Transformation of the German energy system –
Towards photovoltaic and wind power

Technology Readiness Levels 2018

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Abstract

The aim of this thesis is to objectify the discussion regarding the availability of technologies related to the German energy transition. This work describes the state of development of relevant technologies on the basis of Technology Readiness Levels. Further, it points out development potentials and limits as well as the necessary power capacities needed for a certain energy system design that is mainly based on electricity. Thus, the scope is set to renewable energy sources suited to provide electricity in Germany, technologies that convert primary electricity for other energy sectors (heating and mobility) and storage technologies. Additionally, non-conventional technologies for electricity supply and grid technologies are examined. The underlying Technology Readiness Assessment is a method used to determine the maturity of these systems or their essential components. The major criteria for assessment are scale, system fidelity and environment. In order to estimate the relevant magnitudes for certain energy technologies regarding power and storage capacities, a comprehensible simulation model is drafted and implemented. It allows the calculation of a renewable, volatile power supply based on historic data and the display of load and storage characteristics. As a result, the Technology Readiness Level of the different systems examined varies widely. For every step in the direct or indirect usage of renewable intermittent energy sources technologies on megawatt scale are commercially available. The necessary scale for the energy storage capacity is in terawatt hours. Based on the examined storage technologies, only chemical storages potentially provide this magnitude. Further, the required total power capacities for complementary conversion technologies lay in the two-digit gigawatt range.

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1. Introduction

The sufficient supply of a society with resources and energy is a cornerstone for the development of prosperity. Energy supply, in particular, took on an increasingly role in Europe at the end of the 19th century, as mechanization led to considerable increases in productivity and energy demand. This process is by no means finished today. On the contrary, several studies show (cf. [1], [2]) that economic growth cannot be explained by the factors labor and capital alone. An abundant and cheap energy supply enables increases in productivity while scarce energy severely constrains economic growth. It accelerates the production and substitutes expensive labor costs. Therefore, the vital necessity of a rich and economical energy supply is undisputed for an ongoing growth of prosperity. Besides this economic feature, a nation's way of energy supply has to cope with the given ecological, social and political boundary conditions.

If there is a social and political desire to change the prevailing way of energy supply, the society sets the objectives and the legal framework that force the development of technical innovations. This development takes time and it takes even longer to implement these innovative energy systems nationwide. An example may be given by the history of nuclear energy in Germany (based on [3] and [4]). From the first discovery of radioactivity in 1896 by Antoine Henri Becquerel it took until 1954 when the first grid feeding nuclear power plant began operation in Obninsk, Russia with a power of 5 $MW_{el,net}$. The next commercial reactor started with 60 $MW_{el,net}$ in 1956 in Calder Hall, England. The first German nuclear power plant with 15 $MW_{el,net}$ (grid connected) started 1961 in Kahl, Germany and was still designated as an experimental plant. It took further three more decades to install a number of nuclear power plants with ever-increasing power capacities. The expansion was stopped in 1989 and the current phase out is set to 2022 due to ecological and safety concerns. This short outline shows the rise and fall of an energy source in Germany and the time it took for development, implementation and shutdown (deconstruction is not included).

With the current path of the (next) German energy transition towards a renewable energy supply with minimal carbon dioxide emissions a series of questions arise. From an engineering point of view some of these questions are

- How can it be done? (What are necessary technologies for an at least secure supply of energy? What are the options for the energy system and how can different technologies be implemented?) And
- How fast can this transition be done? (What is the current state of the art and what technologies need further development? What is the necessary expansion for the respective technologies? Are the given goals and timeline for the energy transition feasible?)

Therefore, the objective of this work is to contribute to finding answers and to objectify the discussion regarding the available of technologies. This work describes the state of development of relevant technologies on the basis of Technology Readiness Levels. Further, it points out development potentials and limits as well as the necessary power capacities needed for a certain energy system design that is mainly based on electricity. The content and results of the Technology Readiness Assessment were created during the project "Identification of the bottlenecks of the German Energiewende - Study on Technology Readiness Level (TRL) of crucial techniques" for the VGB PowerTech e.V.

For the following investigation the sample or rather the examination object has to be limited. The essentials of the German energy transition are found in the "Energy Concept for an Environmentally Friendly, Reliable and Affordable Energy Supply" [5]. The feasibility has been confirmed by a statement of the German Advisory Council on the Environment [6]. The aim of the energy transition is to gradually increase the share of renewable energies to more than 80 % of the gross electricity consumption. At the same time, primary energy consumption is to be reduced by 50 % compared to the base year 2008. In a rough timeline, the year 2050 was set as final milestone. The transition of energy supply for heat, electricity and mobility is expected to reduce greenhouse gas emissions by 80 to 95 % compared to the base year of 1990 [5]. A spotlight is set on the electric power supply, which has to be delivered by renewable energy sources (RES) and thus must be expanded accordingly. However, the use of volatile RES requires large-scale storage solutions. The options for direct, large-scale storage of electricity are limited. Therefore, an alternative energy supply system is needed that can buffer temporary oversupply from RES by storing it for later use and bring it in line with energy demand. A sample structure for such a system is shown in Figure 1.

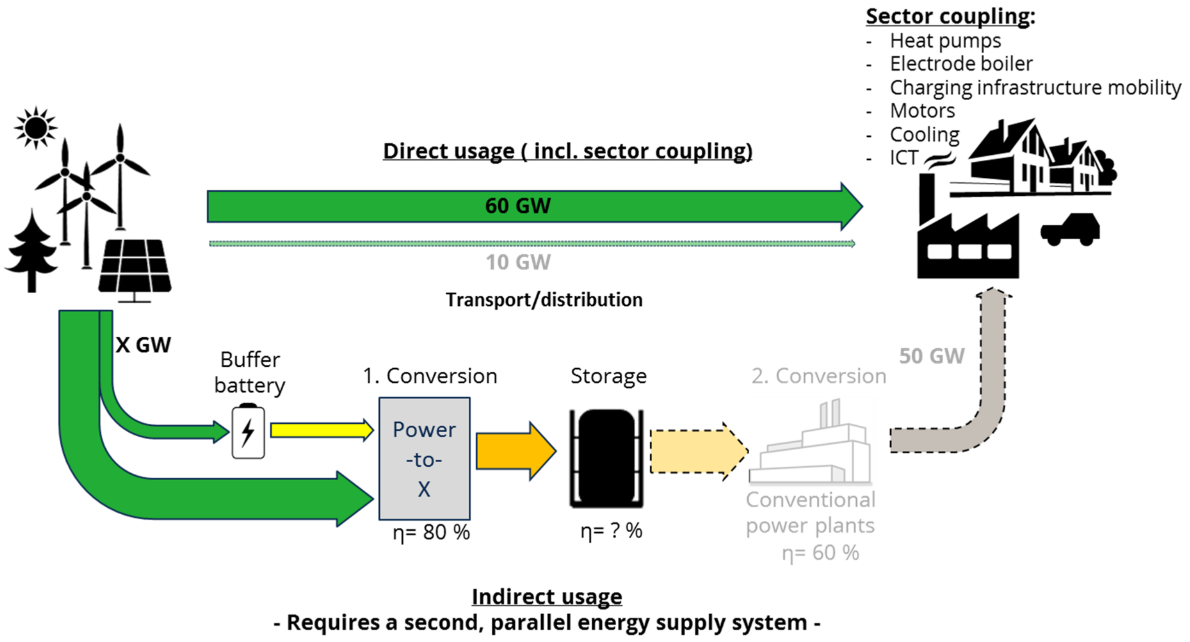

Figure 1: Power supply system dominated by RES with parallel storage system (bold/filled components: sufficient RES supply with surplus; transparent/gray components: RES undersupply with compensation by stored RES energy and conventional power plants; degree of effectiveness illustrative)

In Figure 1 two possible (extreme) situations are shown. The filled components represent full supply by RES. A mean power load of 60 GW$_{el}$, which includes the final energy demand for heating, cooling, electricity and mobility, is completely covered by volatile RES. Temporary surpluses are stored by means of the parallel storage system. This consists of (buffer) batteries, which reduce rapid load changes for the subsequent, sometimes slower, conversion technologies and further serve to provide electrochemical storage. Energy storage after initial conversion may be thermal, chemical or mechanical. The second situation is represented by the gray / transparent components. In the event of an undersupply of electricity (10 GW$_{el}$ from RES), stored energy has to be converted a second time to provide power (here 50 GW$_{el}$). It may also be used without a second conversion e.g. for heating. This consideration leads to the expectation that the power capacity and storage capacity of transformation and storage technologies have to be in the order of magnitude of gigawatts (GW) and terawatt hours (TWh).

In this approach, the supply of electricity is considered primarily in the context of the technology matrix depicted in Figure 2.

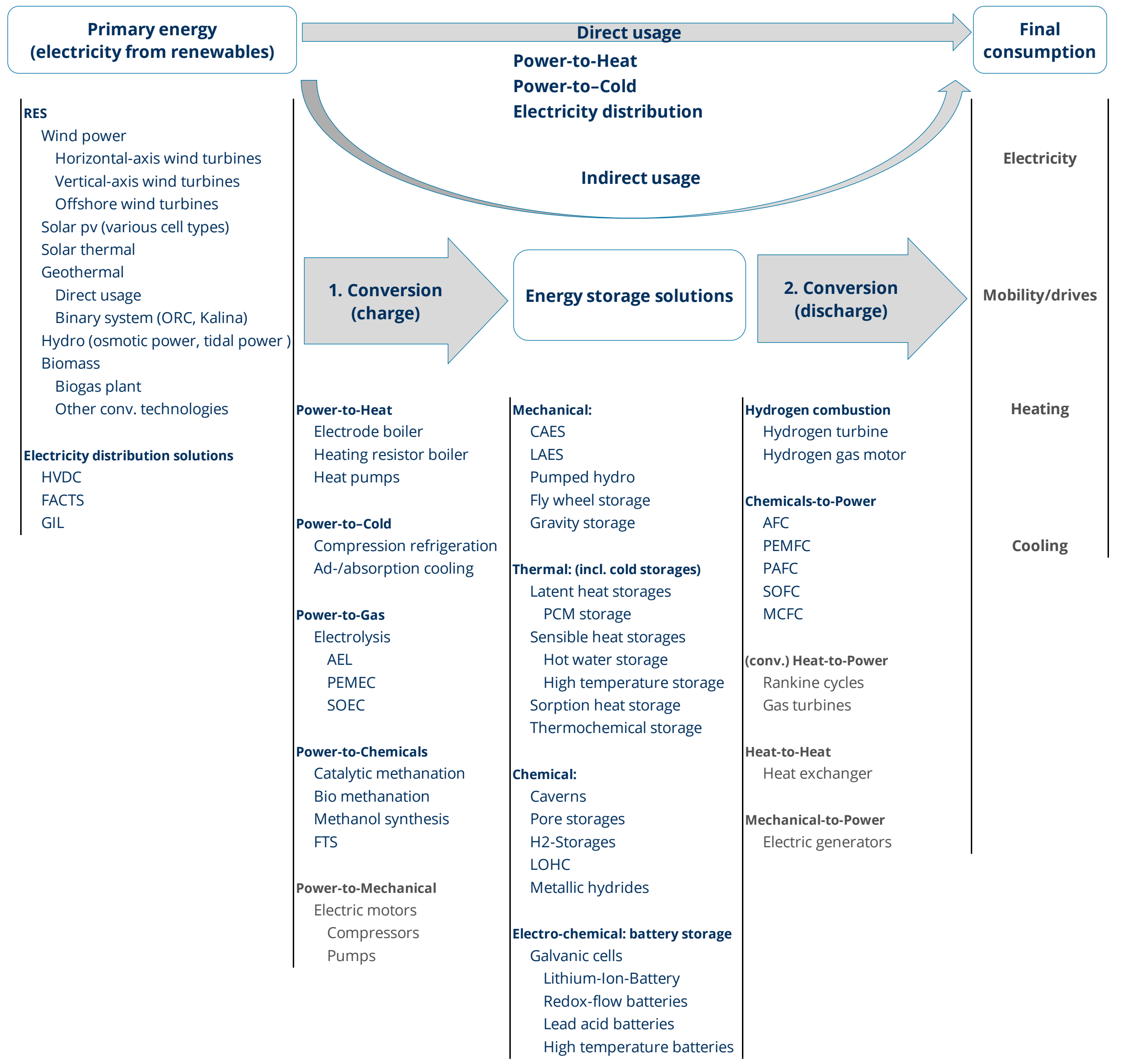

Figure 2: Technology matrix

In order to cope with the vast range of technologies some simplifications in the analysis where necessary, which are shown in the method chapter. It should be pointed out that the focus is based on a) today's electrical energy requirements and b) comparatively recent technologies. For example, conventional, mature technologies for the second conversion stage (gas and steam turbines, electric pumps and motors, generators, electrical transformers, etc.) are not included in the technology matrix (cf. chapter 4. Preliminary Remarks). The direct use of electrical energy is limited to today's electricity needs (for decentralized supply of heat, cooling, light, information and communications technology (ICT), stationary mechanical drives, etc.). In contrast, the future direct use of electricity for mobility might not be limited to rail traffic, but could also include trucks using overhead transmission lines (e.g. eHighway concepts [7]). This topic is not considered in depth for reasons of delineation. Today's electromobility in passenger cars uses electrical energy only indirectly via portable storage batteries.

In this thesis the current state of the German energy transition is roughly outlined and the chosen method of Technology Readiness Assessment is presented. The assessment follows the matrix in Figure 2 and starts with the primary energy supply from RES. Particular emphasis is placed on their technical potential, on significant improvements and expansion potential in Germany. In the following step, the first conversion stage - the transformation of electricity into other energy forms that are better suited for storage - is analyzed. Further, the storage solutions and finally the second conversion to electricity is investigated. For the second conversion stage, the focus is on hydrogen technologies as the conversion of fossil (chemical) energy into thermal, mechanical and electrical energy is widely known and mature (TRL-wise). The conversion of energy in batteries is an inherent part of the technology and thus not explicitly designated as first/second conversion. The technology-specific references are listed at the end of each chapter to simplify and improve readability.

As will be shown later (cf. chapter 4.1), the necessary scale of a technology has a major impact on the TRL. Therefore, a mathematical modell is developed, that considers the weather dependent feed-in from volatile renewables, their expansion limits and the time-dependent energy demand. As a result, the model shows the required scale for technologies of the first conversion step, storages and back-up plants. This assessment does not question the current maturity of certain processes, but the TRL in regard to the mission of a renewable energy supply.

