.

In the supply area of SWU there are already over 4000 PV-systems installed. In some villages the high amount of PV systems results in problems with the voltage level and the utilization of the electric grid infrastructure. The total nominal power of installed PV-systems in the supply area of SWU is 88.6 MWp, while 64.7 MWp are connected to the low voltage grid and 23.9 MWp are connected to the medium voltage grid.

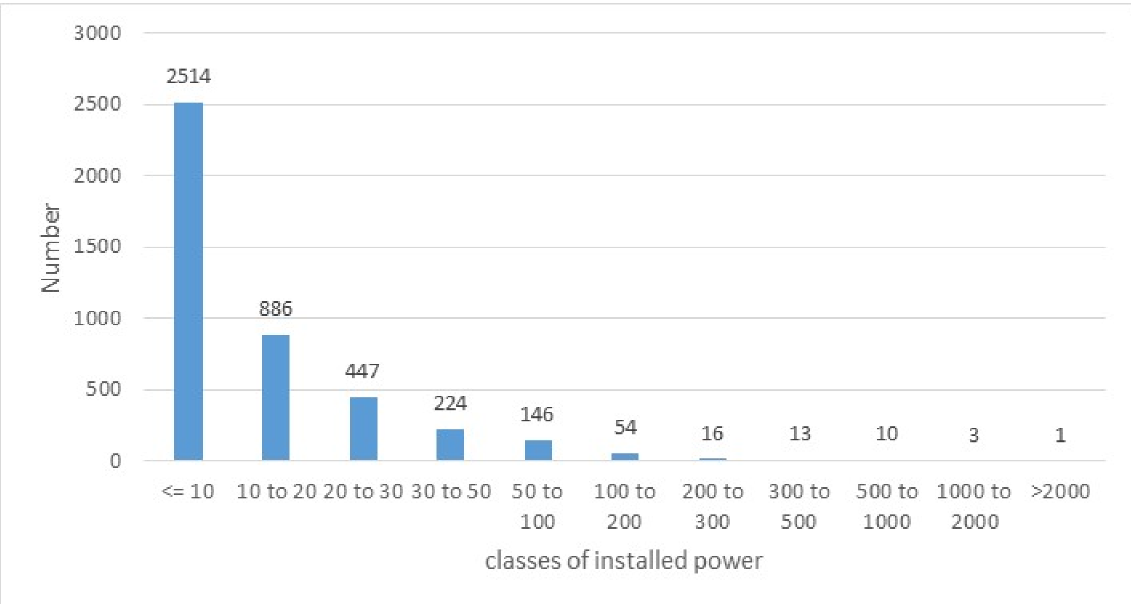


Figure 4-18: Classified installed PV-Systems with a logarithmic scale of the number of systems

Figure 4-18 provides an overview on the installed PV-systems classified in power classes. As it is visualized in the figure most of the installed PV-systems are small scale PV-systems. This means that most of them are roof integrated PV-systems which are typically connected to the low voltage level.

4.5 Power-to-gas

Often peaks in the electrical grid are caused by the fluctuating feed-in of renewable energies. The time with higher generation than consumption grows continuously. Power-to-gas systems could be a solution to minimize electric surplus problems. They can be an opportunity for peak shaving measures and also for seasonable storage. When more energy is produced than consumed the power can be used to transform it into hydrogen by using electrolysis or hydrolysis. Further existing possibilities are:

- Up to 5% of hydrogen can be directly stored in the gas grid [22].
- The hydrogen can be stored in tanks and used in other applications
- With the methanation process the hydrogen can be transformed into methane. This can be realized with the Sabatier process or in a bio-reactor by using specific bacteria

The advantage of methanation is the available gas grid which represents a big storage. It is possible to use the produced gas for heat supply or it can be converted back to electricity if needed. The actual problem concerning this process is the low efficiency. In combination with waste heat recovery processes efficiencies up to 85% are possible [22].

Power-to-gas systems are not state-of-the-art but actual R&D topics with some single demonstration projects around the world. Table 0-1 in the appendix shows an overview of the power to gas projects in Germany.

4.5.1 Distributed gas feed in

The calculation of the dynamic storage capacity of the gas grid is an important component for the Power-to-gas technology. The general gas equation describes the physical interactions between temperatures (T), pressure difference (p), available volume of the pipes (V), mass difference (m) and the universal gas constant (R). However, this is only the energy for the pressure work by pumps. In the Power-to-gas facility the electric energy is converted into caloric energy. This energy can calculate with the caloric value of the gas (mix) and the values of the standard test conditions (STC, T=273.15K and p=101.325kPa).

The values of gas flow into and out of the gas grid is necessary to calculate the gas amount in the grid. Typically, the flow-in can be regulated by the grid operator and should be ensure that enough gas for demand is available. The flow-in is regulated from the grid operator by the pressure level in the gas grid. An overview of the general gas grid values for the demo site Ulm is given in the D6.1. The flow-out is caused by the gas demand of end users or other gas grids, when the grid is connected to lower pressure levels. The temperature has a strong influence of the pressure in the grid and has also a dependency to sessional fluctuations. The pressure value varies between the pressure limits of the next lower and higher level. Therefore, it is necessary to calculate the available gas feed-in potential dynamic over the year.

For the test area in Einsingen in Ulm is a calculated storage capacity of 241 kWh available. It is enough to buffer all PV feed-in surplus in the current situation. The yearly PV surplus is 4734 kWh on the other hand is the yearly gas demand nearly 2400 MWh. But this considered only a small part of the complete gas grid area surrounding Einsingen. To give a statement for the complete storage potential of the gas grid where Einsingen is part of it, it is necessary to involve all pipes demand and PV in the grid area.

General gas equation:

$$E = \Delta p_{gas} \cdot V_{Pipes} = \frac{\Delta m}{M} \cdot R \cdot T_{Ground} \leftrightarrow \Delta p_{gas} = \frac{\Delta m}{M} \cdot R \cdot T_{Ground} \cdot \frac{1}{V_{Pipes}}$$

Equations for the caloric energy amount with the general gas equation:

$$\Delta p_{gas} \cdot V_{Pipes} = p_{STC} \cdot V_{STC} \leftrightarrow V_{STC} = \frac{\Delta p_{gas} \cdot V_{Pipes}}{p_{STC}}$$

$$E_{Caloric} = H_S \cdot V_{STC}$$

Complete energy amount in the gas grid:

$$E_{Gas} = E + E_{Caloric}$$

Table 4-3: Description of the equation components for the gas feed-in calculation

Equation letter	Description	SI Unit
E	Energy	J
p	Pressure is a dynamic value which is influents by the temperature and the mol respectively mass value in the grid	Pa
V	Volume is a constant which is given by the geometric values of the grid	m^3
n	Mol is a number of molecules	mol
R	Universal gas constant	J/kg/K
T	Temperature is a dynamic value which is influenced by the weather and the environment of the pipe.	K
M	Molar mass, for methane CH_4 0.01604	kg/mol
H_S	Caloric Value, for methane 35.883	j/m^3_{STC}

Furthermore, beside the direct feed-in of methane it is possible to feed-in hydrogen. The generation of methane contains an additional transformation with additional losses. Therefore, it seems more efficient to use the potential of hydrogen feed-in until the limitation for the hydrogen feed-in. The DIN 51624 gives a limitation of Hydrogen up to 2%-Vol in Germany. Furthermore, another limitation factor can be given by technical equipment in grid area. Gas turbines can handle hydrogen concentrations between 1 to 5%-Vol. [23].

The Table 4-4 gives an overview for the requirements to the hydrogen concentration for different gas using technical equipment and utilities.

Table 4-4: Possible hydrogen concentrations in selected elements of the gas grid [24]

Grid elelment		Vol-% H_2 in the gas mix
Transmitting pipes	Steel	40 – 50
	Inliner	40 – 50
Compressor/ Turbine		7 – 10 (Limitation cause of Seal parts 5%)
Storage	Cavern	20 – 35
	Sphere	40 – 50
	Tank	40 – 50
Measuring systems	Blind, ultrasonic gas meter, turbine	40 – 50
	Translator	
Control systems	Process gas-phase chromatograph	10 – 15
Distribution pipes	Steel	40 – 50
	Poly ethylene	25 – 25
Applications	Meter	10 – 20
	Burner/ Boiler	20 – 25
	Mobile (Car, etc.)	15 – 25 (Limitation cause of regulations 2%)

Hydrogen in the gas mix changes the caloric and thereby energy properties of the gas mix. It could be necessity for the grid operator to detect the gas molecule to have a precise value for the customers in this area and regulate the hydrogen feed-in.

4.6 Oil boiler

Oil boilers can be used for production of heat as needed for supply of warm water and for supply of the heating systems. When looking at the heating system boilers can be used for single household heating or even for district heating.

It is helpful for the simulation of oil fired boilers to divide the system into three subsystems. The first one is the thermochemical process. In this process the oil burner and the combustion chamber are integrated. The next subsystem is the thermodynamic process in the riser/downer. The third is the thermodynamic accumulation process in the boiler drum. Every subsystem has to be described in mathematical expressions to model these systems [25]. The efficiency of oil boilers typically ranges from 65% to 93.3%. The average value is at 81.2%. The efficiency of oil boilers depends on the system configuration and on the installation. There are scientific papers available where simulation models for oil boilers are described [25, 26].

4.7 Gas boiler

Gas Boiler can be used for heating and warm water production. In this chapter a summary of several different manufacturer data (Viessman, Junkers, Buderus and Weishaupt) is given.

The typical efficiency for older gas boilers is around 90 %. The 10% loss is caused by the heat in the exhaust. Nowadays the systems are modified to reduce the waste heat. This allows efficiencies around 98 – 99%.

Today a big amount of houses operate their heating systems with gas boilers. Normally they are connected directly to the gas grid. In the future it could be possible to convert the electrical power surplus into methane and supply the gas grid or even a micro gas grid.

In Figure 4-19 the nominal input power over the nominal heat power for 117 different gas boilers and four different manufacturers is mapped. The investigated nominal thermal power ranges from 7 to 526 kW while the nominal input power goes from 7.8 to 542 kW. The minimal power consumption of the systems ranges from 15 to 21 W while the maximum goes from 38 to 660 W. The minimal flow rate is in a range from 256 to 600 l/h.

It is easy to see that the different boilers only slightly differ in what concerns the efficiency. The mean efficiency is 97.4%. In the diagram only displays state-of-the-art gas boiler with waste heat recovery [27, 28, 29, 30].

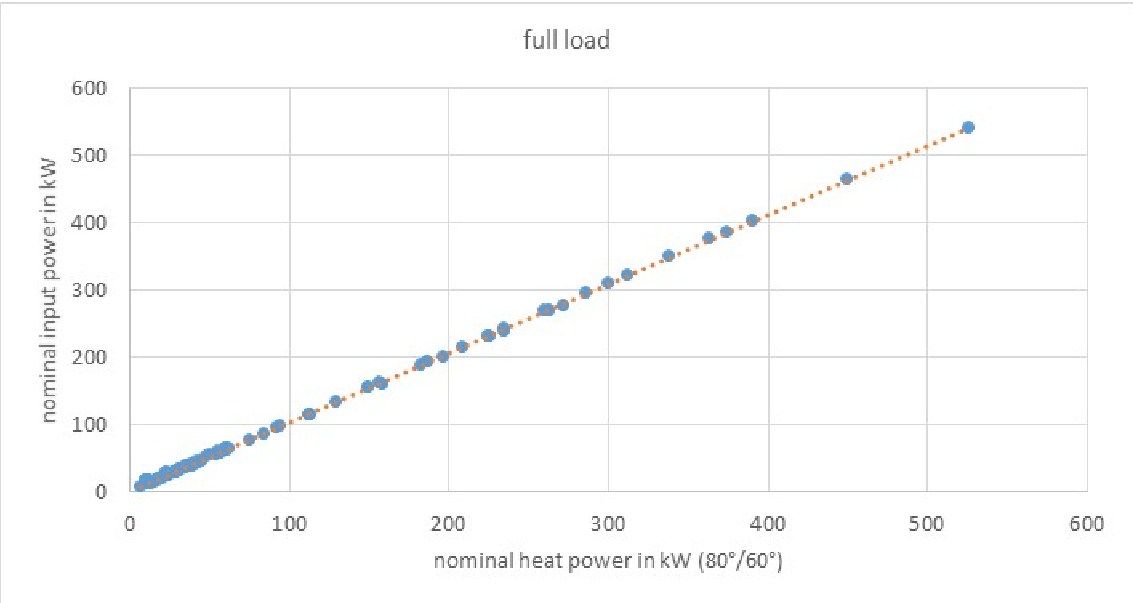


Figure 4-19: Nominal input power over nominal heat power for full load

In Figure 4-20 the nominal input power over the nominal heat power for part load operation is mapped. There are only 58 boilers included because the variance of the technical data sheets. Only for these boilers the nominal input power was given for part load operation. The mean efficiency is also 97.4%.

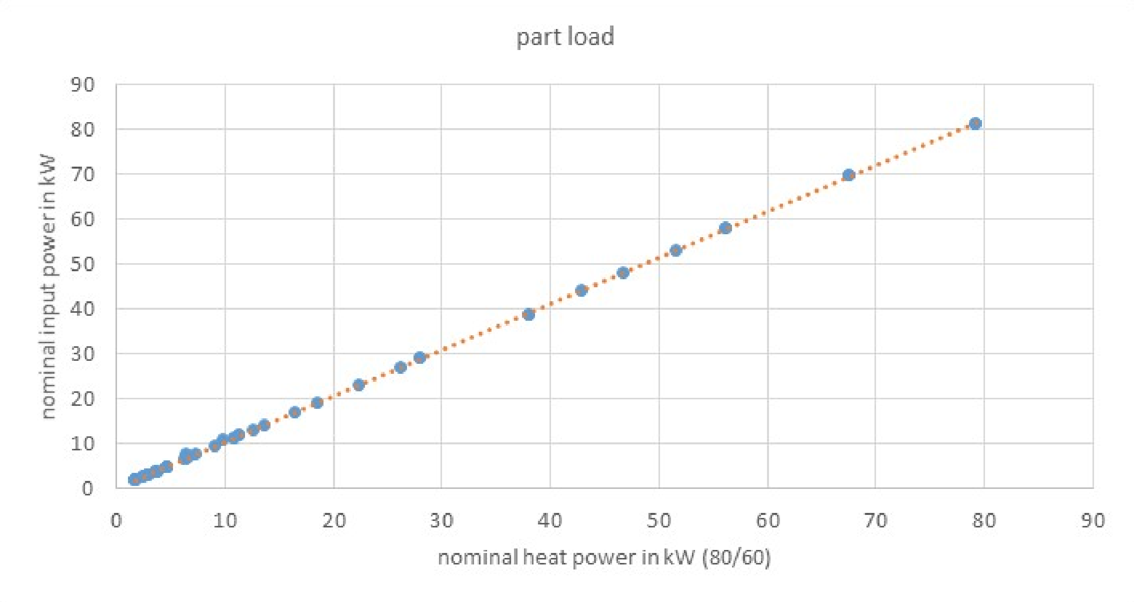


Figure 4-20: Nominal input power over nominal heat power for part load

In Figure 4-21 the nominal flow rate over the nominal heat power for full load is mapped. There are only 22 systems included as they were combined systems of heater and tank. For the other boilers several tanks are available depending on the size of the house.

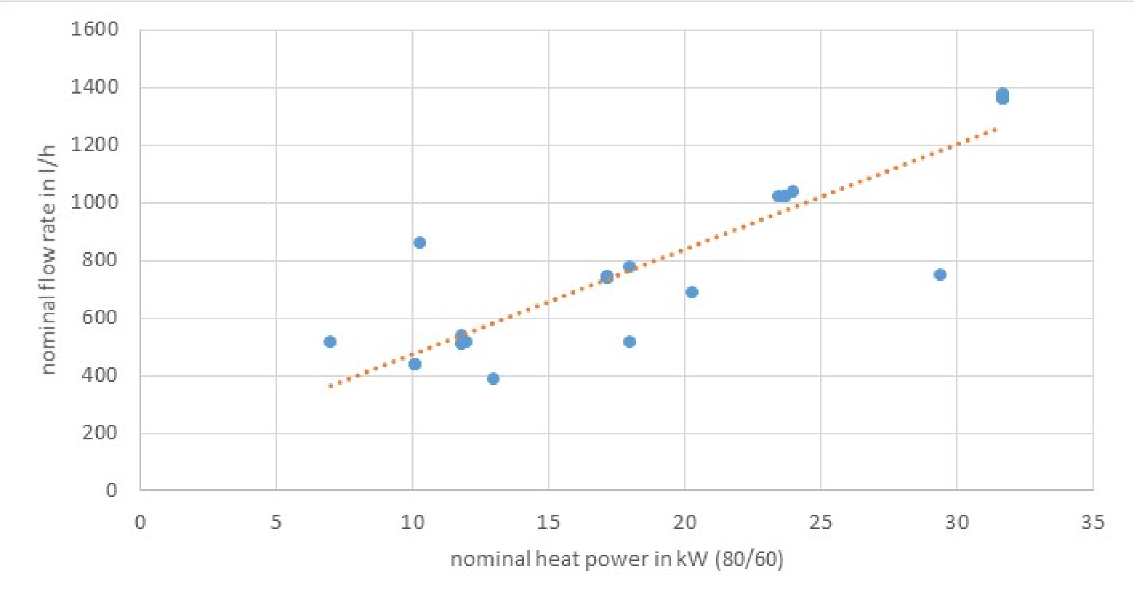


Figure 4-21: Nominal flow rate over nominal heat power

4.8 Thermal Storage

Thermal storages can be categorized according to different properties. Those properties are:

- Application Temperature e.g. low, medium and high temperature
- Duration of the energy storage e.g. short or long term
- Thermodynamic principle of the storage e.g. sensitive, latent and thermo-chemical

Figure 4-22 visualizes this classification [31, 32].

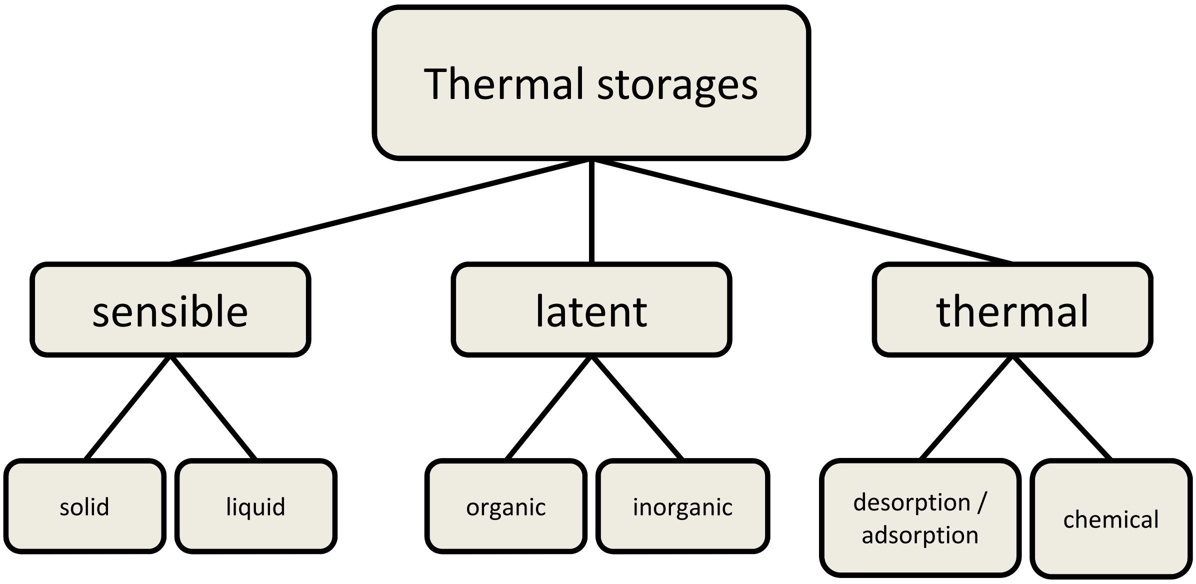


Figure 4-22 Classification of thermal storages depending on the thermo-dynamic principles

Each type of thermal storage has common characteristic values. The efficiency of storages is determined by the relation of the stored usable energy and the energy added to the storage. The efficiency of traditional water storages decreases with time because of the heat losses emitted to the surrounding area. These losses depend on the surface of the thermal storage, the insulating material and thickness as well as the temperature difference between the storage and the surrounding area. An exception of this correlation is the thermo-chemical heat accumulators. The energy storage density describes the maximum storable energy (warm capacity) of storage with respect to its volume (or its mass) under certain conditions. The charging and discharging time is the time that is needed to charge or discharge a certain amount of energy to the storage. The maximum load temperature describes the upper temperature limit allowed for the storage. The period between charging and discharging is called memory period. The sum of charging time, shutdown time and discharging time shows the duration of a memory cycle. During this cycle irreversible processes take place which affect the storage capacity. The quantity of the workable memory cycles is limited. For thermo-chemical heat accumulators this generally applies to the stability of the adsorbent.

Sensible thermal storages change their noticeable temperature during charging and discharging. The basic principle is the use of a heat flow supplying the storage medium e.g. water, junk or ground soil. Between the storage medium and the surrounding area a temperature difference is maintained. Thereby the heat flow is charged. The amount of storable energy depends on the specific heat capacity, the mass and the temperature difference of the storage medium. Insulations of the storages are important because of the difference in temperature between the storage and the surrounding area. The heat losses increase proportionally to the surface (m^2). The storable energy amount is determined by the volume (m^3) of the storage medium. This means, that a bigger storage volumes increase the efficiency. This kind of storage can be used as a long-time storage (seasonal storage) as well as short-time storage [33, 34].