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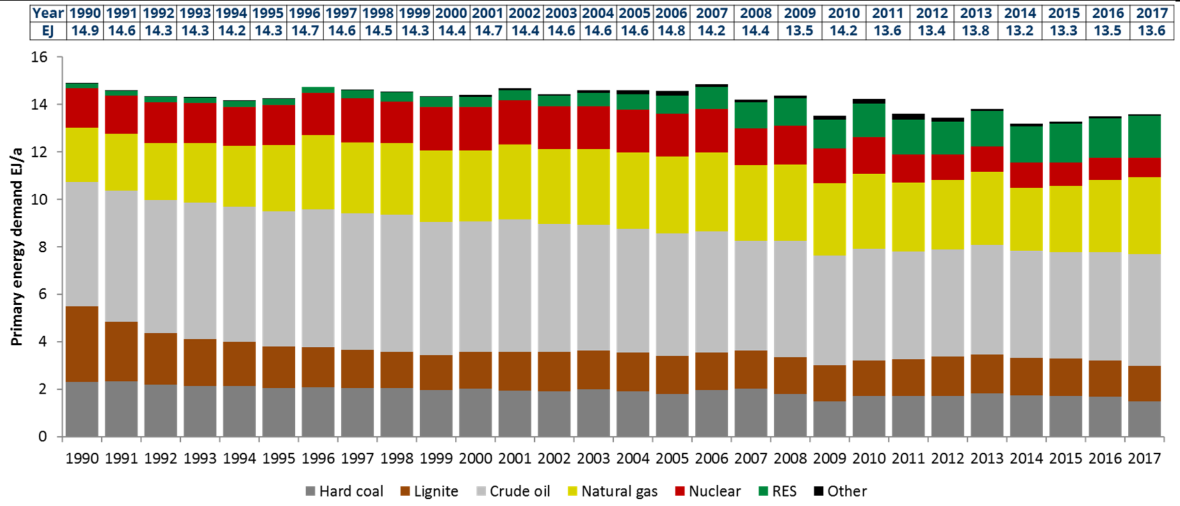
2. General remarks on the current state of the German energy system

The historical development of energy supply in Germany can be viewed from several perspectives. Here it will be discussed from the point of primary, final and electrical energy supply. This perspective is chosen because it allows an easier understanding of the development and influence of RES in Germany. First, Figure 3 shows the composition of primary energy supply since 1990.



Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
EJ	14.9	14.6	14.3	14.3	14.2	14.3	14.7	14.6	14.5	14.3	14.4	14.7	14.4	14.6	14.6	14.6	14.8	14.2	14.4	13.5	14.2	13.6	13.4	13.8	13.2	13.3	13.5	13.6

Figure 3: Development of primary energy supply in Germany since 1990, data from [1]

A slight declining trend in overall primary energy demand can be seen. On the one hand, there are absolute savings in mineral oil, lignite and hard coal. On the other hand, the demand for natural gas has expanded and, in line with the political objectives, the share of renewable energy has steadily risen. Nuclear energy, which is used almost exclusively for electric power supply in nuclear power plants, has lost its importance over the course of time and is expected to disappear altogether from the balance sheet by 2022 (phase out). This will certainly impact the future CO_2 emissions in Germany (see also Figure 4), since electricity from nuclear power has practically no fuel-related CO_2 emissions. The missing supply will at least partially be substituted by other primary fossil fuels.

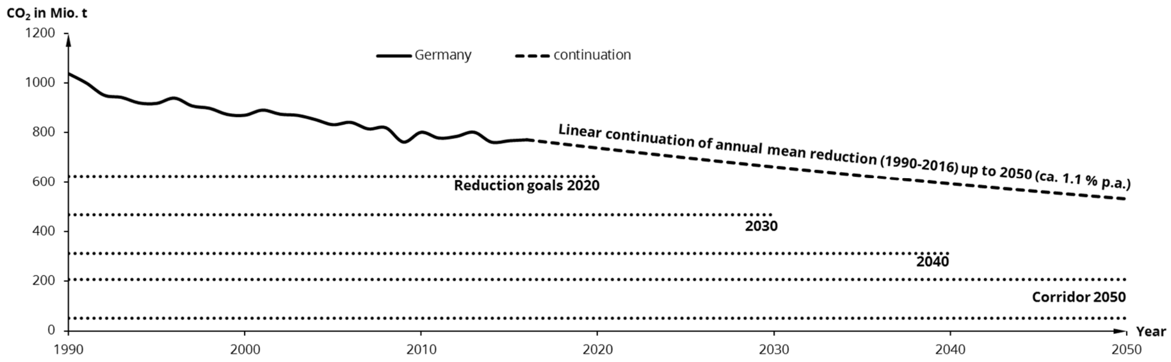


Figure 4: Development of CO2 emissions in Germany since 1990, data from [1]

Figure 4 further shows that the reduction rate of CO_2 emissions over the past 20 years has been insufficient to reach the core goal of the German energy transition. Since the vast majority of CO_2 emissions occur in the energy sector, the most measures for reduction have been taken here. The expansion of renewable energies and the reduction of the total energy demand by efficiency gains are already going hand in hand in Germany. In contrast, economic and (in Germany only qualified) population growth have a retarding effect.

The above-mentioned objectives of the energy concept are expressed as ratio targets. This way, goals can be achieved in principle in two ways. The dividend and the divisor could be adjusted. For CO_2 reduction targets, however, the divisor is fixed at the emission level of 1990. On the energy supply side (here primary energy, see Figure 3), the share of RES in the primary energy supply can be further increased by constantly expanding them. Additionally, the total primary energy demand can be reduced. Efficiency gains and rationalization in all areas of energy usage along the supply chain lead to ever decreasing specific energy requirements for different applications. The energy used in the sectors of industry, transport, trade and services and households for the supply of goods and services is referred to as final energy. The corresponding final energy demand has fallen slightly (1990: 9,472 PJ; 2016 9,329 PJ, - 1.5 % [1]). At the same time, the ratio of final energy to primary energy, which represents the overall efficiency for conversion and transport, has risen from 63.5 % in 1990 to 66.8 % in 2015 [1]. However, the savings and efficiency gains are compensated by an expanded user behavior, the so-called rebound effect. This effect describes that energy savings from more efficient technologies are offset by increased demand or use. An excellent example is the final energy demand for oil-derived fuels, which varies over the years but has actually widened from 2,533 PJ in 1990 to 2,655 PJ in 2016 [1] (cf. Figure 5b)). Reducing the costs of private mobility with motor vehicles (better mileage, cheaper compact cars, short-range battery vehicles, cost reduction in production and price reduction for cars[1]) is leading to an increased fuel demand. An individual will travel farther at the same cost and travel more often than before. This effect is slowed down when the advantages of further use are no longer met or a possible demand is completely covered. Simplified, an energy-efficient LED lamp cannot operate longer than 24 hours a day and the benefit of "light" cannot be increased. Thus, the absolute energy consumption decreases through efficiency gains when the demand for a certain use case is saturated.

Figure 5 below shows the final energy demand of 9.060 PJ of the year 2016 broken down by sector, energy source and application. It further shows the nearly constant total final energy consumption over time, especially for electricity and fuels.

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[1] Taking the hedonic regression method for consumer price indices into the account.

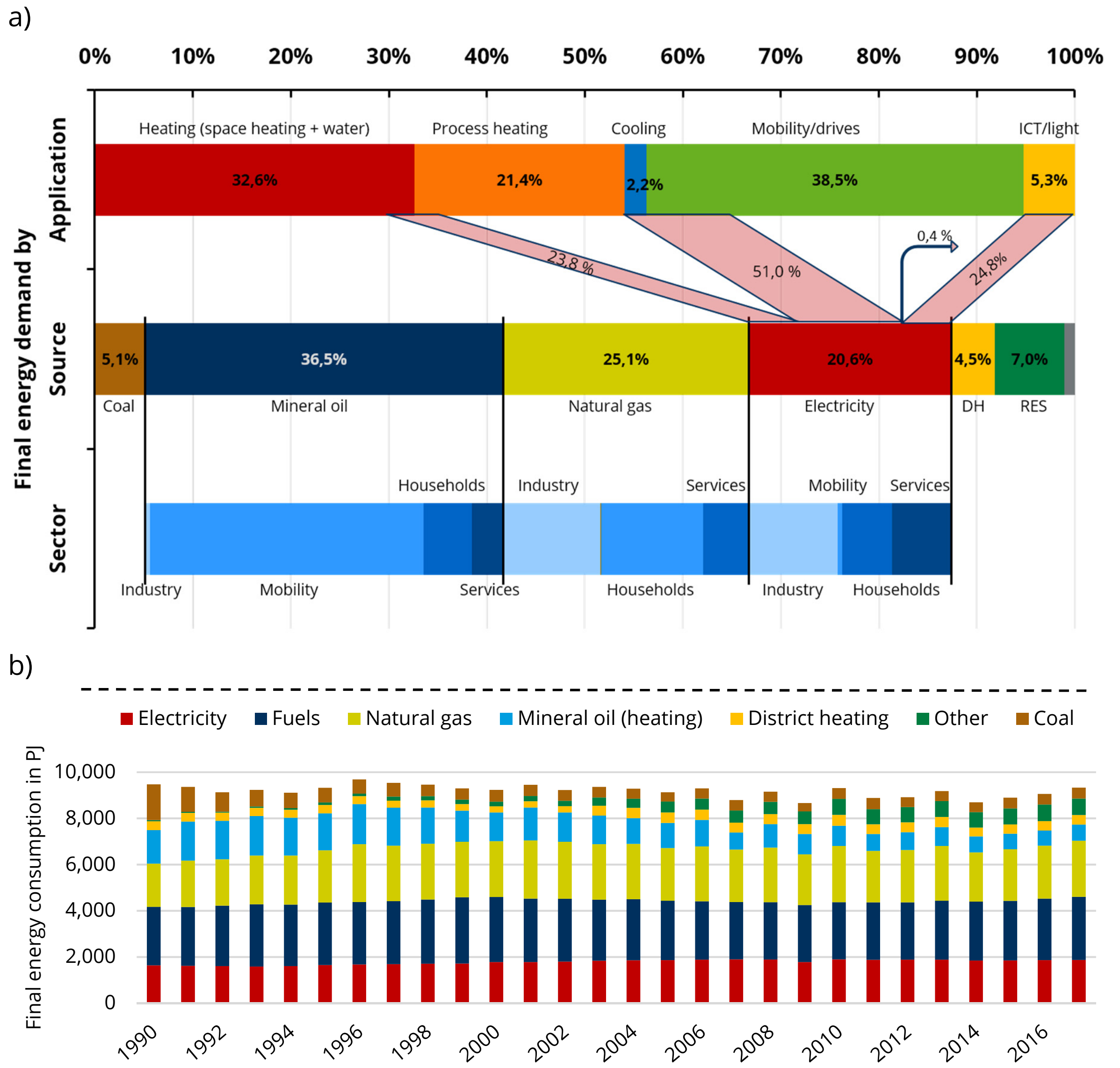

Figure 5: Final energy consumption in Germany a) 2016 (9.060 PJ) by sectors, application and source; dh – district heating [1]
b) Final energy consumption over time [1]

The majority of mineral oil products is consumed in the transport sector (75.7 %), while natural gas and electricity are evenly distributed in the industrial, trading/services and household sectors (electricity: 43.8 %, 28.6 %, 25.4 %; natural gas: 41.2 %, 18.9 %, 39.6 %) [1]. In the trading/services and households, natural gas and oil are often used for (low temperature) heat applications. The rising share of RES is hidden in Figure 5 in two categories. On the one hand, in the section RES, which contains bio-fuels and heat from RES, and on the other hand in electricity, where it accounts currently for about 30 %. So far, the German energy transition until now is primarily an “electricity transition” because the "other" renewable energies only contribute a marginal share for heat and mobility in comparison to electricity. Electrical energy, however, is needed in all areas of the final demand. Mobility and electric drives do not refer to electric vehicles alone, but also to electric motors in industries, trading/services and households.

There are three important findings that can be deduced:

- Mineral oil is primarily used in the transport sector, i.e. for mobility;
- Natural gas is mainly used to provide heat in all three other sectors - industry, households and trading/services;
- The electric energy demand represents only 1/5 of the final energy demand.

However, if electric energy only accounts for a relatively small share of the final energy demand, its dominant role in the public discussion should be questioned. An explanation might be the availability of numerous alternatives. In the field of power generation, wide varieties of regenerative options are available (cf. chapters on primary energy supply from RES). Especially technologies for photovoltaic and wind energy are easily available and ubiquitous to see. Further, any final energy demand can be met with electrical energy. The connection of the energy sectors for mobility and heat with the electricity sector is referred to as “systems integration of energy supply and demand” or short “sector coupling” and naturally expands the demand for electrical energy.

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3. Method of Technology Readiness Assessment

3.1. Fundamentals of the method

The Technology Readiness Assessment (TRA) is a method used to determine the maturity of a technical system or its essential components. Its result is a classification of nine levels - the so-called Technology Readiness Levels (TRL). These levels describe the technology progress from concepts and studies to actual operation as an integrated system in full scale over a prolonged period. The TRL are shown in Figure 6 with a qualitative description of the classification criteria.

The detailed and descriptive classification in the appendix 27.1 is already partially adapted to the requirements of energy technologies, since NASA developed the original scale and accordingly tailored it to aerospace issues. The first considerations for an assessment of technology maturity can be found in a NASA report from 1969 for space station technologies [2]. The concept evolved continuously over the following years and the scale was expanded from the initially seven to nine levels and in a 1995 paper comprehensively described and defined for the first time [3]. Another step towards global acceptance was the adoption of the TRL concept by the United States Department of Defense (DoD) in 1999, initiated by the US Government Accountability Office (GAO). The United States Department of Energy (DOE) was also encouraged by the GAO in 2007 to use the TRA [4].

The main reason for using the TRA is, from the perspective of the GAO, the avoidance of cost explosions and delays in large projects. A high degree of maturity of the technologies used is associated with a high probability of project success. From the experience of GAO, the use of technologies with a TRL < 6 leads to cost increases and delays [1]. The examples given in [1] relate primarily to defense engineering projects. In energy engineering, the GAO 10-675 report [5] noted with particular concern that the DOE was unable to provide an assessment of the maturity of carbon capture and storage (CCS) technologies for coal-fired power plants. The DOE prepared an overview of the TRLs for the Clean Coal Research Program (CCRP) by 2015 [6].

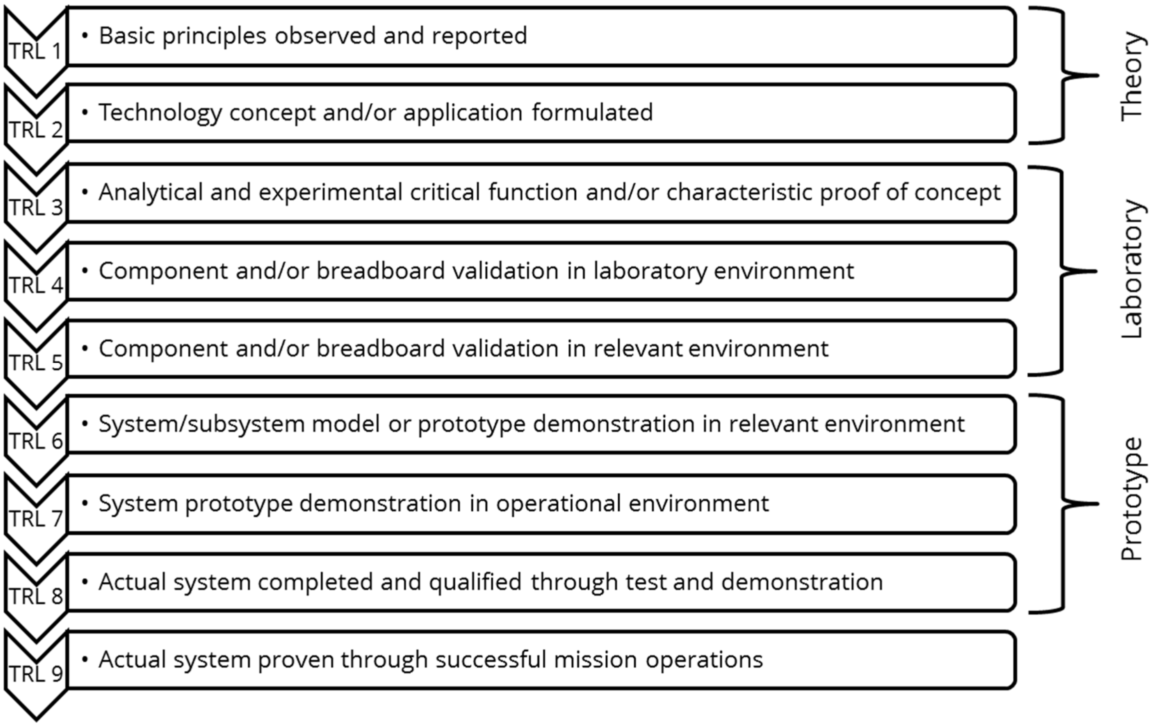

Figure 6: Technology readiness levels and basic properties, based on [1]

The TRA method is presented in detail in [1] and a best practice process is given for conducting TRAs. Additionally, the DIN ISO standard 16290 is available with the latest update of 2016-09, in which the TRLs are presented descriptively [7]. The general process for determining the TRL is as follows:

1. Select Critical Technology Elements – CTE:

The selection of critical elements for a system or application has to be done by the respective expert. In general, parts are considered critical if they are new or completely novel and indispensable for the specified operation of the target system. An element is also critical if it poses a particular risk to compliance with cost, time and performance restrictions [1]. For orientation, two ways are shown that facilitate the selection. Firstly the identification of CTEs in process flow diagrams is explicitly suggested in the area of energy process engineering and secondly a questionnaire for classification as CTE is available in [1].

2. Evaluate critical technologies and determine the TRL:

The classification of a technology or CTE is based on the following list of criteria (see Table 1). The definition of the respective criterion is based on the TRL scale used by the US Department of Energy [8].

Table 1: Classification evaluation criteria of TRLs

TRL	Scale of Testing	Fidelity	Environment	Proof
1		Paper		
2		Paper		Analytical
3	Laboratory/Bench	Partial	Simulated	Analytical Experimental
4	Laboratory/Bench	Partial	Simulated	Analytical Experimental
5	Laboratory/Bench	Similar	Relevant	Analytical Experimental
6	Engineering	Similar	Relevant	Analytical Experimental
7	Full	Similar	Relevant	Analytical Experimental
8	Full	Identical	Operational (limited range)	Analytical Experimental
9	Full	Identical	Operational (full range)	Analytical Experimental

These descriptive criteria are to be interpreted as follows (Table 2):

Table 2: Definition of TRL criteria

Scale of Testing:

- Full scale: system matches final application in performance, power and dimensions
- Engineering: the scale regarding performance, power or dimensions is 1:10 < system < full scale
- Laboratory/bench: the scale regarding performance, power or dimensions is < 1:10

Fidelity:

- Identical: matches final application in all respects
- Similar: matches final application in almost all respects
- Partial: system partially matches the final application
- Paper: system exists on paper (i.e. no hardware system)

Environment:

- Operational (full range): system is tested in deployment environment
- Operational (limited range): system is tested with limited range of real conditions
- Relevant: controlled environment with limited influence/use of real conditions
- Simulated: controlled environment, necessary to prove concept or function

The classification can be supported by the use of TRL calculators, which derive the evaluation from a questionnaire (e.g. [9]). Their application is not undisputed, because the assessment is formalized but sometimes the critical assessment of individual components is disregarded. Therefore, it may be possible to derogate from the formal approach according to [1] and to simplify the method, in particular if the addressee group is limited to an expert audience and a frequent or regular repetition of the assessment is done. A large amount of information about test results, model scaling, environmental conditions or performance specifications is required for a detailed assessment of the maturity. This data can only be found to a limited extent in the context of secondary research, so that some uncertainty in the classification remains. Even within the framework of primary research (e.g. through expert interviews), a classification risk remains. The quantification of that risk has been attempted in [10] by applying statistical methods.

The TRL classification is therefore only a first step in the assessment of a development project. Consequently, a “Technology Maturity Plan" (TMP) should be prepared after the evaluation. It includes the next steps to further maturing a CTE and gives a rough estimate of development costs and time to provide decision-makers with necessary information [11].

In summary, the TRA can show the development gap from the current state of the art to large-scale application. It further identifies in a transparent way critical components in a system and the necessary research steps to eliminate development risks [11].

3.2. Drawbacks of TRA

The TRA focuses in its original context on a technology’s technical feasibility or operational capability for a mission. Therefore, many other factors for a technology deployment are not taken into account or are considered of minor importance. Thus, important goals in the energy supply, namely sustainability and cost-effectiveness, are not in scope of the examination. This exclusion of aims is acceptable, since at first the technical feasibility of the German energy transition with today’s state of the art should be considered in depth.

In addition, the Technology Readiness Assessment has a number of other flaws, which are listed below and briefly explained (bases on [1] and [7]):

- **Limitation of context and time:**
  The TRL rating is a snapshot and with a limited validity period. It applies to a specific element in a particular system with particular timing, purpose and conditions. If the narrow frame is changed, a revaluation is required.
- **Missing life cycle effects:**
  On the one hand, a mature technology (in the sense of TRL 9) can be considerably improved through continuous improvement processes (CIP) over time and, on the other hand, it can become outdated through the advent of new technologies (e.g. the transition from floppy disks to CDs). These effects are not taken into account and are generally difficult to predict.
- **Independence of the components:**
  If the evaluated CTE element is considered detached from the target system, systematically higher TRL valuations may occur. The successful application of the component in the final system also depends on the maturity of the interfaces and the integration with further components, however that connection is not directly examined in a detached maturity rating.
- **Ordinal metric:**
  The ordinal TRL metric itself departs not allow an estimation of time or effort needed to reach the next maturity level. Therefore, the TMP is necessary.

- **Standardized approach:**
  The method must be adapted to the specific industry, case or purpose. General definitions are possible, but only conditionally suitable. The complexity and scope of various elements to be evaluated require specific approaches.
- **Quality of the tools and the evaluation team:**
  The objectivity of the maturity rating depends on the available data, the expertise of the reviewers and is not least limited by their subjective assessment (influenced by goals, corporate culture, expectations of the technology, etc.).

3.3. Extended Readiness Levels

In addition to the TRL, also consecutive, advanced methods of evaluation are used. These are listed below for completeness [1]:

a) Manufacturing Readiness Levels (MRLs): describe the availability of production processes for a technology and are therefore always coupled to a minimum TRL. The scale ranges from 1-10, with 1-9 correlating with the TRL. Level 10 describes the level of continuous process improvement (e.g. lean production practices).
b) Integration Readiness Level (IRL): describes the connectivity and interaction between different technologies or components. Again, a TRL correlating scale of 1-9 is used.
c) System Readiness Levels (SRL): describes, on a scale of 1-9, an overall system consisting of multiple technologies or CTEs and their respective IRLs. Compared to TRL and IRL more than two technologies and their connections are considered.

These approaches at least partially mitigate the aforementioned drawbacks and extend the scope to a system level that takes the interaction of multiple (critical) components into detailed account. An important prerequisite for this is the basic TRA for the individual components, which is the focus of this work. The requirements for the system interaction (e.g. the flexible operation of an energy conversion technology connected to intermittent, renewable energy sources) can basically be included in the TRL rating via the (conjectured) purpose or framework of the respective technology.

3.4. Conducting the Technology Readiness Assessment

In this work, from today's perspective, central system components of the German energy transition are examined. First, a possible basic concept for the implementation of the energy transition was presented (cf. Figure 1) and the corresponding elements were shown in the technology matrix (cf. Figure 2). The primary goals of this initial TRL rating are:

1. Systematic description and presentation of the critical technologies and components for the Energiewende (in relation to generation, distribution, storage, usage) – focusing on electricity,
2. Evaluation of the Technology Readiness Level (TRL) of each of the respective technologies,
3. Description of development potential – in terms of technology and capacity,
4. Identification of development deficits in the respective technologies.

The specific approach summarized in Figure 7 was therefore chosen. Basic assessment (secondary research) in line with the principles of DIN ISO 16290 is supported by several interviews with a range of experts and then reviewed for each technology.

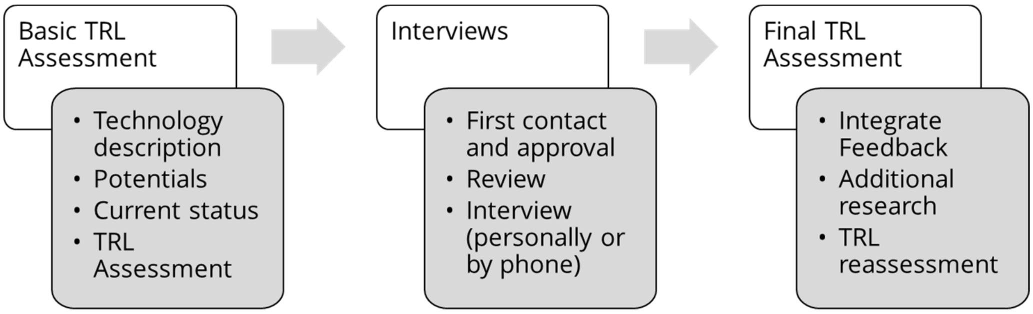

Figure 7: Approach of the study

The interviews were conducted in person and by telephone. The methodological foundations for the interviews are based on [12] with reference to [13] and [14]. Each chapter is structured the same way according to the template set out in Figure 8. This formalized approach supports the conduct of the interview, as there it already represents a detailed guideline for each interview. The evaluation of the interviews is qualitative and the comments and advice have been integrated directly into the technology level assessment.

Technology description

- A basic overview of the respective technology is given (state-of-the-art)
- Physical basics are shown
- Relevant techniques and critical components are shown

Potentials a) Technical development potential

- Focusses on the critical components
- Shows current developments and projects for improvement

Potentials b) capacity potential in Germany

- Gives an estimation of the capacity that could be installed in Germany or would be necessary for a certain purpose (e.g. maximum wind energy onshore; power-to-heat potential from heat pumps for base load in district heating)

Current status in Germany

- Describes current facilities and key indicators in Germany (rated capacities for power, load hours, energy supply etc.)

TRL Assessment

- Summary of the findings from section potentials and currents status
- Resulting in a table with TRLs for presented techniques or critical components

Figure 8: Chapter structure for each technology

3.5. Expert interviews

The experts named in Table 3 were interviewed and helped greatly in improving the final TRL assessment. I like to thank these experts for the support, feedback and the inspiring discussions. I further like to thank all those who were not available for interviews, but who provided helpful references, further contacts and hints towards current research projects.

Table 3: Interviewed experts for TRL assessment

Primary energy (RES)	Expert (Association)
Wind power	Prof. Dr.-Ing. R. Schelenz (RWTH Aachen)
Solar PV	Prof. Dr. rer. nat. habil. T. Hannapel (TU Ilmenau)
Solar thermal power	Dr. J. Krüger (German Association for CSP)
Geothermal energy	Dr. W. Bauer (Geozentrum Nordbayern) Dr. H. Schröder (enpros consulting GmbH)
Hydropower	O. Univ.-Prof. Dipl.-Ing. Dr.techn. H. Jaberg (TU Graz) Univ.-Prof. Dipl.-Ing. Dr. Gerald Zenz (TU Graz)
Biomass	Prof. Dr.-Ing. M. Beckmann (TU Dresden)
Electricity distribution	
Transmission grids	Prof. Dr.-Ing. C. Rehtanz (TU Dortmund)
1. Conversion	
Power-to-heat	A. Tost (BVA Elektrokessel GmbH) F. Sachse (KLÖPPER-THERM GmbH & Co. KG)
Power-to–cold	Prof. Dr.-Ing. U. Hesse (TU Dresden)
Power-to-Chemicals (Power-to-Gas)	Dr.-Ing. C. Bergins (Mitsubishi Hitachi Power Systems Europe) Prof. Dr.- Ing. D. Stolten (Forschungszentrum Jülich)
Storage solutions	
Mechanical	Dr. S. Zunft (Deutsches Zentrum für Luft- und Raumfahrt e.V.)
Thermal	Prof. Dr.-Ing. habil. T. Urbaneck (TU Chemnitz)
Chemical	H.-J. Polk (VNG AG) Dr. M. J. Schneider (HYDROGENIOUS TECHNOLOGIES GmbH)
Electro-chemical battery storages	Prof. Dr.-Ing. Thilo Bocklisch (no interview, TU Dresden)
2. Conversion	
Hydrogen combustion	Dr. Peter Kutne (Deutsches Zentrum für Luft- und Raumfahrt e.V.)
Chemicals-to-power	Prof. Dr.- Ing. D. Stolten (Forschungszentrum Jülich)

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4. Preliminary remarks on the TRL assessment

The TRL method and a fundamental method critique has been presented. There are further important aspects for understanding and interpreting the results that are explained below. These include the technology mission and necessary simplifications in the TRA. The following state of the art chapters (“technology description”) present the essential core components for sector coupling. The basic functions will be discussed only briefly, since those are generally known and are already extensively presented in overview books. The focus in the respective chapters is on the decomposition of technologies into Critical Technology Elements (CTEs), which are essential for the assessment of the overall maturity of a process or system according to the TRA method.