Table 4-3: Overview about different sensible storages

Kind of storage	Storage medium	description
Boiler	water	- Economical priced design - Simple transport facilities of storage medium - High heat capacity - Established storage variation (in dwelling houses)
Steam storage	steam	- One or several pressure-sealed steel kettles - Storable energy depends on pressure and temperature - Quick availability - Application in the industry
Earth probe heat storage	Ground soil and aquifuge	- Sluggish heat management in the ground soil - Sesquipedalian access time - Long time storage
Gravel water heat accumulator	Gravel-water-mixture	- Plastic lined caverns - Heat exchange by water exchange or indirectly about pipe coil - Construction-partly economical than storage of concrete or steel
Aquifer heat storage	Natural appearing, hydraulically concluded ground water layers	- Ground water withdrawal about “cold bore” - Surface temperature rise and return about “warm bore” - Distance of the bores between 50 and 300m - High requirement in hydrogeological, hydrochemical and microbiological seismotectonic situation - Storable energy depending on the subsurface - Seasonal storage

The storage medium (chloride, hydrates, fluorine ¬ ide or paraffins) of latent heat storages changes their condition of aggregation during charging and discharging. They do not change their temperature. These storages are primarily used as long time storages.

The energy storage works upon the exploitation of the enthalpy of reversible thermo-dynamic changes of state. The state of aggregation of the heat storage medium changes (from liquid to solid or vice versa) without noticeable temperature change. However, the storage medium can be charged or discharged according to the latent heat capacity. This leads to a rise of the temperature. According to the slight increase of the temperature the heat storage density can be increased by 10 to 20 times. The phase transition from liquid to gaseous is barely used because the change of the density (water - / steam factor in 1000) is hard to be technically controlled [31, 33, 35].

The energy storage capacity depends on the glaze temperature, the specific heat capacity and the mass of the storage medium. Huge heat transfer surfaces are needed because of the low flow heat conductivity.

The phase transition needs a lot of energy. Hence, the storage density is relatively high. The possible expansion of the heat medium is to be respected in the dimensioning of the storage.

In theory the thermo-chemical heat storages or sorption storages have the highest heat storage-density. The heat is stored as chemical internal energy. The possible material pairs are limited because the reaction cycle must lie in the range of the necessary temperature segment (low temperature 10 °C to 100°C). Refer to the working temperature primarily metal hydride, silica gel or zeolites are used. These storages can be used on many applications as for example seasonal storage, buffer storage or also for cooling systems.

The thermo-chemical heat storages store the heat by means of an endothermic reaction (like desorption) while the discharging of the storage is done using an exothermic reaction (like adsorption or absorption)

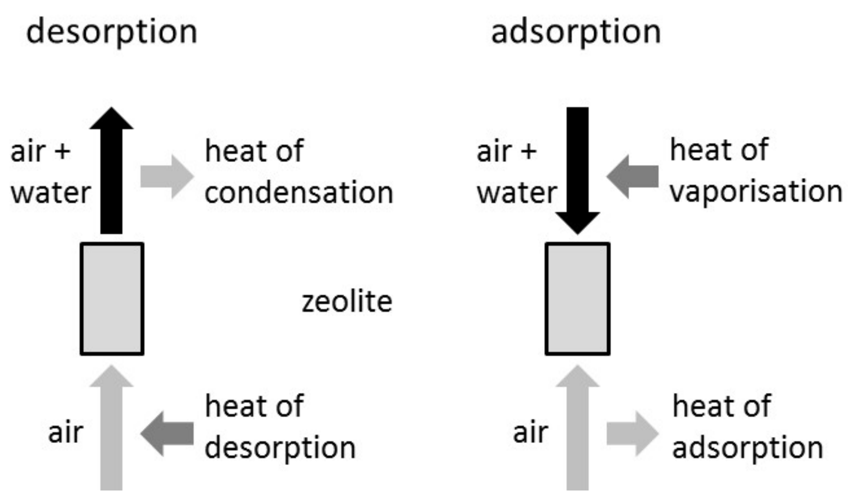


Figure 4-23: Function of absorption and desorption of zeolite storages

A zeolite-storage for heating and cooling is used in a school in Munich for load balancing of the district heating grid [33, 36].

4.9 Batteries

Because of the high number of PV-systems and wind power plants there are high power overproduction in the electrical grid. For this problem batteries could be a solution for the future power supply system. They are able to support peak shaving and short time energy storage. This chapter gives an overview about today's common battery systems, control strategies and theory for battery simulations.

4.9.1 Technical parameters

In the project SYSPV-NS some market enquiries for batteries are made [37]. There are detailed information about different cell types available. The different types are: Lithium (Li)-, lead (Pb)-, Redox Flow-, sodium-nickel-chlorine (NaNiCl) and sodium-sulfur (NaS)-batteries. The project investigates the types for using in households and the electrical grid support. The results are that Li and Pb batteries are the best solution which is shown in Table 4-4 and Table 4-5. In the tables are evaluations of the different battery types for the different requirements included. The diverse types are provided with points between 1 and 5 where 5 is very suitable for the considered requirement. Than the points are multiplied with the emphasis which describe how important the requirement is. More detailed information are available in [37]

Table 4-4: assessment of battery types for using in households [37]

Requirements	Unit	Emphasis	LI	Pb	NaNiCl2	Redox-Flow	NaS
Specific energy	Wh/kg	2,00	5	2	3	1	3
Energy density	Wh/l	2,00	5	2	3	1	2
Specific power	W/kg	2,00	5	2	3	1	3
P/E-ratio	h^-1	2,50	4	4	2	5	1
Lifetime	Years	3,75	5	1	4	4	4
Cycle-lifetime	Full cycle	4,00	4	1	2	5	2
Efficiency/ self-discharge	%	3,00	5	4	1	2	1
Marketability	1…5	4,00	5	5	2	1	1
Safety	1…5	4,50	1	5	3	4	3
Costs	€/kWh	3,75	2	5	4	1	4
Sum			121.75	103	86	85	77
Total assesment			1	2	3	4	5

The battery types Redox-Flow, NaS and NaNiCl2 are not usable for households. Only a small number of companies produce this battery types. Today these systems are only available as big stationary batteries and it is implausibly that in future small scale systems will be developed.

Table 4-5: Assessment of battery types for electrical grid support [37]

Requirements	Unit	Emphasis	LI	Pb	NaNiCl2	Redox-Flow	NaS
Specific energy	Wh/kg	2.00	5	2	3	1	3
Energy density	Wh/l	2.00	5	2	3	1	2
Specific power	W/kg	2.00	5	2	3	1	3
P/E-ratio	h^-1	2.50	4	4	2	5	1
Lifetime	Years	3.50	5	1	4	4	4
Cycle-lifetime	Full cycle	4,00	4	1	2	5	2
Efficiency/ self-discharge	%	2.00	5	4	1	2	1
Marketability	1…5	43.75	5	3	4	1	4
Safety	1…5	4.00	1	5	3	4	3
Costs	€/kWh	4.00	2	5	4	1	4
Sum			117.75	91	91	82.5	86.5
Total assesment			1	2	2	5	4

In fact of the results in SYSPV-NS a market enquiry only for existing Li and Pb battery systems are used for this report. These two systems are the best solution for using in households and for electrical grid support.

Table 4-6: Overview about different battery systems [38]

Battery Type	Capacity in kWh	Depth of discharge in %	Number of cycles	System Efficiency in %	Discharge power in kW
Li-Ion	1.22-200	80-95	2,500-7,000	85-97	1.5-250
Li Polymer	6-22.5	97	10,000	94	4.5-12
LiFePO/PO_4	2.8-900	70-90	5,000-8,000	75-96	2.6-1000
$LiNiCoAlO_2$	4.4-13.2	70-80	n.a.	90	2.5-5
$LiFeMnPO_4$	4.6-9.2	85	3,500	80	3.5
LiTiO	3.2-9.6	100	15,000	n.a.	3.2-9.6
LiCoO/O_2	2.7-13.8	100	4,500	90	3
LiMn	3.24-5.4	80	5,000	90	1.5
Lead Acid	8-200	50	2,500-3,200	85-90	2.5-250
Lead gel	2.35-200	35-50	2,500-3,000	75-94,5	2-250
Pb AGM	3-17	70	2,500	93-94	6-10.2

Table 4-6 shows an overview about common Pb and Li battery systems which are available at today's market. For the comparison are 146 different battery systems from 41 different manufacturers used. The system efficiency means the losses between the power producer and the AC load. The discharge power is already the output power of an inverter convenient to the battery. Today the investment costs for Pb battery systems are round about 500 - 1,000 €/kWh and 1,000 – 3,000 €/kWh for Li-ion systems, depending on the manufacturer. The operating costs are 0.2 €/kWh for Pb and 0.3 €/kWh for Li-ion systems [37, 39].Table 4-6: Overview about different battery systems

4.9.2 Battery simulation

One challenge for the integration of volatile renewables is, that energy is not feed-in at the same time as the demand is. Battery storage systems can be a solution and will probably play a big role in future energy market. Batteries can be used for peak shaving and to support the self-consumption of PV-systems.

Today different battery types are common, which are Pb, Ni, Li and Redox Flow systems. Because of the different characteristics they have different ambits.

The characterization of certain battery parameters is needed. The state of charge (SOC) delivers a value in percentage terms for the energy stored during the charging process. It provides a value for the stored energy in per cents in relation to the battery's nominal capacity. When the battery is in discharge it is important to know how much energy is left in the system. This value is the depth of discharge. It is provided in percentage terms and expresses the energy left in the system in relation to the nominal capacity. The nominal cell voltage depends on the electrochemical characteristics of the anode and cathode. Each battery type has its own particular nominal cell voltage. The capacity of a battery is provided in Ah. It is the period of time in hours during which the battery can support the current of 1 Ampere. An important parameter is the charge efficiency. It can be calculated as a function of energy stored in the battery divided by the energy which the battery can provide. Another parameter is the energy density. It tells how much space is needed for each Wh. It is provided in Wh per liter. The current rate is important for charge and discharge operations. With a current rate of 1 C it is possible to completely charge or discharge a Battery within 1 hour.

There are two different ways to simulate a battery. The first method is to build an electrochemical simulation model. Several electrochemical parameters have to be considered. To set up this kind of model, a profound knowledge of electro chemistry is necessary. Due to that, this model is not examined in this report.

The second possible way is using an electric model. There are various electric battery models. Most of them only work for specific applications. They can be categorized into three main types: Thevenin-, impedance- and runtime based. Their electrical descriptions are displayed in Figure 4-24.