As mentioned above, the content and results of the Technology Readiness Assessment were created during the project "Identification of the bottlenecks of the German Energiewende - Study on Technology Readiness Level (TRL) of crucial techniques" for the VGB PowerTech e.V. For the translation of the fully formulated German script of chapters 5 to 19 the service of the translation agency "SprachUnion" in Chemnitz was used[2].

4.1. Mission and environment

A key component for the TRA is the definition of the application environment and the performance requirement, i.e. the mission for the technology use. The mission is slightly different for each technology field and may differ within a field. For example, the purpose and boundary conditions for underground natural gas storage are clearly different from electrochemical, stationary battery storage. Thus, the field of application for a technology has to be delimited at an early stage for further examination.

The respective scaling of a system in itself can vary the TRL considerably. For example, commercial 2 MW_{el} PEM electrolysis systems are currently in operation at several locations in Germany [1]. Thus, system fidelity, operational environment and the descriptive prerequisites are given for a TRL 8 or even TRL 9 assessment. If the range of application is limited to the magnitude of the electrical power output of waste-to-energy plants in Germany (mean 19.3 $MW_{el,net}$ according to [2], energy source "waste" and status "in operation"), the electrolysis plants need to be scaled by approx. 10 and therefore reach only slightly TRL 6 - engineering scale. This problem is addressed in the following TRA by limiting the scale to available magnitudes. If possible, the relevant scale is named in the final TRL classification. The current mission of a technology is presented in the technology description.

Closely related to this is the application environment, which can also be best illustrated with an example: modern stationary lithium-ion batteries are used today in Germany to provide primary ancillary services. The demand for primary reserve power is approximately 1,400 MW_{el} and the minimum block size for a tender is 1 MW_{el}. The

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[2] SprachUnion, Technologie Centrum Chemnitz, Annaberger Str. 240, D-09125 Chemnitz

duration is at least 30 minutes and the plant must be available within 30 seconds [3]. From a technical point of view battery storages fulfill these requirements (TRL 9). However, these requirements may shift significantly in the future, whereby the exact specifications are difficult to foreseen today (e.g. short-term damping of power peaks from volatile RES to start up slower conversion processes, see chapter Electrochemical Storages),

4.2. Simplifications and neglected aspects

For the following examinations some simplifications were made, which are given on the one hand by the method of TRA and on the other hand allow a necessary reduction in complexity without diluting derivable key messages:

- The focus is on electricity and its usage in Germany. Technologies primarily used for e.g. heating (solar heating) or mobility (fuel from biomass) are therefore excluded.
- The study focuses on new or recent technologies. Mature and conventional technologies such as gas turbines, steam turbines, pumps, electric motors, generators, el. transformers etc. are thus excluded (TRL 9, grey in Figure 2).
- A TRL 9 does not mean that all aspects of a technology are fully developed, e.g. although technologies for using hydropower as primary renewable source of energy are well advanced, approaches to further improve water turbines and the complementary systems (flow control, generators etc.) are less so. These improvements are indicated where possible, but they do not affect the readiness level.
- Economic and ecological issues are also excluded. For all technologies with TRL 6-9, one of the major goals for further development is improvement of scalability by means of, and in order to achieve, cost degression.

4.3. References

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5. Wind power

5.1. Technology description[3]

Wind energy is a secondary form of solar energy. It is the result of the movement of air masses caused by local and global variations in pressure. “Of the total quantity of solar radiation impacting the outer edge of the atmosphere, approximately 2.5 % or $1.4 \cdot 10^{20}$ J/a is consumed by atmospheric motion; this yields a theoretical total wind power of approximately $4.3 \cdot 10^{15}$ W […].” [1]. The instantaneous, locally available power from wind (eq. (1))

$$P_{Wi} = \frac{1}{2}\dot{m}_{Wi}v_{Wi}^{2} = \frac{1}{2}\,S\rho_{Wi}v_{Wi}^{3} \tag{1}$$

can be calculated based on the kinetic energy of the wind (eq. (2))

$$E_{Wi} = \frac{1}{2}m_{Wi}v_{Wi}^{2} \tag{2}$$

using the mass flow of the area through which it passes (eq. (3))

$$\dot{m}_{Wi} = S\rho_{Wi}\frac{dx}{dt} = S\rho_{Wi}v_{Wi} \tag{3}$$

This means that the available wind energy increases in proportion with the cube of the wind speed, which in turn increases exponentially with the height depending on the surface roughness and can be determined approximately using Hellmann’s exponential law. According to Betz’s law, only 16/27 (~59 %) of this energy can be converted into mechanical energy per rotor plane of a wind turbine[4].

Modern wind turbines (WTs) are generally classified as either horizontal axis wind turbines (HAWTs) or vertical axis wind turbines (VAWTs) based on the position of their drive shaft. Three-blade HAWTs have dominated wind turbine development in the output range of just a few kW up to today’s MW turbines and have come to define the state of the art (see also section 6.5). This is a result of the structural disadvantages of VAWTs, which experience comparatively higher vibrations and stresses. Strong resonances can occur, resulting in a reduction of the maximum structural height. This means that the wind speeds available for conversion are lower on average. In conjunction with lower wind speeds, the as-yet poorer coefficient of power that VAWTs have achieved according to Betz’s law leads to significantly higher costs per kilowatt hour [2]. Despite the advantages of simplified maintenance (due to conversion technology that is nearer the ground) and the fact that wind tracking is not required with VAWTs, their comparatively lower profitability has caused development to focus on HAWTs, which dominate developments on the market today. VAWTs are currently used exclusively in small wind turbines with a

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[3] The following explanations and correlations are based in part on the following research project carried out by Paul Kriegel and supervised by myself: “Analysis of the potential of large-scale wind farm implementation options, based on a technology readiness assessment”, student thesis, TU Dresden, 2015.

[4] This relation is based on the fact that the wind cannot stand still behind the plane of a rotor. The deduction assumes that the air passes the infinitesimal thin rotor plane once and is therefore decelerated.

rated output of up to 200 kW_{el} (e.g. [3]). For this reason, they are not taken into account as an essential element in any well-known analyses of scenarios for the energy revolution in Germany.

The basic structure of HAWTs is illustrated below in Figure 9. In terms of their structure, the question of whether the turbines will be installed onshore or offshore is only relevant for their base or foundation. However, more powerful turbines are erected in offshore applications, which means that all of the elements (generator, rotors, blade bearings, drive train, cooling system, etc.) are designed to be stronger, and the higher weight requires an adaptation of the towers and bearings. The state of the art of these main components is described below. Section 5.2a) addresses further potential development.

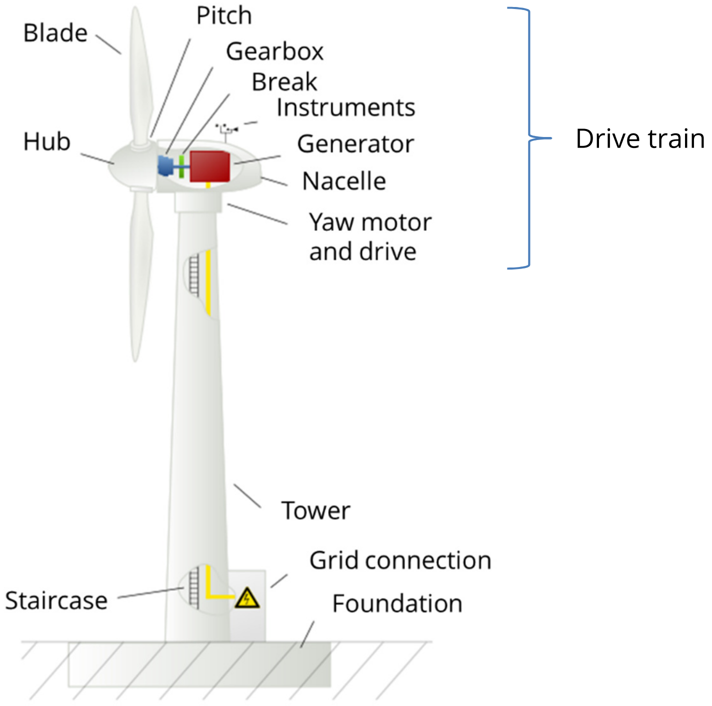

Figure 9: Basic structure of a HAWT, translated, [4]

Drive train

The drive train of the WT can be individually considered as a large assembly. It comprises the rotor, the components that transmit power (gearbox) and the generator. As illustrated in Figure 10, the energy losses are distributed across the conversion chain in the drive train as follows:

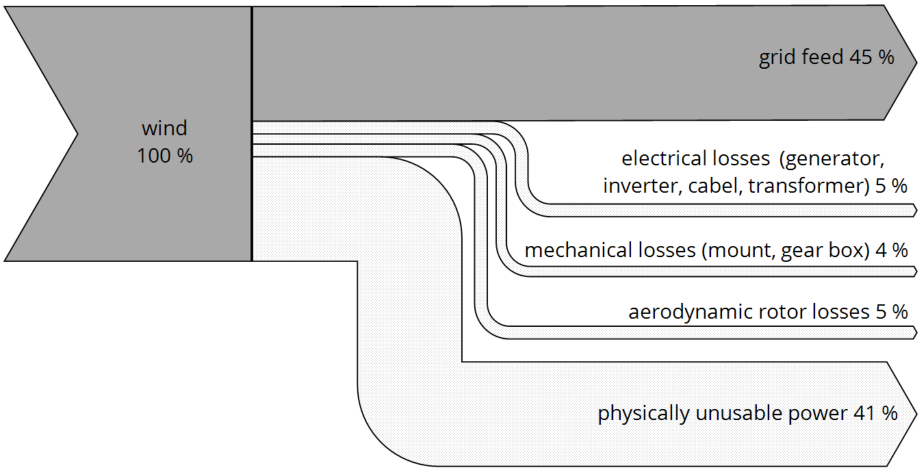

Figure 10: Efficiency chain of a HAWT-type wind turbine,values based on [5]

Overall, drive trains are more differentiated today with respect to their location. In an attempt to achieve optimal levels of rated output and utilization, the specific generator output per square metre of rotor surface is reduced in the onshore area so that locations with low wind speeds can be exploited. A wind turbine which is designed for high nominal speeds and is therefore more powerful will nonetheless achieve its rated output less frequently due to the inconsistency of the wind. Meanwhile, turbines that are designed for a high degree of utilization – that is, for the use of lower wind speeds as well – are unable to attain outputs of comparably high levels but nonetheless feed into the grid on a more consistent basis [6]. Increasing the diameter of the rotor causes the swept area of the rotor, and thus the potential wind yield, to increase quadratically. However, enlarging the rotor in this manner results in the rotor blades being subjected to unevenly distributed loads. Due to the large dimensions, the loads vary not only between the individual rotor blades, but also over their length. The method of controlling the turbine using the pitch concept, which changes the angle of the rotor blades to the wind and thereby decreases the aerodynamic loads, has been developed over time and now enables each rotor blade to be turned individually on the rotor hub. The system nonetheless proves to be too slow to counteract suddenly occurring gusts, and arising loads that are distributed across the radius likewise cannot be compensated [7].

In total, the specific increase in output (per WT) in recent years is to be attributed primarily to the further development of the rotors. However, this further development in particular has its limitations in a number of aspects [2]:

- Larger blades result in ever-higher blade tip speeds, which are restricted to approximately 70 m/s in onshore applications (for noise control reasons), requiring that the frequency be reduced (which in turn requires stronger, heavier gearboxes);
- The height of the blade tips attains altitudes that are relevant from a regulatory perspective (e.g. 220 m in North Rhine-Westphalia);

- The use of pre-bent rotor blades is no longer sufficient to avoid contact with the tower;
- The blade mass has a limiting effect, as the mass increases quadratically with the length, and increasingly strong blade bearings and main bearings thus become necessary as well;
- Longer blades require increasing blade diameters at the blade bearing, and the capacity to transport these is restricted (max. transport diameter of 4.3 m under Autobahn bridges).

Because costs and mass increase with the cube of the increase in the rotor's size, manufacturers are interested in designs that are as lightweight as possible. However, this can only be achieved with new materials and small loads. In order to produce effective rotor blades of the next generation, there will have to be new load reduction concepts that enable loads to be controlled via the radius of the rotor [8]. In conclusion, a number of technical thresholds which cannot be derived from current technology must be exceeded in order to attain further increases in rotor size. The main bearing of a WT will be the obstacle to this development, as it simply becomes too large [2].

Drive train concept

With respect to the translation of the rotational movement of the rotors into electrical energy via a generator, a basic distinction is made between two concepts: WTs with and without a gearbox. Turbines that increase the rotational speed with the help of a mechanical gearbox – and thus permit the use of a compact, rapidly rotating generator – are more mechanically complex and therefore require more intensive maintenance. Altogether, however, the gearboxes appear to be mature with efficiency levels of approximately 98 %. Of course, the high output of modern WTs gives rise to significant quantities of heat, which must be discharged with cooling lubricant via heat exchangers [9]. According to [2], continuous further development towards medium-speed generators has taken place in recent years. These can be built more compactly and with fewer components. As a result, higher performance classes have been attained, but smaller design sizes with greater output place higher requirements on the cooling concepts (e.g. water cooling).

Gearless turbines, meanwhile, run with a large ring generator that provides variable frequency alternating current. This is first changed into direct current via a converter and then into three-phase alternating current suitable for the grid. However, this requires generators of significantly larger dimensions, which in turn results in a significantly higher tower head mass [10]. The specific gondola weight for gearless turbines (from 5 MW_{el}) is 75–88 t/MW and 35–52.4 t/MW with a gearbox [11]. In the case of the gearless turbines, the advantages of the low-maintenance direct drive are offset by the considerably higher costs for installation and transport that result from the high masses of the gondolas. Using permanent excitation via permanent magnets can mitigate this problem. However, the permanent magnets in turn require rare earth elements, which represent a great price risk [2].

Tower

The assemblies discussed above (with the exception of the rotor blades) are housed in the gondola, which is mounted on the tower. The tower bears the weight of the gondola and the rotor and must withstand the vibrations and loads which arise during operation. Welded or flanged steel towers have been used for this purpose thus far.

The further challenge comes about as a result of the increasing height of the hub in the construction of the towers, which is already responsible for up to 30 % of the total investment costs and large portions of the installation and transport costs. The increasing heights of the towers have led to the development of so-called hybrid towers. The lower part of a tower of this type is made of concrete elements, while the upper section consists of conventional steel tube components [12].

Foundation

The foundation must absorb the forces of the tower on land. For cost reasons, raft foundations (as illustrated in Figure 9) are used wherever possible. Pile-based deep foundations are used in cases where the ground is unable to support the turbine's weight. Offshore foundation concepts are significantly more challenging. In comparison to onshore wind power, the investment costs make up a significantly greater share of the overall investment costs, amounting to around 65 %. These costs are dominated by the foundation structures [13]. Figure 3.5 shows the platforms, which are currently in use:

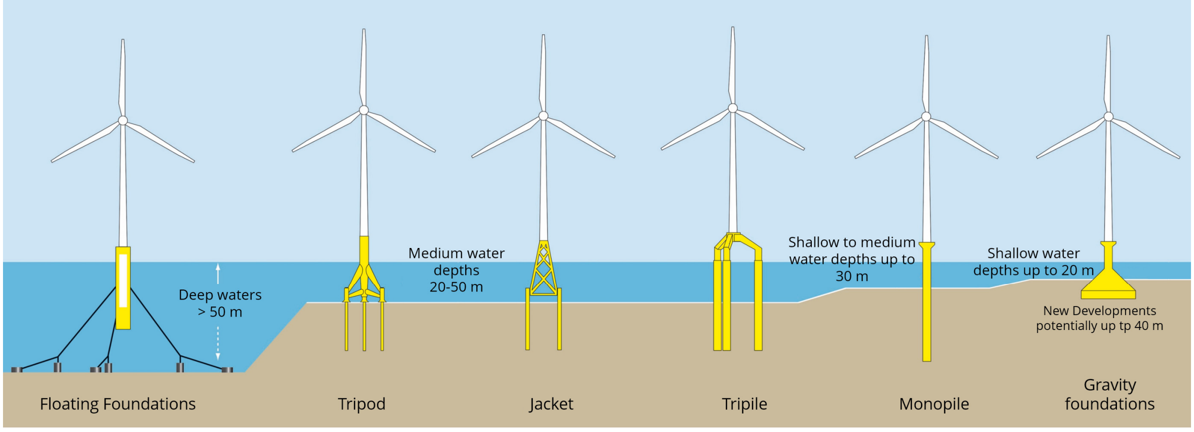

Figure 11: Overview of foundation structures, based on [14], translated

As indicated in Figure 11, the respective foundation structure is determined by the water depth at the location. While monopile and gravity foundations are used up to 20 m as per [14], tripods (three legs) or jackets (four legs) are used for depths of 20–80 m. Floating foundations are then suitable for greater depths. Germany's offshore WTs are positioned at an average of approximately 60 km from the coast in a water depth of 28 m [15].

In addition to the foundation, the grid connection or the options for grid integration should also be mentioned here as per Figure 9. WTs can have a stabilizing effect on the grid depending on the requirements of the grid code. Common options include the provision of reactive reserve, maintaining frequency stability (either by providing reserve power or utilizing the rotating mass of the generator) and fault ride through (FRT, i.e., maintaining synchronous operation even in the event of severe grid disturbances for a short period). These options are primarily based on the control and regulation of the converters and transformers. These components are discussed in chapter 10. A distinction should be drawn between this and the capacity to provide operating reserve, which is only possible to a limited extent without further generating sets (see also section 5.2a)). It is known from [16] that the wind turbines with active power control are used to stabilize the frequency in grids with a high proportion of wind energy (such as Ireland); that is, they provide primary operating reserve.

Interim conclusion

The state of the art described above already makes it possible to achieve significant output levels for HAWTs. For example, offshore WTs with an output of up to 8 MW_{el} are now commercially available [17]. The rotor diameter of these turbines is 167 m and the drive train is gearless. A prototype constructed by Vestas (based on the MHI Vestas V164) can achieve an output of 9.5 MW_{el} with a similar diameter and was commissioned in 2017 [18].

5.2. Estimation of potential

Part a) below describes the further technical developments and the current technically foreseeable potential. Part b) focuses on the possible expansion of output in Germany.

a) Technical development potential

Rotor concepts to reduce loads

As described above, the rotor diameter represents a central dimension in terms of the maximum amount of energy that can be converted. If the rotor blades of WTs whose rotors are facing into the wind (upwind) continue to increase in size, the stiffness of the rotors must be increased or the load reduced into order to prevent them from striking the tower. In terms of load reduction, a distinction is drawn between active and passive load reduction. The active variants aim to achieve a controlled modification in the geometry of the blade profile. Wing flaps similar to those used in the aviation industry are mounted on the rotors. These change the flow of air around the profile and thereby influence the lift and resistance of the blades. The German wind power industry, for example, is involved in an advisory committee for the Smart Blades joint project, which consists of the German Aerospace Center (DLR), the ForWind research council as well as the IWES [19]. This project is investigating two variants with the active components positioned in front of and behind the blade [20]. The control of the systems should work significantly faster than the pitch control. The project is in the numerical simulations phase with the goal of determining an ideal design for the various variants. Initial wind tunnel trials have only been carried out for the adaptive slats system thus far, and these trials confirmed the analytical assumptions [21]. Thus, the second variant has therefore already reached TRL 3, while the flaps have remained at TRL 2 due to a lack of experimental trials, . As with the passive variants, there are plans to fabricate a 20 m long demonstration blade for the flaps at the end of the project, which could therefore also achieve TRL 6 should the test prove successful [20]. The adaptive slats, meanwhile, will only be tested in a wind tunnel, as their development is expected to require significantly longer periods of time. Due to the testing conditions, it will therefore not be possible to exceed TRL 5 for the time being [19].

In the case of the passive load reduction concepts, the structure of the blade is designed in such a manner that the rotor changes its shape under load and thereby enables a more favourable flow around the blade. This type of load reduction is based on the principle of bending-torsion coupling. When loaded, the rotor blades twist around their own axis at the point of the load and can thereby change the angle of attack relative to the wind [19]. This is achieved through a processing of the fibre composite materials, which permits various material characteristics depending on the direction of loading [22]. A rotor blade with a length of 20 m was completed in December 2017 and is currently in the test phase in the wind tunnel [23].

The ‘SUMR’ research project at the US Department of Energy is examining segmented ultralight morphing rotor concepts for downwind applications as a further approach for WTs up to an output of 50 MW_{el}. In this case, the rotor is positioned in the lee of the tower and the flexible rotor blades can morph, thereby avoiding the risk of a collision. If a storm occurs, the blades are intended to change their shape and align with the wind – similar to the leaves of palm trees – in order to reduce resistance and stresses. This concept should make it possible to use offshore blade lengths of up to 200 m, that is, rotor diameters of approximately 400 m [24].

Drive train concept

The drawbacks of gearless turbines described in section 5.1 can potentially be compensated for with superconducting generators. Based on an externally excited direct drive, it combines the advantages of the low-maintenance drive train without a gearbox and the ability to avoid large quantities of rare earth metals for the permanent magnets. However, the key advantage is the sharp reduction in weight of 50 % in contrast to conventional direct drives, whereby the weights of the drive trains with gearboxes would also be undercut [25]. The presented projects use superconducting[5] coils in the rotor of the generator, which permit high current densities due to the minimal resistance. This

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[5] Superconductors are materials which no longer have any electrical resistance when cooled below their material-specific critical temperature.

results in a significantly more compact design. The two larger research projects Suprapower and EcoSwing are currently attracting attention. Suprapower was completed in July 2017. During this project, a 15 kW_{el} generator was built which, according to the final report, is [26] scalable up to 10 MW_{el} and was a tested under similar conditions. The performance class of the developed prototype is therefore very small in relation to the final target system, and the TRL is no greater than 4 (operational environment simulated).

In the case of EcoSwing, the development objective is a pilot generator for an existing WT with a rated output of 3.6 MW_{el}. According to a presentation in August 2017 [27], the generator was in the assembly phase and was to be tested on a test rig in 2018. The installation of the demonstrator into the WT is part of the project objective, which means that TRL 6 (prototype in relevant operational environment) will be attained if the project is successful.

Tower

Despite the described modular design, the components are still heavy due to the materials used and cannot always be transported using standardized methods because of their dimensions. Further developments are currently being made by constructing the towers from composite materials. If the base of the tower is designed as a three-part shell structure and the hollow space is filled with synthetic material, this results in significant savings in materials according to [28]. Furthermore, less welding work is required to maintain the same bearing capacity and shock absorption characteristics of these towers in comparison to steel towers, even though the dimensions are the same. Separating the elements also offers a solution for the transportation problem.

Towers made of wood are a further variant. The spruce framework used for these towers is estimated to be 20 % cheaper than conventional models due to the efficient use of materials, the low weight of the spruce wood and the resulting decrease in loads as well as the good dynamic properties. Furthermore, the towers are expected to have an extended service life and significantly lower dismantling costs. The tower is clad with plywood panels and protected against external influences by weather-resistant synthetic sheets which are affixed to it [29]. The first prototype, a 100-m-high tower, was inspected and approved by the TÜV in 2009 and set up with a 1.5 MW_{el} wind turbine near Hanover in 2012. The technology thus achieved TRL 8 based on the successful testing of the prototype in its operational environment. A further five towers for 2.5 MW_{el} WTs were planned but not built [30].

Foundation

Various concepts for the floating foundation have been developed [7], but none have moved beyond the demonstration stage thus far [31], [32]. The Hywind Scotland project, which includes five, 6 MW_{el} WTs, is anchored off the Scottish coast in a water depth of approximately 100 m and represents the greatest progress in this area so far [33]. Each tower is anchored in the water with three so-called suction caissons, which “[look like] oversized buckets turned upside down and moored to the sea bed. A vacuum is then created, which pulls the cylinder towards the ground.” [34]. This method can only be used for very homogeneous seabeds with few rocks. Another key challenge is continually maintaining the stability of the cable connection, as forces caused by movement continuously impact the cable in the case of floating positioning [2].

The floating platform can also be enhanced by combining it with the use of wave energy. Danish company Floating Power Plant has developed the only offshore-tested floating platform for wind turbines thus far that also uses the kinetic energy of the waves. The company’s planned P80 platform – the successor to the first prototype – offers space for a wind turbine with an output of up to 5 MW_{el} ([35]→ TRL 6). The kinetic energy of the waves is converted into electrical energy by moveable attenuators and generators. Incoming waves lift a float, which drives a generator via a hydraulic system. The 80-m-wide platform can thus convert an additional 2.4 MW_{el} of wave energy, thereby resulting in a maximum combined output of 7.6 MW_{el} [36]. A further advantage is that the water is considerably calmer on the rear of the installation, so the platform can be reached even in inclement weather conditions.

Concepts for the future

The developments presented above will be supplemented by further concepts which are likely to be implemented in the more distant future. For example, there are expected to be two options for providing operating reserve from WTs: “an integrated battery and the instantaneous reserve from the oscillating weight of the rotor”. This will allow turbines to store energy from supply peaks for a short period and then subsequently feed it into the grid. And the instantaneous reserve will support the mains frequencies in particular.” [37]. The Operating Reserve from Wind and Photovoltaic Farms (ReWP) research project [38] focused primarily on concepts, supply strategies and IT solutions that were intended to support the provision of operating reserve. A demonstration unit has already been implemented at the Feldheim Regional Regulating Power Station (RRWK). Here, a10 MW_{el} Li-ion-battery (10.7 MWh_{el} capacity) provides operating reserve in conjunction with 55 WTs (122.5 MW_{el} total output) [39]. In this case, however, the battery rather than the WT supplies the operating reserve, and the concept is therefore not being included in the TRL classification.

In addition to the further development of the currently dominant HAWT concept, a variety of alternative approaches are also being pursued. These include, for example, multi-rotor concepts in which several rotors are located on a single tower. The most recent demonstrator in this group is a Vestas turbine with four rotors and a total rated output of 900 kW_{el} [40]. A further option is flying wind turbines, which have rotors that are raised to very high altitudes using blimps and would thus ensure a more consistent yield [41]. Crosswind kite power systems, in which a kite rises and falls in a similar movement to that of a stunt kite and thereby drives a generator winch, represent another variation. These approaches have yet to advance beyond the prototype stage (20 kW_{el}). The target figure for the system output is around 100–500 kW_{el} [42], as the German manufacturer EnerKite believes that there is a relevant gap in the market for small wind turbines in this range.

b) Expansion potential

During the last two decades, turbines were naturally first built in coastal locations with high winds; now more turbines are being installed inland and at other sites that tend to be less windy [43]. The necessary technology is developing in the form of an increased differentiation between so-called strong and weak wind turbines. Turbines whose location falls under the IEC III class (average wind speed of approximately 7.5 m/s) can be classified as weak wind turbines [44]. These wind turbines are manufactured with higher rotor diameters as well as greater hub heights and can thus achieve outputs comparable to those of strong wind turbines despite lower nominal wind speeds [7]. The [45] study worked on the assumption that onshore WTs can achieve approximately 2800 full load hours per year by 2050 if the rotor-generator ratio[6] of weak wind turbines in inland locations is further increased. The [45] study also emphasizes that offshore WTs already have significantly better forecasting accuracy than onshore WTs today due to the more consistent wind conditions at sea and can also provide more than 8000 operating hours[7] in addition to a significantly higher number of full load hours. An offshore WT would thus reduce flexibility-related costs in a German energy scenario consisting largely of renewable sources.