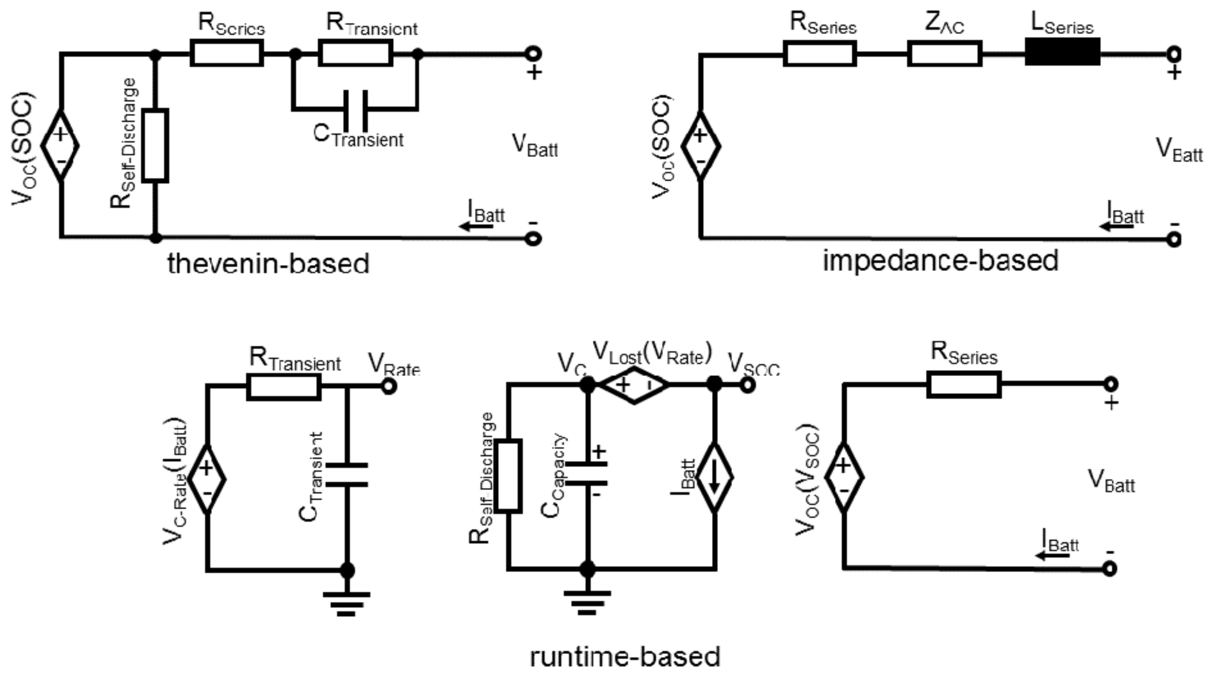


Figure 4-24: Different kind of battery models

These models can be used for different applications. Table 4-7 shows the usability of the different models.

Table 4-7: Usability of the different base types of models

Predicting Capability	Thevenin-Based Model	Impedance-Based Model	Runtime-Based Model
DC	No	No	Yes
AC	Limited	Yes	No
Transient	Yes	Limited	Limited
Battery Runtime	No	No	Yes

The fundamental form of the thevenin-based model is shown in Figure 4-24. It consists of a serious resistor and an RC-parallel network. The RC-network is necessary to get the response of transient load changing. The open voltage of the battery is set to a constant value. A variable capacitor is necessary to provide the non-linear behaviour of the V_{OC}. When using this set up it works quite proper but additional mathematic equations are needed to provide the SOC and estimate the runtime. These functions are not implemented in circuit simulators.
The basic form of the impedance-based model is shown in Figure 4-24. For this model a method of electrochemical impedance spectroscopy is needed. This is performed by setting up an AC-equivalent impedance model for frequency as well as a complicated equivalent network. The model also operates on a fixed SOC and temperature. Hence, neither a DC response nor the battery runtime are available in the model.
The model for the run time simulation is shown in Figure 4-24. It is set up as a complex RC-network. This set up delivers the runtime of the battery and also the DC voltage response. For this model a constant discharge current is necessary.

To get a complete working system for a broad area of usability a combination of those models is needed. This model is shown in Figure 4-25 below.

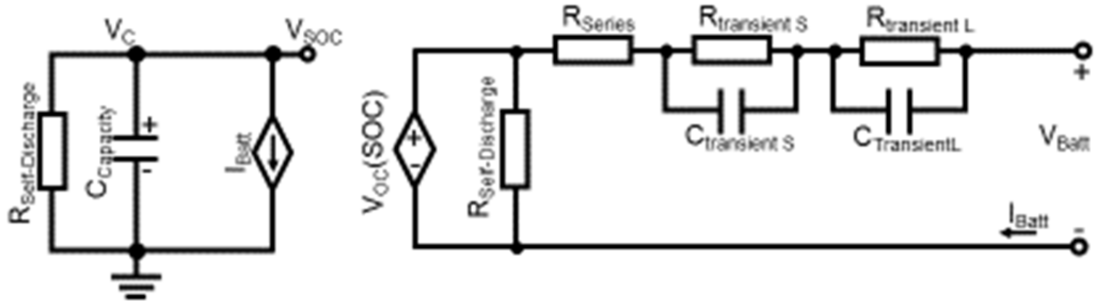


Figure 4-25: Combination of run-time-based-and thevenin model

This model, obtained by combining the run time based and the thevenin based model, can be used for many different simulation scenarios. When it comes to setting up a model, the resistors and capacitors have to be measured at an existing battery cell [40].

4.9.3 Load strategies of battery systems

In SYSPV-NS three different load strategies are simulated. They are direct loading, delay loading and peak shaving.

The scenario direct loading is typically used today. There the battery start charging once the PV system produces more energy as needed. This strategy optimising the self-consumption but it has no influence on the daily peaks as soon as the battery is charged.

Delay loading means that the battery charges in a linear way up to a maximum state of charge over the day. This scenario reduces the daily peaks and supports the grid

Peak shaving is the electrical grid optimising scenario. The battery starts charging if a given limit of PV-feed in is reached. In this scenario the total battery capacity is usable for the electrical grid support. In Figure 4-26 the overview of the results for the different load strategies are shown. For this simulation the feed-in limit is 50 % of the nominal PV-system power, which is an assumption made for future scenario [37].

The results confirm the assumptions for the different load strategies. For direct loading the battery is fully charged early in the morning. So over the day no capacity is less for peak shaving. In this case a lot of feed-in limitation is necessary. For the delay loading a better mix between self-consumption and peak shaving is reachable. For the strategy peak shaving nearly no feed-in limitation is necessary. However, self-consumption is worse than with delay loading.

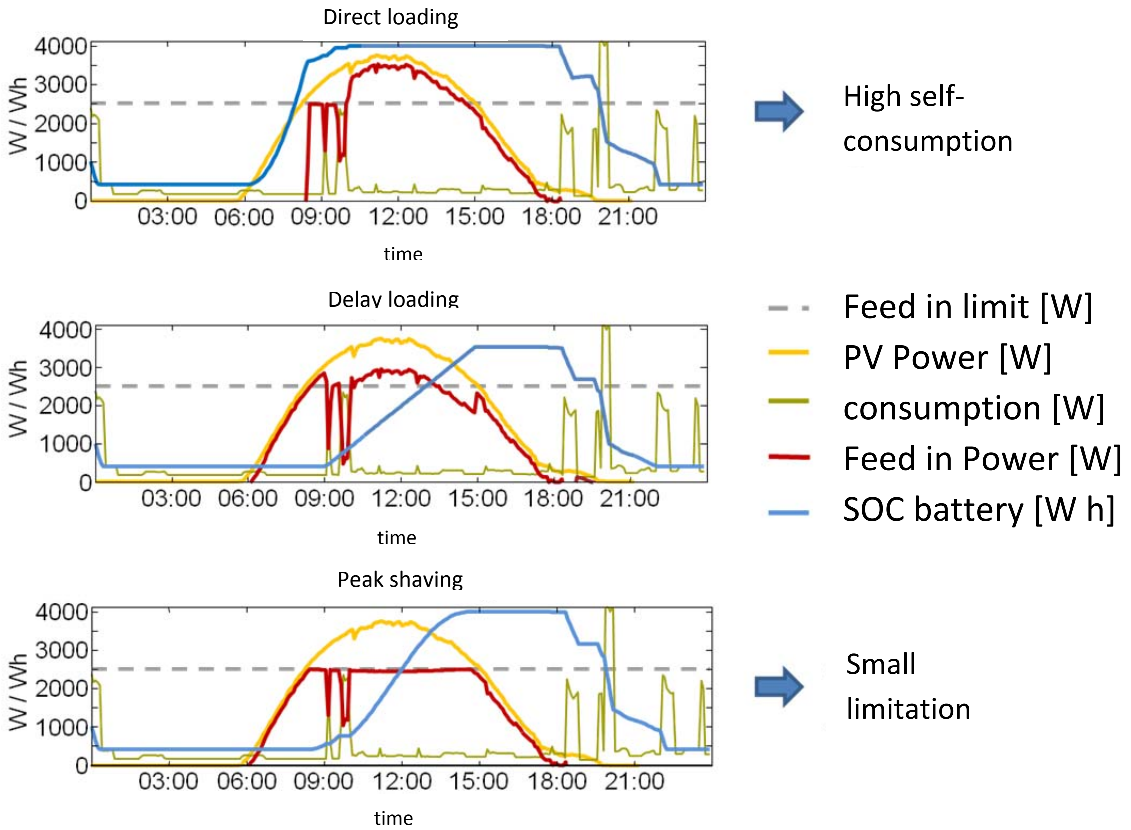


Figure 4-26: overview for the three different loading strategies [37]

The three aforementioned load strategies are rule-based controlled and easy to implement. However, in fact of this it is not possible to optimise command variables. Therefore a model predictive control (MPC) is investigated. A further development a prediction, based on the last three days, is adjusted to the MPC. More detail information are available in the project report [37].

Figure 4-27 shows a comparison between the different loading strategies of the battery for a feed-in limitation of 25 % of the PV peak power. It is observably that the best result is reachable with the investigated MPC compared with a prediction. Therefore, a high self-consumption and a small feed-in limitation is possible.

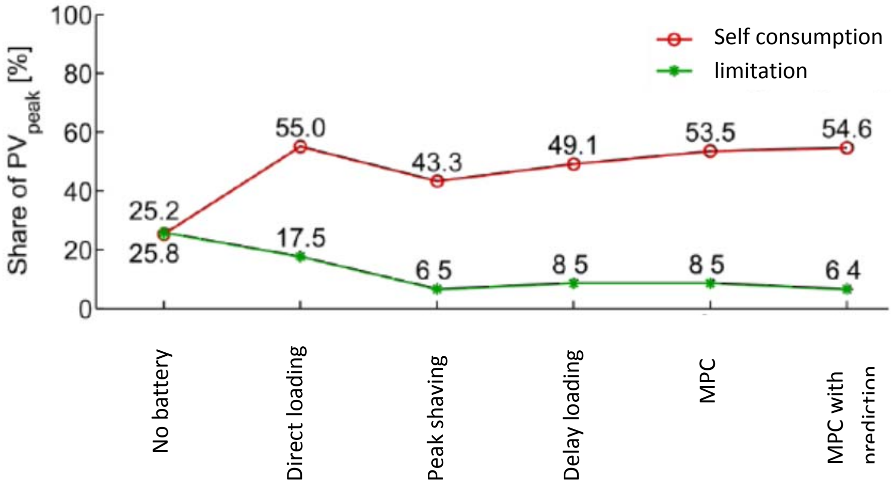


Figure 4-27: Comparison between different battery loading strategies for a feed-in limitation of 25 % of the nominal PV-system power [37]

Figure 4-28 shows a comparison between the different loading strategies of the battery for a feed-in limitation of 50 % of the PV peak power. Again the best result is the investigated MPC compared with a prediction. Therefore a high self-consumption is possible and nearly no feed-in limitation is necessary. Between the MPC with prediction and only the MPC only a small difference is visible. The decision which strategy should be use is depend on the more costs and implementation time for the prediction.