This stands in contrast to the VGB study on wind energy [46], which states that a secure supply cannot be ensured with WTs. "Despite the additions to the wind fleet throughout Germany, and contrary to the intuitive assumption that a wide-ranging distribution of locations for wind power should lead to balancing or smoothing of the aggregate electric power output from all wind turbines, since the year 2010 no increase can be detected in the annual minimum values (output feed-in data recorded hourly to quarter-hourly). 2016 also saw unchanged values of less than 150 MW or 1 % of the cumulative rated output of the German wind fleet." [46]

According to a study by the German Wind Energy Association (BWE)[8] in 2012, the expansion potential for WTs on land was determined to be equal to a maximum potential of 8 % of Germany's area which would be available for use without restrictions (forests, nature reserves, minimum clearances must be maintained). If 3-MW turbines (adjustment via the rotor diameter) were installed at strong and weak wind locations, this would theoretically yield a wind output of 722 GW_{el}. However, the study assumes it is more likely

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[6] Rotor-generator ratio = rotor diameter/generator output

[7] Refers in this case to the operating hours achieved; the potential operating hours or technical availability is significantly higher at 97–98% of annual hours [2].

[8] German Wind Energy Association

that a maximum of 2 % of Germany's area could be available. This would result in a maximum wind output of 189 GW_{el} with an annual yield of 390 TWh_{el} [47].

A recent study by Fraunhofer IWES[9] determined the potential in offshore areas. Based on a spatial plan from the German Federal Office of Navigation and Hydrography, the study calculated a maximum installable output of 54 GW_{el} with an annual yield of 258 TWh_{el}[45].

5.3. Representation of the achieved state of expansion

With approximately 50 GW_{el} of installed output [48] and 77.4 TWh or a 12 % [49] share in Germany's gross power generation, wind energy can certainly be described as one of the driving forces of the energy revolution (see Figure 12). These figures can be attributed to a considerable increase in additional installations over the last decade. The newly installed turbines have also become increasingly powerful on average. In Germany, a WT had an output of approximately 500 kW_{el} at the end of the 1990s. Today, the average turbine output is 2.97 MW_{el} [50]. The concept of the three-blade, upwind wind turbine is generally the most prominent around the world.

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[9] Institute for Wind Energy Systems Kassel

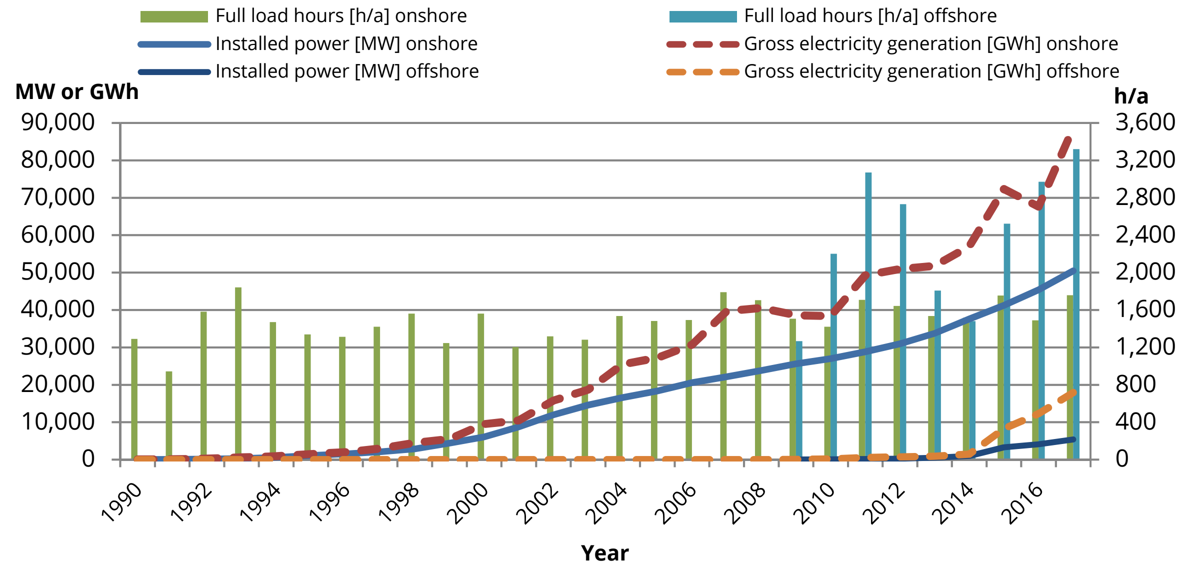

Figure 12: Development of wind energy output, feed-in and full load hours in Germany [50]

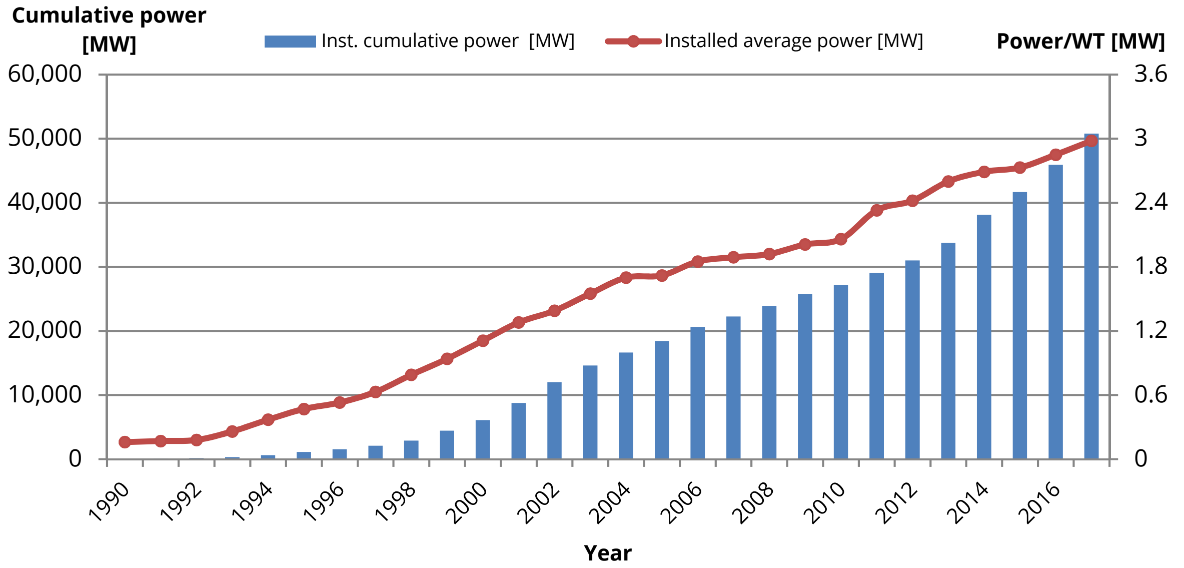

Figure 13: Cumulative new installations of onshore WTs since 1990 and average power of newly installed WTs each year [51], [52]

The active, continuous installation of new WTs and the intensified competition between manufacturers paved the way for the rapid technological development of the turbines, resulting in higher rated outputs along with a decline in costs. With an installed output of nearly 45.8 GW from over 27,000 wind turbines (as of December 2016), onshore wind energy continues to represent the significantly larger share of the output in comparison to offshore turbines (4.2 GW_{el} with 970 turbines) [53].

In addition to the general trend towards more powerful turbines with larger rotors (average annual increase in output of 6.2 % since 2001, cf. Figure 13) the differences between wind turbines depending on their location are becoming more pronounced, as previously described in section 6.

5.4. TRL assessment

Overall, three-blade rotors with a horizontal drive train can be considered mature technology on land or in coastal areas. The high degree of overall utilization and the large number of installed turbines leave no room for interpretation in this regard. Nonetheless, WTs are not yet fully developed. There are numerous research projects and approaches which could make WTs larger, cheaper and more durable in future, particularly in terms of improvements to their main components. An increasing focus is also being placed on WTs' potential usefulness for the grid due to the high rate of expansion, and this aspect is therefore being addressed as well. The TRL classifications are compiled in Table 4 below on the basis of research.

Table 4: Results of the TRL analysis

Technology	TRL	Supplementary sources
HAWT, three-blade rotors	9	
Rotor concepts – load reduction		
Smart Blades, active		
Front/rear edge	3/2	[54]
Smart Blades, passive	4	[23]
SUMR	2	[55]
Suprapower	4	[26]
EcoSwing	4	[27]
Sandwich tower	4/6	[28], [56]
Timber tower	8	[29]
Floating foundations	8	[30], [32]
Suction bucket	8	[33]
Multi-rotor turbines	6	[40]
Flying wind turbine	5	[41]
Crosswind kite power systems	5	[42]
Grid stabilization via reactive power, maintaining frequency stability, fault ride	9	[57] ,[16]
through secondary operating reserve	2	[37]

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6. Solar energy

6.1. Technology description

In principle, solar energy represents the source, the primary driving force, for all other energy sources. The average long-term irradiance reaching the earth is 1367 W/m². This radiant power is decreased by what is known as extinction, i.e. the combination of absorption and scattering in the atmosphere as well as reflection. In Germany, between 150 and 1000 W/m² reach the earth's surface depending on the season and the weather. Germany has region-specific energy inputs of 900 to 1300 kWh/m²a over a period of one year [1].

This paper focuses on the direct utilization of this source of energy. A distinction is drawn between two fundamentally different technological approaches for using the sun's energy. In the first approach the radiant heat can be harnessed in solar thermal technologies, while in the second approach the radiation can be converted directly into electrical energy by the photoelectric effect of particular materials.

6.2. Solar thermal energy

As mentioned in the introduction, this study primarily addresses the supply of electricity for the German energy revolution. Solar thermal energy as a branch of technology is therefore not considered in depth, but an outline of the main points will be presented below for the sake of completeness.

Modern solar thermal energy technologies are based on solar collectors. A common factor among these collectors is the use of the most absorptive surfaces possible on which the impacting radiation is converted into sensible heat and transported by suitable fluids (water, thermal oils) for use. Compared to solar thermal energy systems aligned for large-area absorption, it is possible for the thermal fluid to reach higher temperatures when the solar radiation is concentrated. This is achieved with the use of parabolic trough power plants or power tower plants surrounded by heliostats. These technologies, however, are reliant on direct solar irradiation, and the hours of sunshine required are simply not available in Germany. The technical and economic cost seems too great in regard to the potential yield in Germany. Concentrated solar power (CSP) is an important branch of technology, which, from a German perspective, can be used primarily in what is known as the MENA region (Middle East & North Africa). To this end, the German Association for CSP (DCSP) [2] was consulted as part of this study. It has been established that there are currently no commercial CSP projects in Germany, yet the possibility may exist in the future as a solar collector field with parabolic troughs is already being operated economically for district heating in Denmark by Aalborg CSP A/S (6.8 MW_{th}). There are plans for an additional field (16.6 MW_{th}) already in operation to be combined with an Organic Rankine Cycle (ORC) plant to provide electrical energy in the future ([3],[4]). It is therefore not completely beyond the realm of possibility that CSP plants may one day be used for district heating in Germany. In addition, it should be noted that CSP could also be used as a process heat supply in industry due to the inherently high temperatures. This system concept stands to benefit from the excellent storage capacity of the thermal oils used as well as a possible coupling with other energy supply systems (heat pumps, biomass combined heat and power). For this to happen in Germany, it will be necessary to develop and demonstrate intelligent approaches [5].

In contrast, numerous solar thermal power stations with parabolic troughs are already operating in sunny regions of the earth (mostly in blocks up to 50 MW_{el})[6]. The area needed for this is between 110 to 200 hectares depending on the location. Projects for solar tower plants with capacities of over 100 MW_{el} are in planning and operation (for example, Crescent Dunes Solar Energy Project [7], 110 MW_{el}, approximately 650 ha; Ivanpah Solar Electric Generating System (ISEGS), 377 $MW_{el,nt}$, 1414 ha [8]).

6.3. Photovoltaic technologies

Photovoltaic (PV) technology is already being used in Germany as an alternative to solar thermal energy. The term photovoltaic refers to the direct transformation of solar radiation into electrical energy using solar cells. The basic operating principle of the various solar cells is largely similar. In combined n- and p-doped semiconductor materials, electrons are knocked loose on a p/n boundary layer by solar irradiation. The electrons become separated due to the positive and negative space charge of the n-type and p-type layers and an electrical potential form (cf. Figure 14).

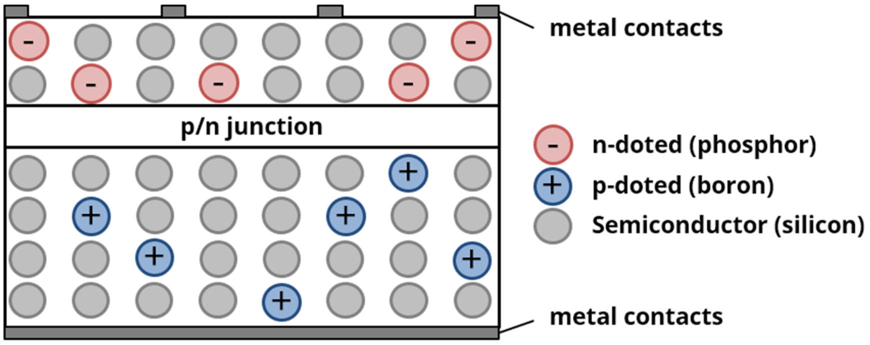

Figure 14: Basic structure of a solar cell (doping materials typical for silicon cells)

Over time, different cell systems have been developed that are suitable for generating energy from solar radiation. Two important product groups are available for commercial application: silicon-based poly- or monocrystaline solar cells and thin film cells (amorphous silicon, CIGS (copper indium gallium selenide), CdTe (cadmium telluride)). The thin film cells have a market share of approximately 6.6 % [9].

As the solar radiation reaching the earth cannot be influenced, utilization of the radiant energy stands and falls on the efficiency of the cells used. A distinction must be made between cell efficiency and module efficiency. Cell efficiency only concerns individual cells (eq. (4)):

$$\eta_{cell} = \frac{P_{el,cell}}{P_{irr}} \tag{4}$$

While module efficiency encompasses an entire module consisting of several cells (eq. (5)):

$$\eta_{module} = \frac{P_{el,module}}{P_{irr}} \tag{5}$$

An overview of the known cell types and their current cell efficiencies is shown in Figure 15.

The NREL[10] figure has been expanded for this study and likewise shows the module efficiencies for solar modules currently available. These values represent a snapshot (from November 2017) in the rapidly changing PV market. The manufacturers mentioned are representative of the technology branch in question and have the highest module efficiencies according to their published data sheets (cf. also Table 5).

Table 5: Efficiencies in % under standard test conditions – STC, based on datasheets

	Germany				**USA**	**Japan**		**China**		**India**	**Canada**
Manufacturer	Solarwatt	Q-Cells	Manz CIGS	Avancis GmbH	First Solar	Sharp	Kyocera	Yingli Solar	Trina Solar	Moser Baer	Canadian Solar
Si mono	18.2%	19.6%				19.8%		20.1%	19.3%		18.3%
Si multi		17.4%				16.8%	16.4%	18.5%	17.5%		17%
CdTe					18%						
Amorphous Si										8.4%	
CIGS			14.6%	13.8%							

Two aspects become clear from Figure 15. Firstly, the module efficiency for a cell type is considerably lower than the pure cell efficiency. This can be attributed to several factors. The interconnection of many cells results in large conduction losses. The conductors introduced for picking up the charge carriers also obscure a part of the solar cell, which thus can no longer contribute to the supply of power. Likewise, released electrons are lost in part by being reintegrated into neighbouring “holes” (free electron spaces) in the adjacent molecules. Furthermore, the housing on the edges, protective glass surfaces, as well as the gaps between cells constantly reduce the module efficiency and therefore the surface yield. The overall PV system (with cables, inverters and storage system where applicable) has even lower system efficiency.

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[10] National Renewable Energy Laboratory (NREL) – research laboratory for RE in the USA, funded by the U.S. Department of Energy

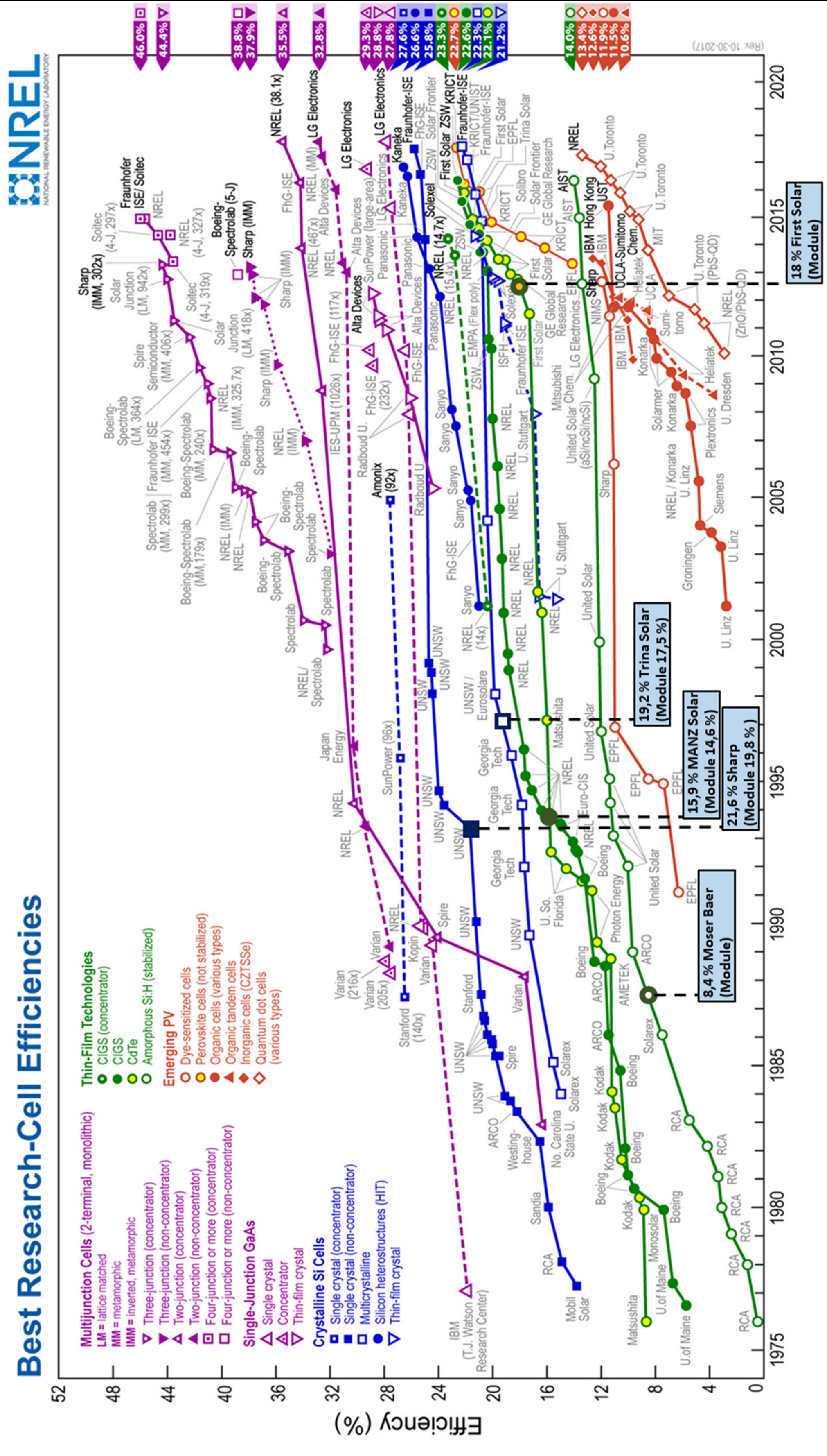

Figure 15: Efficiencies of solar cells and corresponding module efficiencies of current commercial solar modules [10], extended with module efficiencies. This plot is courtesy of the National Renewable Energy Laboratory, Golden, CO.

Secondly, the current module efficiency for the most widespread technologies (poly- and monocristalline PV modules) corresponds to the laboratory efficiency for cells from over 20 years ago. The efficiencies for CdTe modules are, in contrast, much closer to the current values for the research cells. This can be explained by the near-monopoly position of the manufacturer First Solar, which makes it possible for in-house research results to be rapidly transferred into practical production. Over all, it can be concluded that the laboratory efficiencies achievable today for solar cells will be available commercially and in mass production in 10-15 years at the earliest.

Gallium arsenide (GaAs) cells and stacked and tandem cells (multijunction cells) are also state-of-the-art technology as they are commercially available. However, due to the low market penetration and specific field of application (GaAs in particular for space flight), they will be considered in section 6.4a).

6.4. Estimation of potential

The estimation of potential is divided into a) the technical development potential and b) the expansion potential for Germany. Part a) describes the technical advancements and the current technically foreseeable potential. Part b) focuses on the possible expansion of output in Germany.

a) Technical development potential

Solar cells are confined by a physical limit known as the Shockley–Queisser limit, which describes the maximum efficiency of a single p-n junction [11]. This is determined primarily by the bandgap of the semiconductor used. In [12], the limits for different bandgaps are tabulated and displayed with the state-of-the-art technology (2016) for various laboratory cell types (cf. Figure 16).

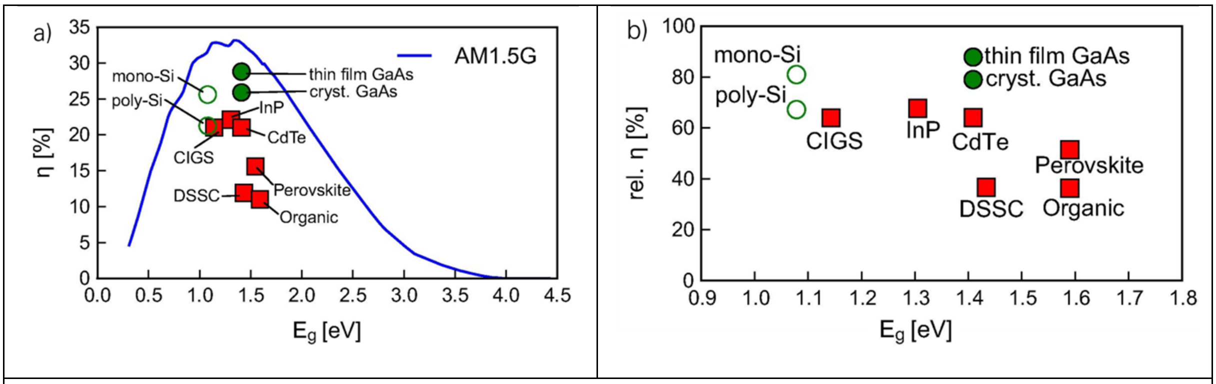

Figure 16: a) Maximum efficiency of solar cells with a p/n junction under standard test conditions (STC) subject to the bandgaps,
b) Status of the research cells regarding the respective maximum possible efficiencies [12]

Thus, the maximum efficiency for silicon cells with a bandgap of 1.12 eV is 32.73 %, for example. This maximum value applies only under standard test conditions. The limit can be overcome by concentration of the solar radiation, reduction of the air mass (e.g. AM <

1.5)[11] and cell temperature (e.g. very low in outer space) as well as a multi-layered composition (tandem cells).

In silicon cells, premature recombination in the cells is avoided by placing the metal contacts closer together. Yet this causes greater concealment, which in turn can only be reduced by thinner metal contacts [12]. Furthermore, parts of the module are shaded from light by the frame, and defects arise in production on the cut edges of the solar cells which consequently lead to output losses. Selected laboratory cells of the highest quality were used in the tests for the cell efficiencies shown in Figure 15. This production quality is not directly transferable to mass production. The difference between laboratory performance and realistic areas is a problem of homogeneity, as scaling to large areas is problematic for different materials. The thermodynamic parameter windows during the production process are occasionally very small, and many other subprocesses (kinetics) are not equilibrium processes [13].

Other solar cells still in development have a classification that is anything but trivial. This so-called “third generation” of PV cells is, according to [14], still in the demonstration or development phase. So the following will examine the “Multijunction cells” and “Emerging PV” branches of technology shown in Figure 15. Because of the wide variety of variations, representative examples from the branches will be considered in more detail.

The Grätzel or dye-sensitised solar cell (DSC) is a thin film cell in which a thin, sensitised, metal-doped (titanium dioxide - TiO_2) organic dye layer absorbs sunlight and serves as an anode [9]. The cell can be produced using the cost-efficient roll-to-roll printing process; it is semi-transparent, flexible and can be varied in colour. This, in combination with the use of the relatively inexpensive titanium dioxide as a substantial part of the cell, means that economic production is definitely conceivable.

The cell also contains platinum (the catalyst) and ruthenium (which dopes the organic dye layer); these prove more problematic due to limited availability and higher prices. Furthermore, DSCs contain a fluid (solvent-based) electrolyte which hinders the operational capability in diverse climate conditions as it corrodes seals and is volatile [16], [9]. The efficiencies achieved so far of up to 11.9 % (laboratory cells, see above) appear promising, but no information on the efficiencies could be determined for the two known demonstration systems. Article [14] states an efficiency of around 7-11 % (STC), which can be used to determine the possible output levels of the areas:

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[11] The air mass AM is a relative measure for the path length of the light through the atmosphere. $AM= l/l_0 = 1$ represents a vertical incidence of light. AM = 1.5 represents an angle of incidence of approximately 48° in relation to the vertical incidence of light.

[12] The concept is described clearly in a technology video from Hanwha Q CELLS [15]

Table 6: Demonstration systems for DSC

Demonstration system	Area	Assumed efficiency	Output (for STC)
EPFL window façade [17]	300 m²	9%	27 kW_P
Office building in Graz [18]	60 m²	9%	5.4 kW_P

Organic solar cells are another new form of solar cells. The market leader Heliatek from Dresden has been able to show demonstration systems on various surfaces (steel, concrete, glass) integrated into existing architecture or technical systems. According to the homepage, the largest system, with an output of 22.5 kW_p, is installed on the roof of a school in France [19]. With an area of 500 m², standard test conditions (1000 W/m²) yield an average system efficiency of 4.5 %. The manufactured cells have an efficiency of 7-8 % (laboratory cells > 13 %).

Further improvements of DSCs and OSCs are currently being explored in which the materials used and chemical bonds for the active layers (donor, acceptor, organic semiconductor) are varied and combined in new ways [20].

Another type of cell is the perovskite solar cell. It belongs to the thin film cells, which are of particular interest due to the rapid development in efficiency (cf. figure 1). The instability of perovskite solar cells continues to present the greatest problem. The crystal lattice is very sensitive to environmental influences. In conditions with too much moisture, heat or UV light, it changes, losing its ability to transform light into power. Also, the production processes for large-area modules have not yet been developed [21]. In addition to the stability problem, perovskite solar cells currently have another large deficiency: the crystal lattice contains lead. The heavy metal means that economic application is not yet conceivable even if the stability problem is solved. European RoHS (Restriction of Hazardous Substances) policy still prohibits the use of lead in solar cells [21]. An alternative tin compound is being researched as a replacement for the lead compound; however, this is also toxic [13].

Neither commercial providers nor large-scale demonstration systems could be investigated for perovskite-based solar cells. It was shown in [22] that it is theoretically possible to scale the technology, but in the case of large areas (>100 cm²), there is a considerable efficiency gap in relation to the laboratory cells. It should be noted that the newness of the development (first cell 2012 cf. Figure 15) means that the technology is still in the laboratory stage (cf. Table 7).

According to [13], solar cells with organic components (DSC, OSC, perovskite cells) have the general problem that they are unstable when exposed to oxygen, light and high temperatures. These influences lead to irreversible transformations in the organic matter over time.

Another cell type is the so-called III-V semiconductor solar cell composed of semiconductors from the third and fifth main groups. The most prominent representative here is the gallium arsenide (GaAs) cell. According to [23], these cells distinguish themselves as single cells due to superior efficiencies, because they exhibit both high absorption coefficiencies and an almost ideal bandgap. The stability of the cells is also excellent. However, the extremely high price is disadvantageous for all large-area applications. The cost of a GaAs wafer is approximately £3000 compared to £3 for a silicon wafer. The prohibitive price primarily permits application in aerospace technology (satellite supply) at this time, where the excellent performance-to-weight ratio justifies the extreme cost [23]. Large-scale terrestrial application could be realised by technologies in which very small areas are illuminated by concentrated solar radiation, which they then transform in a highly efficient manner [24].