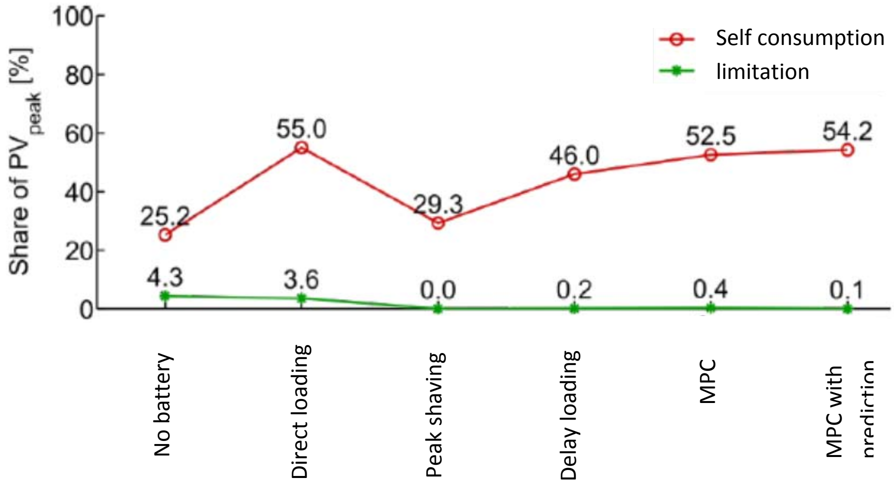


Figure 4-28: Comparison between different battery loading strategies for a feed-in limitation of 50% of the nominal PV-system power [37]

4.10 Relation of coupling points and use cases in demo sites

This chapter provides an identification of the coupling points connecting the different energy grids and links to the use cases and the demo sites in OrPHEuS.

Several coupling points are needed to fulfil the energy exchange between the different energy grids. Furthermore, each conversation to another energy need different technologies (see chapter 4). Caused by this the following coupling points are needed to connect the electrical grid and the district heating grid:

- e-boiler
- heat-pump
- CHP

The coupling points connecting the gas and the district heating grid are:

- CHP
- gas boiler

There are also some possibilities to connect the gas and the electrical grid:

- CHP
- Power-to gas

To develop and optimize the control strategies in a proper way storage systems in the grids are required. This can be specific storages like:

- Thermal storages
- Electrical storages

The integration of power-to-gas systems allows the usage of the gas grid as storage for the energy. Renewable energy sources like PV-systems are necessary to achieve the goal of CO_2 reduction. The description of the oil boilers is necessary to calculate the achieved CO_2 reduction caused by the hybridization. The CHP can connect the three different energy grids. This makes this technology a point of special interest for the hybridisation. Furthermore, it is necessary to integrate storage systems in the grid in order to get a proper working hybrid energy network with a flexible capacity for load shifting and demand response.

The Table 4-8 gives an overview of the different use cases, coupling points, involved grids and a link to the addressed demo site. Some of the coupling points are options. They are marked by the (✓) symbol.

Table 4-8: Overview of the coupling points linked to the used cases and demo sites

Use CaseB	Title	Condition for execution	CHP	E-Boiler	Heat Pump	PV	Power-to-Gas	Oil boiler	Gas boiler	Thermal storage	Electric storage	demonstration site Ulm	Skelleftea	affected or connected grids
1	Phase-out of oil usage for peak heat generation	Skelleftea: replace oil-boilers by other fuel devices	✓						✓				✓	heat
		Skelleftea: peak shifting through control of heat storage(s) usage/ efficiency	(✓)	(✓)	(✓)					✓			✓	electric/heat
		Skelleftea: adaptation of heating production profile according to dynamics in demand and weather information	✓	✓	✓				✓	✓	(✓)		✓	electric/heat
		Skelleftea: installation of e-boilers, e-storages and usage of wind		✓	✓					✓	(✓)		✓	electric/heat
		Skelleftea: peak shifting through DSM for heating consumption (ON/OFF, volume flexible loads),	✓	✓	✓				✓	✓			✓	electric/heat
		Skelleftea: dynamic heat tariffs with active end-user participation controlling there devices		(✓)	(✓)					✓	(✓)		✓	heat/electric
2	Single- versus multi-utility generation and customer supply	Ulm/ Skelleftea: single-utility green tariff (heat or power)				✓				✓	✓	✓	✓	electric/heat
		Ulm/ Skelleftea: multi-utility green tariff	✓			✓	(✓)			✓	✓	✓	✓	electric/heat/gas
		Ulm/ Skelleftea: conditions to join efforts on operational costs/ sharing costs										✓	✓	electric/heat/gas
		Ulm: "Large-scale" Power2heat + thermal energy storage, and cooperation between Electricity and synthetic District Heating to deal with PV feed-in		✓	✓	✓				✓		✓		electric/heat
		Ulm/ Skelleftea: local DR programs with group of customers (real or virtual communities)	(✓)	✓	✓	(✓)	(✓)			✓	✓	✓	✓	electric/heat/gas
3	Optimal asset management and extension planning of distribution grids	Skelleftea: modification of coupling point operation (CHP, +ESS, +e-boilers) versus wind generation link	✓	✓						✓	✓		✓	electric/heat
		Ulm: investment +ESS (medium/large) to serve power+heat demand versus transformer investment (operation of ESS not possible due to regulations)		✓	✓	✓				✓	✓	✓		electric/heat
		Ulm: local balancing (local DR, sharing +ESS small/medium size, community level) versus transformer investment		✓	✓	✓				✓	✓	✓		electric/heat
		Skelleftea: modification of coupling point operation (CHP), +distributed power-based heating devices to reduce heat load peaks	✓	✓	✓				✓				✓	electric/heat
		Skelleftea: dynamic heat/power loads with multi-utility DR control											✓	electric/heat
		Ulm: dynamic power loads/ RES feed-in with DR control	✓	✓	✓	✓	(✓)			✓		✓		electric/heat/gas
		Ulm: local balancing (local DR on community level; inter-community DR, local sharing of RES+ESS)		✓	✓	✓				✓	✓	✓		electric/heat
4	Maximizing local consumption of remote self-generation	Ulm: Impact of different pricing signals on acceptance conditons and levels, penetration and impact on power grid	✓	✓	✓	✓	(✓)			✓	✓	✓		electric/heat/gas
		Ulm: local balancing (community level; inter-community balancing, local sharing of RES+ESS)	✓	✓	✓	✓	(✓)			✓	✓	✓		electric/heat/gas
		Ulm: DR control on prosumer and/or prosumer community level: support self-usage, support feed-in; sharing DSO-owned ESS	✓	✓	✓	✓	(✓)			✓	✓	✓		electric/heat/gas
5	Dynamic end-user loads and comfort levels	Skelleftea: dynamic heat/power loads with single and/or multi-utility DR control								✓	✓		✓	electric/heat
		Ulm: dynamic power loads/ RES feed-in with DR control		✓	✓	✓				✓	✓	✓		electric
		Skelleftea: dynamic heat/power loads with single and/or multi-utility DR control		✓	✓					✓	✓		✓	electric/heat
		Ulm: dynamic power loads/ RES feed-in with DR control		✓		✓				✓	✓	✓		electric
Special	Weather-related seasonal extreme situations		✓	✓	✓	✓			✓	✓	✓	✓	✓	gas/heat electric
			✓	✓	✓	✓			✓	✓	✓	✓	✓	gas/heat electric
	PV usage	PV to reducing gas demand houshold level		✓	✓	✓				✓		✓		gas/electric
		PV feed-in to district heating grid household level		✓	✓	✓						✓		electric/heat
		PV feed-in to gas grid urban sector	✓			✓	✓					✓		gas/electric

5 Conclusions

The simulation results of the electrical low voltage distribution grids in the two test sites next to Ulm and the development of the spot market prices suggest that coupling of several energy domains could be benefical. The hybridization is one opportunity to avoid unnecessary costs for the electrical grid reinforcement, to guarantee a secure energy supply.

The analysis of different physical coupling points shows some opportunities for hybridization in the demo sites. The reduction of overproduction of electrical energy is applicable for electrical boilers or heat pumps in combination with a thermal storage. Both are well developed systems which have already been used for a long time. Another possibility to store the overproduction of electrical energy are batteries, but they are quite expensive nowadays and their lifespan is currently under discussion. During the last years the batteries have been getting more and more important, among others due to the emerging electro mobility. Thus, a lot of research is in this area with the target of cost reduction in future.

In the demo sites in Ulm, Hittistetten and Einsingen, power-to-gas systems could be an opportunity for seasonal storage and avoidance of grid reinforcements. In Hittistetten und Einsingen over production of electrical power are frequently occurring. A connection to the gas grid is possible. At the moment, the challenges are the low efficiency and the high costs of power-to-gas systems. One possibility could be to transform electrical power to hydrogen, in order to avoid high losses. But the allowed amount of hydrogen in the gas grid is limited. Power-to-gas systems are also being researched and the current stage of development implies that the power-to-gas method will become an important role in future. Hence, decreasing prices can be expected.

The operation of oil boilers covering peaks in heat demand could be replaced by CHPs with an additional feed-in of electric power. We expect the opportunity to store this electric surplus energy in batteries. Furthermore, in Skellefteå the oil boilers could be replaced by electrical boilers using the surplus of wind energy plants and reducing the CO_2-footprint.

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Appendix

Power-to-gas projects

Table 0-1: Overview of power-to-gas projects in Germany [22]

Project name	Location	Project partner	Category	Technical information
Windpark RH_2-WKA and RH_2-PtG	Grapzow	-WIND-projekt -NOW -HaasEngineering -Architekturbüro Karsten Klünder -Hydrogenics -Senergie	Innovation & Demonstration	-in test stage -140MW power input -1MW electrolyzer -210Nm³/h hydrogen -CHP 250kW electrical & 400 kW thermal -grid connection 110kV/380kV -generation of electricity 125.000 households -waste heat recovery -hydrogen feed into gas grid -hydrogen to electricity -hydrogen as fuel
Pilotanlage Falkenhagen	Falkenhagen	E.ON	Demonstration	-operating stage -2MW electrolyzer -360Nm³/h hydrogen -hydrogen feed into gas grid
Hybridkraftwerk Prenzlau	Prenzlau	ENERTRAG AG	practice	-operating stage -0.5MW electrolyzer -120Nm³/h hydrogen -waste heat recovery -hydrogen feed into gas grid -hydrogen storage -hydrogen as fuel
Multi-Energie-Tankstelle H2BER	Airport Berlin Brandenburg	-Total Deutschland GmbH -Linde AG -Enertrag AG -McPhy Energy -2G Energietechnik	Practice	-operating stage -3MW power input -0.5MW electrolyzer -210 kg/d hydrogen -hydrogen feed into gas grid -hydrogen storage -hydrogen as fuel -hydrogen to electricity -hydrogen for heat production

H_2 Forschungs-zentrum Cottbus	Technische Universität Cottbus	-BTU Cottbus -Enertrag Ag	prototype site	-operating stage -0.145MW electrolyzer -20Nm³/h hydrogen -hydrogen storage -hydrogen to electricity
Audi e-gas Projekt	Werlte, Niedersachsen	Audi AG	Practice	-operating stage -6MW electrolyzer -1.300m³/h hydrogen -300m³/h methane -CO_2 resource biogas plant -methanation -methane as fuel
H_2 Herten	Zeche Ewald in Herten	-Bundesland Nordrhein-Westfalen -AHG GmbH	demonstration	-testing stage -0.280MW electrolyzer -30m³/h hydrogen -hydrogen as fuel -in future waste heat recovery
CO_2RRECT	Niederaußem	-Bayer Technology Services -Bayer Material Science -BMBF -RWE AG -Siemens AG	Research	-operating stage -0.3MW electrolyzer -50Nm³/h -CO_2 resource brown coal plant -methanation
Methanisierung am Eichhof	Bad Hersfeld	-Fraunhofer IWES -Hessische Ministerium für Umwelt, Energie, Landwirtschaft und Verbraucherschutz -Thüringer Ministerium für Landwirtschaft, Naturschutz und Umwelt, -ZSW Stuttgart, SolarFuel GmbH	Demonstration	-operating stage -0.025MW electrolyzer -6m³/h hydrogen -4m³/h methane -CO_2 resource biogas -methanation
Strom zu Gas Demonstrations-anlage der Thüga Gruppe	Frankfurt a. Main	Unternehmen der Thüga Gruppe	Demonstration	-operating stage -0.320MW electrolyzer 60Nm³/h hydrogen -hydrogen feed into gas grid -hydrogen to electricity -research for waste

				heat recovery
Verbundprojekt "Power to Gas"	Stuttgart	-ZSW Stuttgart -Fraunhofer IWES	R & D	-testing stage -0.250MW electrolyzer -50m³/h hydrogen -12.5m³/h methane -different CO_2 resources are possible -methanation -waste heat recovery
Power to Gas im Eucolino	Schwandorg	MicrobEnergy GmbH	research	-operating stage -0.108MW electrolyzer -21.3m³/h hydrogen 5.3m³/h methane CO_2 resource biogas -methanation -waste heat recovery
Mikrobielle Methanisierung		-MicrobEnergy GmbH -Zweckverband Verbandskläranlage Schwandorf Wackersdorf -Hoschschule Regensburg Fakultät Elektro- und Informationstechnik -Schmack Biogas GmbH	Pilot project	-operations stage -methanation with specific bacteria (microorganism) -methane to electricity -methane for heat production
RWE-Demonstrations-anlage	Ibbenbüren	RWE Deutschland AG	demonstration	-construction in progress -0.1MW electrolyzer -20m³/h hydrogen -hydrogen feed into gas grid
Bio Power2Gas		-Cube Engineering -IDE Kassel -Eon Mitte -MicrobEnergy GmbH	practical	-construction in progress -methanation -methanation feed into gas grid -methane for heat production Waste heat recovery
Energiepark Mainz	Mainz-Hechtsheim	-Stadtwerke Mainz AG -Hochschule Rhein Main -Linde AG -Siemens AG	R & D	-construction in progress -3x2MW electrolyzer -1.000Nm³/h hydrogen -hydrogen as fuel -hydrogen storage

				-hydrogen for heat production -hydrogen to electricity -hydrogen feed into gas grid
HYPOS	Sachsen-Anhalt	-Fraunhofer-Institute for material mechanic -Europäische Metropolregion Mitteldeutschland	Practice project	-in developement -methanation -hydrogen feed into gas grid -hydrogen storage
Sunfire Power to liquids	Dresden	-sunfire GmbH -BMBF	Practice project	-in development -round about 1 barrel liquid fuel per day -hydrogen as fuel

Electrical optimization possibilities

The following chapter give an overview of the used elements in the electric distribution grids. Furthermore, some information on possible voltage regulation systems is given.

Lines

For the transmission and distribution of electrical energy outside cities in general overhead lines are used. The benefits of overhead lines compared to underground cables are:

- Lower costs
- Easily accessible for maintenance
- Shorter off times after error
- Improved short time overload capability

Overhead lines are constructed with at least 7 single wires. The basic material is copper, aluminum or aluminum alloys (e.g. Aldrey). Basically overhead lines can be categorized in one-material-, bi-metal- and composite lines. Often the costs are determined by the material that is used. On the one hand Copper has very good electrical characteristics on the other hand it is more expensive than aluminum. Furthermore, copper has a higher weight, a fact that is very crucial to overhead lines. For the determination of the cross section the most important parameters are the ampacity, the boundary field force and the slack span of the lines.

The ampacity is dependent on:

- Maximum temperature of the material (ϑ_{Al}=80°C, ϑ_{Cu}=70°C, ϑ_{Aldrey}=90°C)
- Environmental temperature (in Germany ϑ_{max}=35°C, regional up to 40°C)
- Solar irradiation
- Wind speed (standard value in Germany v=0,6m/s)
- Surface condition of the line

In urban energy supply grids underground cables are established. This is caused by the limited space and the decreasing acceptance of overhead lines by the population. Furthermore, underground cables have a smaller sensitivity on atmospheric influences. Underground cables are built-on by the conducting medium, the isolation, the casing and the shielding. As conductor material electrolytic copper or aluminum is used. The conductor design can be single lines or multi lines with round or sector conductors. For the isolation of the conductors from themselves or from the ground impregnated paper-isolation, plastics like PVC, PE or VPE and natural or synthetic rubber are used. For PVC cables the maximum temperature is 70°C while for VPE it extends to 90°C. The alpha numeric nomenclature is in the references.

Underground cables and overhead lines have capacity and inductivity covering. This is important for the reactive power e.g. delivered by the inverter of PV-systems. Inductivity covering of power lines is an important part. The capacity covering to the ground can be neglected for overhead lines. Hence, the delivery of reactive power is a good opportunity to decrease the local voltage and avoid overvoltage. The capacity covering of underground cables is higher than for overhead lines and reduce the ratio between resistance and inductivity. So the influence of the delivering of reactive power is reduced [1, 41, 42].

Transformers

The voltage generated in the power plants and the corresponding currents is not suitable for an economic energy transport. Thus, the electrical grid is separated in different voltage levels. Transformers are used to realize those different voltage levels. For the transport over long distances high voltages are used. For the low voltage distribution network the nominal voltage is 0.4 kV, while the medium voltage level ranges from 10 to 30 kV. In this part of the grid, transformers with a dimensioning apparent power of 250 kVA up to 2,000 kVA are used. Typical used values are 250, 400, 630, 1,000 and 1,600 kVA. Specific dimensioning apparent power values exist for special situations, for example 315 kVA. In the two test sides of Ulm 630 kVA transformers are installed. In test side 2 Hittistetten a 315 kVA transformer was installed in the past. The massive feed-in of PV-systems forced the distribution grid operator to replace the existing transformer with a 630 kVA transformer [1, 41, 42].

Between the high- and low voltage side of the transformers different connection groups are used. Delta, star and zig-zag connections are possible. For the choice of the connection group the economic aspect is decisive. For high voltages the star connection is preferred because of the 1/√3 line-to-line voltage which leads to a smaller isolation. For higher currents the delta connection is much better because the phase windings are only loaded with 1/√3 line current which leads to smaller conductor cross-sections. For voltages smaller than 30 kV the reduction of conductor cross-section usually yields more economical savings. For transformers between the middle and low voltage grid with a dimensioning of apparent power higher than 200 kVA the Dy-connection is the preferred choice because of the neutral point treatment [1, 41, 42].

Low voltage transformers normally have the possibility of a manual tap change. It is necessary to make the transformer de-energized to change the turn ratio because the connection is mechanically fixed with a copper rod. Thus, the turn ratio in a transformer operating in the low voltage grid is fixed and not automatically adjustable. This means that the middle and low voltage grid are connected in a fixed ratio. Today, because of the fluctuation of feed-in power, an automatic adjustment of the transformers in the low voltage grid can avoid grid reinforcements. Some solutions for this problem are available and described in chapter 0 and 0 [1, 41, 42].

In time of fluctuating feed-in of decentralized generation in the power grid, for example by PV-systems, the load flow is changing the direction and amplitude. In the past, the transformers were dimensioned for the highest consumption. Today, the feed-in power of distributed generation could be higher than the transformer dimensioning apparent power. Hence, it is necessary to know the influence on the transformer lifetime for the distribution network operator. Concerning this topic, an analysis has been already done by G. Kerber and R. Witzmann. This network analysis shows that an overload of the transformer exists only for few hours. The research of Kerber and Witzmann shows, that this short time of overloading does not have a high influence on the transformer's lifetime. The relative lifetime loss is less than one day per year with 1.5 times higher feed-in than the dimensioning apparent power of the transformer [43].

The analytic modelling of a transformer requires some assumptions. A finite and constant permeability and a very small electrical conductibility of the magnetic material are suggested. Thus, the transformer model does not have any reversals of magnetism, so the model can be described in linear theory. The generated magnetic flux of one winding does not fully reach the second winding. It is subdivided into a main and stray flux.

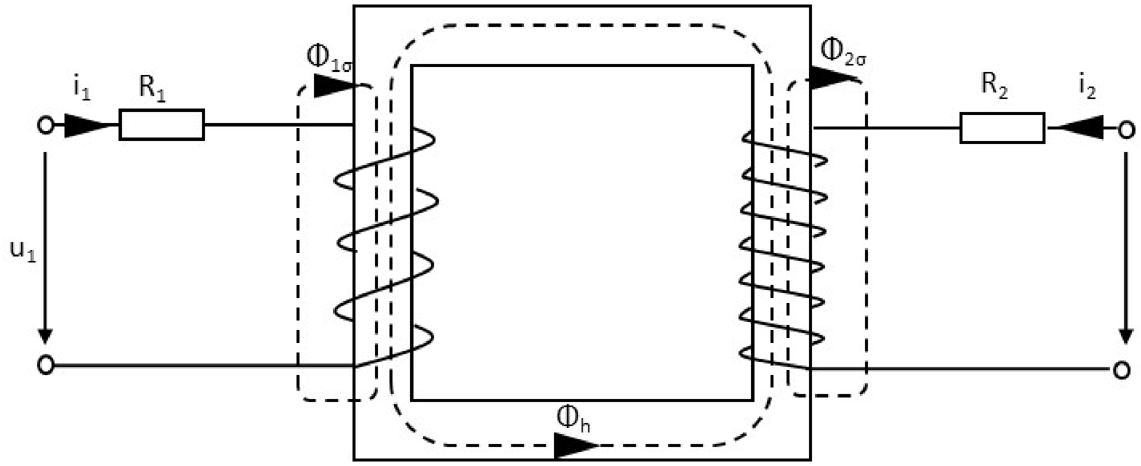

Figure 0-1: Schematic of a transformer

Hence, the primary winding is interspersed with$\Phi_1 = \Phi_h + \Phi_{1\sigma}$ and the secondary winding by $\Phi_2 = \Phi_h + \Phi_{2\sigma}$. With the magnetic fluxes we get the field flux linkage of the two coils:

$$\Psi_1 = w_1 * \Phi_1 = w_1 * \Phi_h + w_1 * \Phi_{1\sigma}$$

$$\Psi_2 = w_2 * \Phi_2 = w_2 * \Phi_h + w_2 * \Phi_{2\sigma}$$

So the transformer can be described with the following equivalent circuit diagram. The point on the coils shows the sense of the windings.

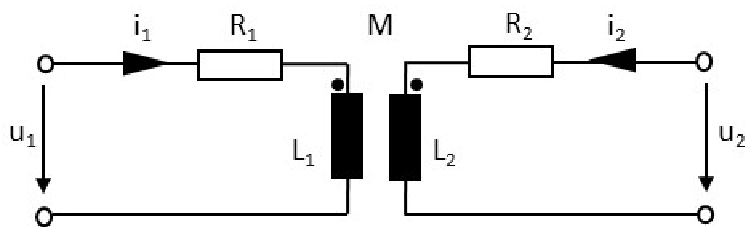

Figure 0-2: Equivalent circuit diagram of the transformer

As a result of the linear magnetic relation there is a linear relation between the field flux linkage and the currents. With the mutual inductance between the windings 1 and 2 and the self-inductance L_1 and L_2 follows:

$$\Psi_1 = L_1 * i_1 + M * i_2$$

$$\Psi_2 = L_2 * i_2 + M * i_1$$

With these equations for the voltages it is possible to create an equivalent circuit diagram with the ohmic resistances of the windings and the leakage inductance beside the main inductance. With the implementation of the inductance law we get the following loop equation:

$$u_1 = R_1 * i_1 + \frac{d\Psi_1}{dt} = R_1 * i_1 + L_1 * \frac{di_1}{dt} + M * \frac{di_2}{dt}$$

$$u_2 = R_2 * i_2 + \frac{d\Psi_2}{dt} = R_2 * i_2 + L_2 * \frac{di_2}{dt} + M * \frac{di_1}{dt}$$

This form of the voltage equations has some disadvantages. With the implementation of these parameters it is possible to make an equivalent circuit diagram which includes beside the resistances and inductances an ideal transformer. For a better presentation this parameters are transformed from the secondary to the primary side. The transformed parameters are marked with a dash in the following equations.

$$u'_2 = \frac{w_1}{w_2} * u_2 = \ddot{u} * u_2$$

$$i'_2 = \frac{w_2}{w_1} * i_2 = \frac{i_2}{\ddot{u}}$$

$$L'_2 = \left(\frac{w_1}{w_2}\right)^2 * L_2 = \ddot{u}^2 * L_2$$

$$R'_2 = \left(\frac{w_1}{w_2}\right)^2 * R_2 = \ddot{u}^2 * R_2$$

The summation current i_μ is designated as the magnetizing current.

$$i_\mu = i_1 + i'_2$$

With the definition $L_{1\sigma} = L_1 - \ddot{u} * M$, $L_{1h} = \ddot{u} * M$ and $L'_{2\sigma} = \ddot{u}^2 * L_{2\sigma} = \ddot{u}^2 * L_2 - \ddot{u} * M$ the voltage equations are as follows:

$$u_1 = R_1 * i_1 + L_{1\sigma} * \frac{di_1}{dt} + L_{1h} * \frac{di_\mu}{dt}$$

$$u'_2 = R'_2 * i'_2 + L'_{2\sigma} * \frac{di'_2}{dt} + L_{1h} * \frac{di_\mu}{dt}$$

With the last three equations the following equivalent circuit diagram with the transformed parameters is possible [1, 41, 42].

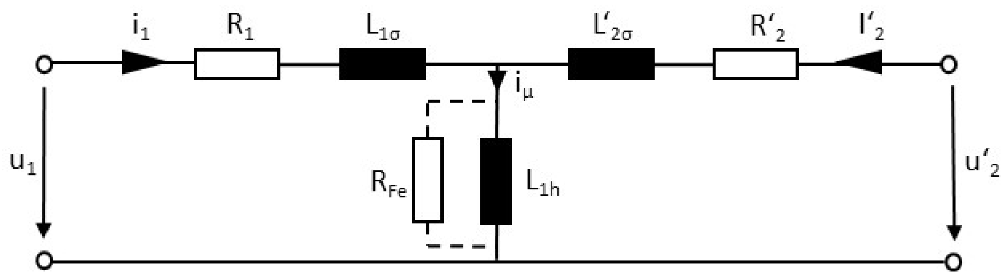

Figure 0-3: Equivalent circuit diagram with transformed parameter

Controllable transformer

Regulated transformer

The turn ratio of conventional transformers in the low voltage network usually can be adjust manually without load. This is realized by dividing the windings into a stem and a tap winding. The stages have a tap with which the voltage can be tapped. For transformers for low voltage +/- 2 steps are common, where one level typically corresponds to a voltage change of 2 to 2.5% of the rated voltage. The transformers have to be de-energized to change the levels, which leads to a disconnection of all customers connected to the transformers, as long as they are not associated with any second feed point. The manual adjustment of the levels is not suitable for the control of voltage increases, which are caused by DEA. A possible alternative is offered by controllable distribution transformers. They are available in different versions. If desired up to +/- 6 steps are available. Furthermore, the voltage change per step is optional. 1.5 to 2.5% is typical. The regulated local main transformers are available in all popular performance classes.

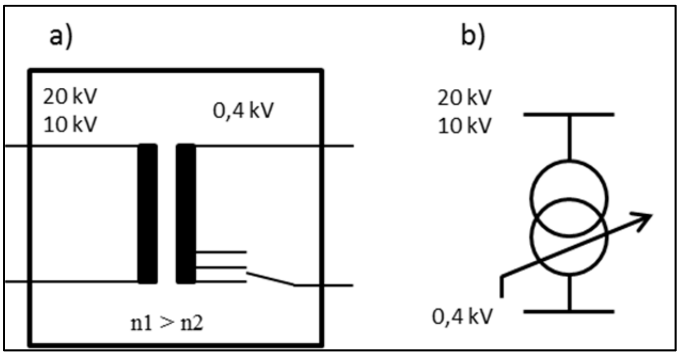

Figure 0-4: a) Schematic structure of a separate winding transformer b) Equivalent circuit diagram of a controlled transformer with controllable secondary voltage

The controllable distribution transformer is composed of a conventional transformer with manual full step mode. Here, the individual steps are connected with the connection point of the transformer through circuit breakers. They allow a tap change under load. The load switches are actuated by a motor, which is externally controllable and thus provides the ability to switch the levels automatically.

The circuit breakers are vacuum switches, which have a very long life time. There are up to 700,000 possible switching operations and they have the advantage of maintenance-free operation. For the regulation the voltage at a selected point in the network must be permanently measured and compared with the nominal voltage. The load switch, the motor and the measurement and control technology make the controlled distribution transformer more expensive than a conventional distribution transformer. Due to a possible breakdown of the measurement and control technology of the regulated distribution transformer the reliability is lower than with a conventional distribution transformer.

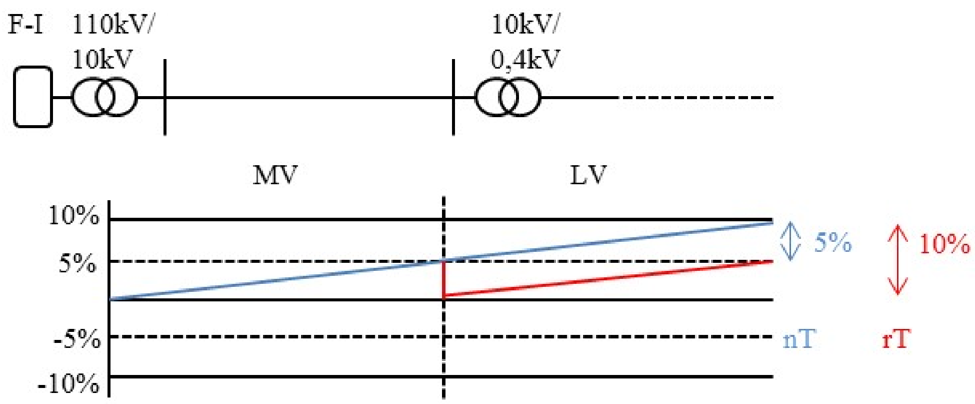

Figure 0-5: Extended use area of the predetermined voltage band by decoupling of the medium- and low voltage network by using a controlled transformer (r-ONT)

In Figure 0-5 a schematic representation of the voltage rise, in the MV- and LV level, through the feed-in of PV-systems (blue), is given. Furthermore, the influence of a regulated transformer is shown (red). Due to the conventional distribution transformer formerly used the medium- and low voltage network is rigidly connected. Therefore the tolerances for the voltage compliance of +/- 10% shall be shared to the medium- and low voltage network. Hence, in both network areas a tolerance of only +/- 5% is available. Furthermore, for the voltage drop of the transformer 2% are reserved. However, the most photovoltaic systems are connected to the low voltage network the 2% are subtracted from the tolerance of the medium voltage. Because of the topology of the network the partition of the tolerances is freely eligible by the operator.

The advantage of a controllable transformer is that the medium- and low voltage networks are decoupled from each other, which is shown in Figure 0-6. Thus, the whole voltage tolerances are available for the low voltage network. With a regulated transformer, however, only the voltage can be regulated. On the utilization of resources, no influence can be taken [44, 45, 46].

Low voltage regulation system

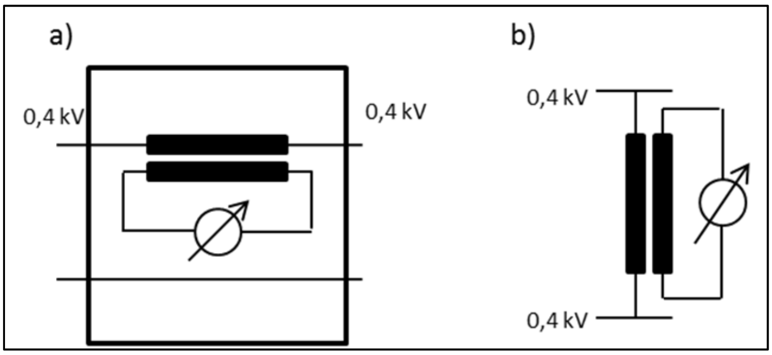

Figure 0-6: a) schematic structure of a low voltage regulation system b) equivalent circuit diagram of a low voltage regulation system

For low voltage regulation systems auto or booster transformers are used. They are low voltage equipment and are installed as a longitudinal transformer directly into the regulated feeder. In this way, individual feeders can be controlled separately. Other feeders are not affected in the network by a voltage change of the low voltage regulation system. The voltage steps are generated the same way as in a regulated transformer, by windings of the coils.

The regulation of voltage levels can also be done with switches. Thyristors can be used for low voltage regulation systems. These are operated well below their maximum characteristic values. Thus, according to the manufacturer, leads to a theoretically unlimited service life. This ensures that the load switches have a longer life time than the transformers themselves. For the regulation an arbitrary point for voltage measurement to control the process is essential.

To compensate the voltage increases through the supply of DEA the low voltage regulation system is a cheaper alternative to a regulated transformer. By using a feeder regulator the controlled feeder is decoupled from the rest of the network. In this way it is possible to utilize the full voltage range of +/- 10%. Furthermore, the voltage change of the individual steps can be varied, typical values steps are 1.5 to 2.5%. With a low voltage regulator only the voltage is controllable. The utilization of resources cannot be controlled [44, 45, 46].

Reactive power feed-in

In an AC power grid the value of current and voltage changes constantly. Thereby, for example, long cables are acting as a capacitor because of the closely spaced conductors. A capacitor is charged at the beginning of the flow with high current. With increasing charging time the flowing current decreases until maximum voltage and a current flow of zero is reached.

During the process of unloading changes in voltage and current are inversible. These properties of the capacitor cause the current to run ahead of the voltage. This corresponds to the behaviour of a capacitive reactance. If inductivities are installed e.g. in transformers, things are exactly the opposite. The magnetic field induces a voltage, which causes a counteracting current flow. Therefore, in inductivity the current flow runs behind the voltage. This behaviour corresponds to an inductive reactance. The reactance X_L and X_C are calculated using the angular frequency ω and its respective inductance L or capacitance C, as shown in the following formula.

$$X_L = \omega * L \,;\, X_C = -\frac{1}{\omega C}$$

The existing reactance leads to a phase shift in the network. This phase shift causes the reactive power within the AC grid. Even though reactive power cannot perform any work it is pushed forth and back inside the net. Therefore, in the network more resources will be used than without reactive power. The total power transmitted in the grid is called apparent power S and it is calculated by use of the active power P and the reactive power Q as shown in the following formula.

$$S = \sqrt{P^2 + Q^2}$$

This behavior is taken advantage of by the inverters equipped with the ability to provide reactive power, be it capacitive or inductive. Capacitive means that by providing the reactive power the voltage at the feed point of the photovoltaic system is reduced. Conversely, inductive means that the consumption of reactive power leads to a higher voltage at the photovoltaic system feed in point. To estimate the incoming voltage change the maximum installed nominal power at the grid connection point S_{Amax} is multiplied by the ohmic resistance R_{kV} and the reactance X_{kV}, which are beforehand multiplied by the power factor. Eventually the result is divided by the voltage squared, which is described by the following formula.

For inductive: $$u_a = \frac{S_{Amax}*(R_{kV}*cos|\varphi| - X_{kV}*sin|\varphi|)}{U^2}$$

For capacitive: $$u_a = \frac{S_{Amax}*(R_{kV}*cos|\varphi| + X_{kV}*sin|\varphi|)}{U^2}$$

Figure 0-7 visually represents the operation of the reactive power control. Overhead lines and cables act inductively, therefore, the voltage can be reduced locally by capacitive reactive power supply. If the reactive power is provided is inductively, this would lead to an increase of the local voltage, a consequence shown by the blue colored line [47].

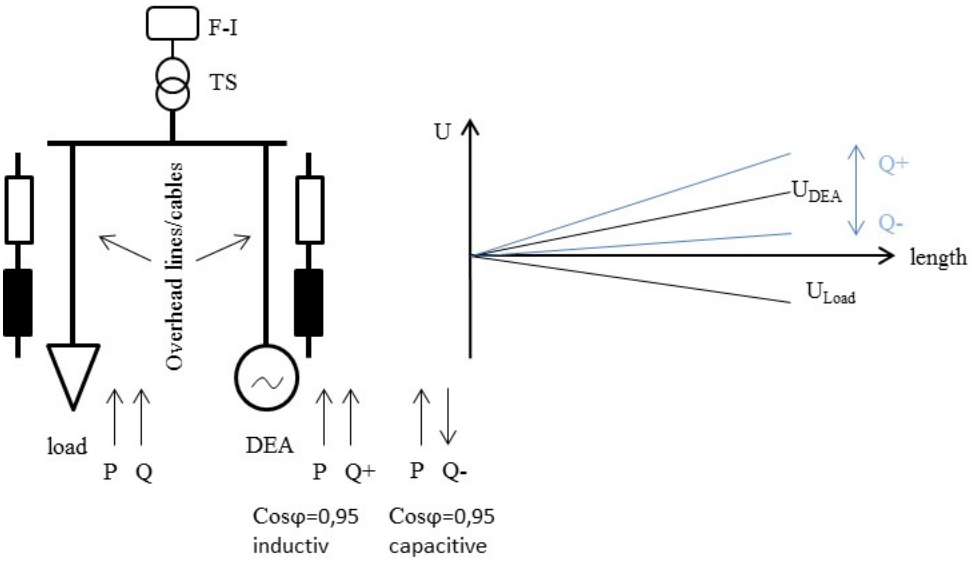

Figure 0-7: Representation of the operation of the reactive power control

Gas engine power plant

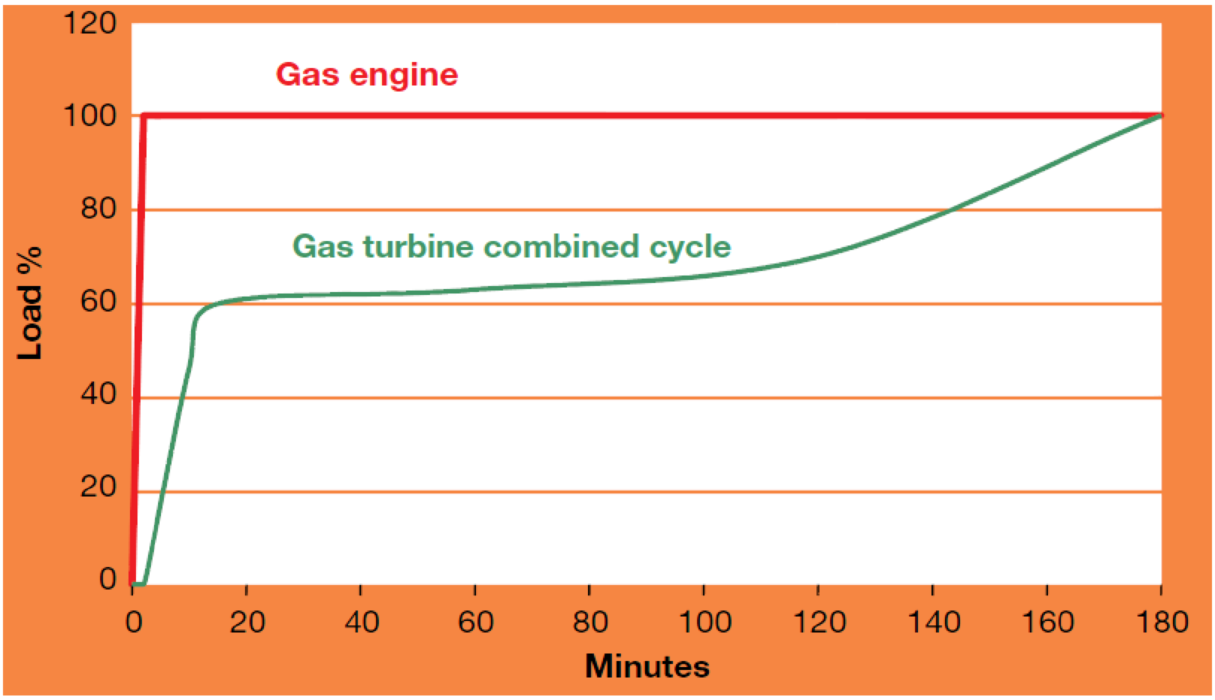

Figure 0-8: Start-up and loading of a gas engine power plant compared to a gas turbine combined cycle. The starting time is about 2 min. [48]

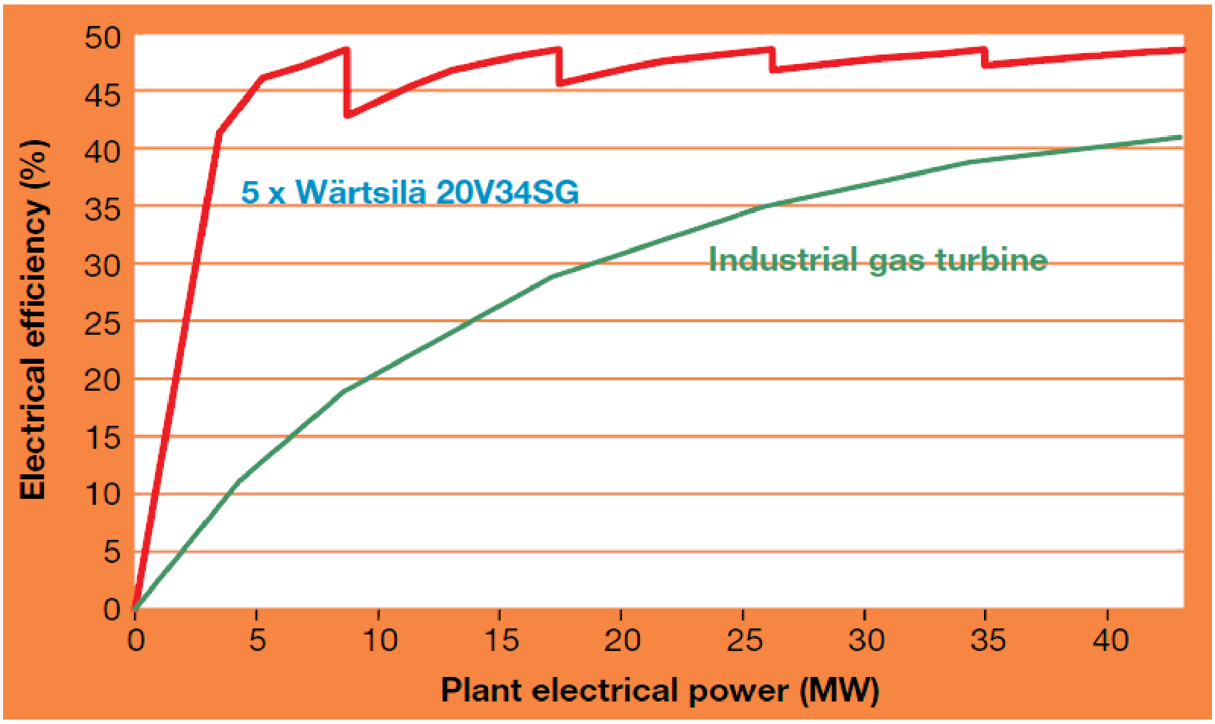

Figure 0-9: The multi-unit gas engine power plant has very high part-load efficiency. [48]

7 Disclaimer

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The sole responsibility for the content of this publication lies with the authors. It does not necessarily reflect the opinion of the European Commission.

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