To achieve this, *stacked or tandem cells (multijunction cells)* are used in which different III-V cells are combined absorbing a broad spectrum of solar radiation. These are then combined with mirrors and lenses, which are cheap by comparison with PV cells, to produce concentrator photovoltaics (CPV). A 3 MW_p demonstration system is already being operated by the Instituto de Sistemas Fotovoltaicos de Concentración (ISFOC) in Castilla-La Mancha, Spain. “Concentrix Solar GmbH (a spin-off company of Fraunhofer ISE, Freiburg) has prepared [18 III-V-based] CPV systems in Puertollano, each with an output of 5.75 kilowatts (kW_p), for connection to the grid.”[25] The systems have a module efficiency of 27 % and a system efficiency (including tracking) of 25 % [26].

The high-end product therefore demonstrates III-V concentrator tandem cells that have a high efficiency and very high resource efficiency. However, a breakthrough is still beyond reach due to the complexity [10]. Tandem cells can also be produced with perovskite and CiGS solar cells, since they each preferentially absorb different parts of the sunlight. Combined, they can better cover the sunlight spectrum [21]. Flexible PV laminates based on amorphous silicon are also marketed by Uni-Solar as tandem cells. The maximum module output is 144 W_p and has an efficiency of 7.1 % [27]. Multi-layered III-V cells are also commercially available, for example in GaP/GaAs/Ge cells with dimensions of 12 x 6 cm (at a thickness of approximately 230 µm) and an output of 2.7 W_P [28]. In summary, tandem cells or multijunction cells are already commercially available, but not on a scale that would be relevant to the expansion potential for implementation in the German energy revolution.

b) Expansion potential

The amount of PV output that can be installed in Germany has been estimated in several studies and by means of various derivations. These derivations consider the available areas as a matter of principle, and so the assumed efficiency is a significant component of the estimate. In [29], using [30], the German Federal Environment Agency (*Umweltbundesamt*, UBA) came up with an installable output of approximately 275 GW_p on 1,620 km² (19 % efficiency, only roofs, façades and sealed surfaces). However, only 120 GW_p are set to be installed by 2050 in the energy scenario presented. A 100 %

renewable energy scenario with approximately 112 GW_p of installed PV output (average module efficiency 22 %) is calculated in [31]. [32] and [33] state that for average, economically optimised expansion scenarios, approximately 200 GW_p suffices for a full supply using renewable energy. The figures mentioned concern scenarios that could represent a possible future but that make no claim to be a prediction, i.e. of the probable future. In summary, sufficient "non-critical" potential areas are available, according to the UBA. The areas that are actually required and deducible continue to decrease with advancing development in the module efficiencies.

6.5. Representation of the achieved state of expansion

With approximately 40 GW_p of installed output [34] and 38.2 TWh or a 5.9 % [1] share in German gross power generation, photovoltaics is one of the most important renewable energies of the energy revolution (see Figure 17). These figures can be attributed to a considerable increase in additional installations over the last decade. A positive development during this time has been the rapid cost degression for photovoltaic modules. The average price per kW_P for a rooftop system (up to 10 kW_P, net system price) dropped almost a quarter between 2006 and 2016, from € 4906 to € 1236 [36]. But Figure 17 shows that there has also been a degression in additional installations since 2013. In [33], this decline (2013: -57 %, 2014: -42 %, 2015: -30 %) is attributed to punitive tariffs for Chinese modules by the European Commission, as well as the limitation of the once relatively risk-free profitability of private consumption and feed-in. For example, systems with >10 kW_P must also pay a percentage share of the EEG levy on self-consumption. Feed-in tariffs were lowered and direct marketing constraints set for larger systems.

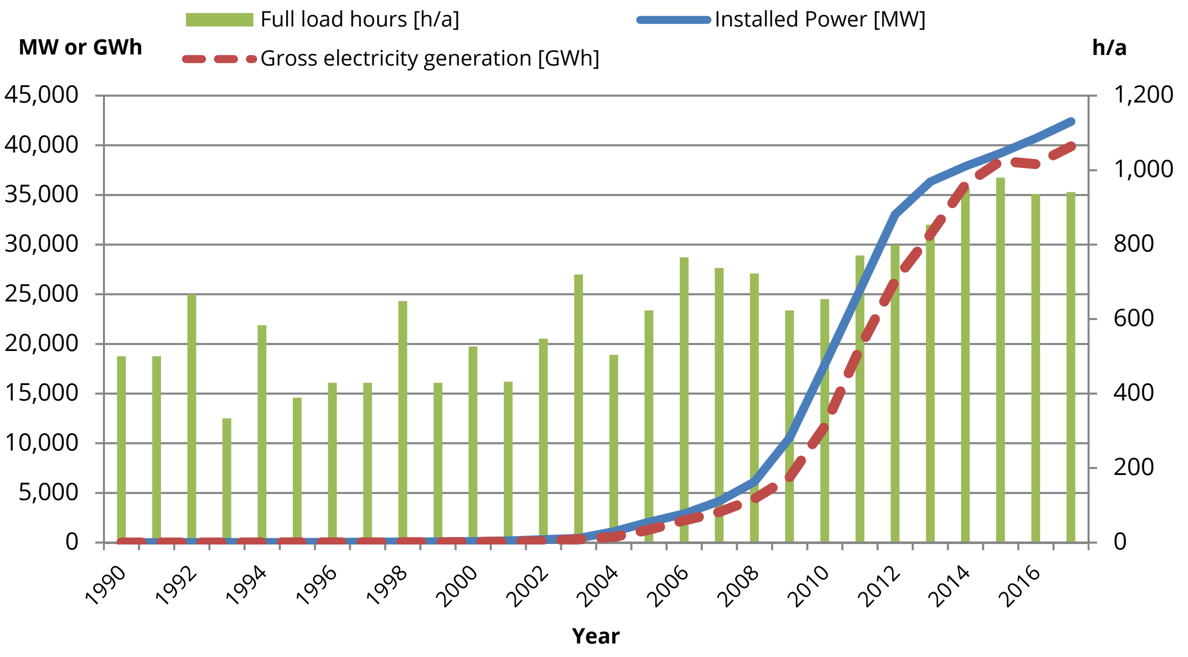

Figure 17: Development status of PV systems in Germany [34]

6.6. TRL assessment

With 300 GW_P of installed output worldwide, the PV technologies mentioned in Table 5 are commercially and industrially available. Therefore, the technology readiness level can be easily classified as TRL 9. “But this isn’t the end of development; product optimization is currently under way, as would be the case with trainers, cars, etc. Considering its short development time, the technology is still in its infancy!” [13]. The question regarding a relevant or preferential plant size for PV plants cannot yet be answered, “as any answer would be premature. The driving force for a technology lies in the scaling. PV can be deployed centrally, but also very de-centrally” [13].

The following overall TRLs can be registered for the PV technologies presented here:

Table 7: Summary of TRLs for PV cells

Cell type	TRL	Supplementary sources
Silicon cells	9	
CIGS	9	
CdTe	9	
Dye-sensitised solar cells (DSC)	6	[17]
Compounds III–V	9	[28]
Perovskite solar cells	4	[24], [37]
Organic solar cells	6	[19]
Tandem cells	9	[27], [28]

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7. Geothermal energy

7.1. Technology description

The term ‘geothermal energy’ describes the use of enthalpy stored within the earth. The thermal energy reaching the surface from underground, primarily by convection and conduction, is approximately 0.05 W/m² to 0.12 W/m² [1]. The thermal flow is fed in part (approx. 70 %) by the decay of radioactive elements in the earth and in part by the liquid hot core of the earth (approx. 30 %) [2].

Geothermal energy is classified into the following categories according to depth, temperatures and storage system (Table 8):

Table 8: Classification of geothermal energy [1], [2]

Near-surface geothermal energy	**< 400 m depth**	**Soil/sediment**	**Groundwater**
		Temperatures usually up to 25 °C	
Deep geothermal energy	> 400 m depth	Petrothermal systems (hot dry rock)	
		Hydrothermal systems (thermal water)	
		High enthalpy reservoirs > 200 °C	Low enthalpy reservoirs < 200 °C

The source temperatures for the means of power generation being examined here should be as high as possible to ensure that the conversion process is technically possible and economically viable. So for Germany, only deep geothermal sources come into consideration. As depth increases, the temperature rises by approximately 3 K per 100 m (approximate value heavily dependent on location). The following processes are employed in geothermal power generation around the world:

- Direct utilization
- Flash process (also possible as double flash process)
- Binary cycles: Organic Rankine Cycle (ORC) and Kalina process

Geothermal power generation only makes use of open loop systems in which thermal water is typically extracted through one or more production wells and, where applicable, returned through one or more injection wells to maintain pressure ratios and mass balance [3]. Near-surface geothermal energy for heat supply in particular uses closed loop systems with geothermal probes that conduct the heat transfer medium, and there is no exchange of material with the reservoir [4].

The technical details of these processes will be discussed later. This examination intentionally omits several aspects that are currently of paramount importance for utilizing geothermal energy. These points should therefore be mentioned for the sake of completeness (according to [5] unless otherwise specified):

- Site exploration
    - Reliable determination and assessment of the geological conditions plays a central role when implementing geothermal projects

    - It encompasses a description of the chemical, hydraulic, physical and poroelastic properties of the rock and fluid in the reservoir
    - Estimation of seismic risks
- Tapping
    - Advances in site exploration can significantly reduce the costs for tapping geothermal reservoirs, as the drilling costs, at approximately 35-50 % [3], [6], are a considerable portion of the investment costs
    - Improved reservoir stimulation for the tapping of petrothermal systems using directional drilling technology, mechanical (hydraulic stimulation – exclusively with water [3]) and chemical processes (acidification) to increase permeability and extraction (also referred to as "Enhanced Geothermal Systems" – EGS) [7]
- Reservoir management
    - Optimizing operations by monitoring the reservoir (seismic effects, improving reservoir models)
    - Adjustment of operation if needed, as a site can be utilised as a thermal source for approximately 20-30 years [3] and regeneration can take centuries due to the low energy flows [7]

There are several different ways to utilise geothermal energy to generate power. High enthalpy reservoirs are candidates for direct utilization or single or double flash processes. ORC or Kalina processes are used for low enthalpy reservoirs.

Direct utilization (dry steam) is only possible if the reservoir contains saturated steam, which is expanded directly through a steam turbine. Non-condensable steam and gases are released into the environment and the condensate is returned to the reservoir [3].

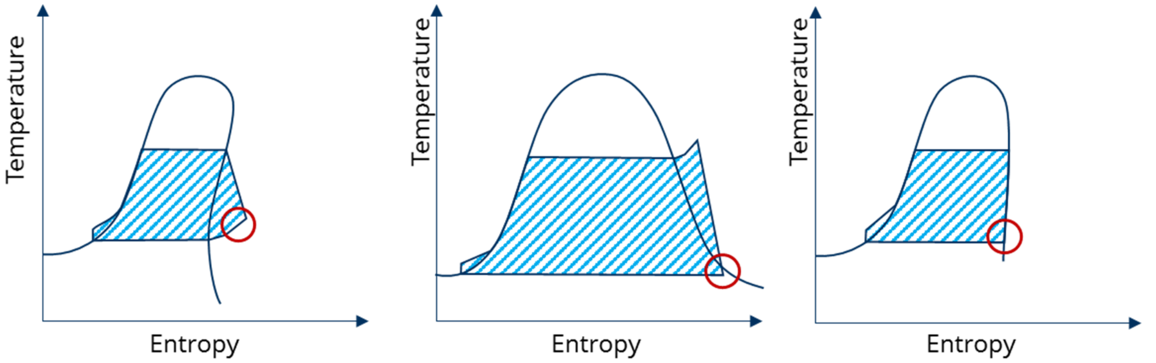
In the single flash process, the extracted water-steam mixture is expanded through a throttling device in an isenthalpic process (increasing the steam content) and the phases are subsequently separated in a separator. The steam is expanded through a conventional steam turbine.

The double flash process works according to the same principle, only the superheated water from the first separator is expanded through an additional throttling device and more low-pressure steam is obtained in a second separator. Therefore, the double flash process makes use of one high- and one low-pressure turbine.

In summary, this process comprises conventional power plant technology with open loop Clausius Rankine cycle processes. The technological degree of maturity of power plant technology and generator sets is therefore very high (TRL 9). Yet the high enthalpy reservoirs required for this do not occur in Germany.

Power plants with binary cycles are used for the low enthalpy reservoirs predominantly found in Germany. The primary cycle is formed of mostly gas-rich, aggressive thermal water, whose energy is transferred by means of heat exchangers to the working substance of the secondary cycle. The working substance is adjusted to the reservoir temperature, and organic working substances are used in the ORC, or a water-ammonia mixture in the Kalina process.

Adjusting the working fluid in the ORC process yields major differences compared to the Clausius Rankine process with steam. The working fluid should have a high enthalpy of evaporation, a high density and a high specific thermal capacity, so that high energy densities in the cycle are achieved. This results in the need for lower volume flow rates, more compact plant sizes and a smaller pump capacity. The working fluids are divided into wet, dry and isentropic fluids, which differ according to their characteristics in the T–s diagram. Figure 18 provides an overview:



„Dry“ fluids
- Expansion does not end in wet steam region
- recuperation necessary
- E.g. R22

„Wet“ fluids
- Expansion into wet steam region
- Superheating necessary
- E.g. isopentane

„Isentropic“ fluids
→ ideal cycle
- No superheating
- No recuperation
- E.g. R11

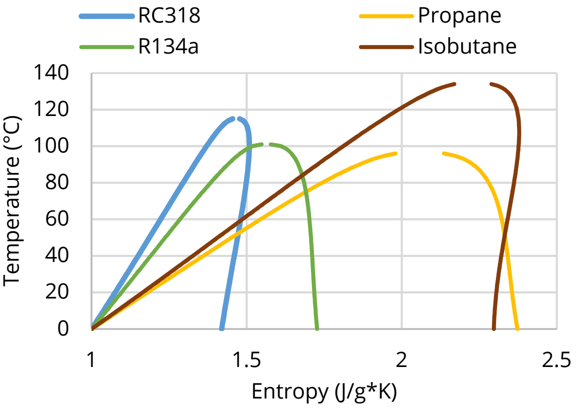
Figure 18: Working fluids in the ORC process, according to [8], translated.

It is evident from Figure 18 that some working fluids exhibit a very steep dew point curve. This means that no condensation forms during expansion in the turbine and, consequently, no drop erosion occurs, or this can be avoided by slightly superheating the working fluid.

The working fluids used depend primarily on the temperature level of the geothermal source. The plant equipment of the ORC system needs to be adjusted according to the chosen fluid. Commonly used working substances are shown in Table 9, as specified in [9]:

Table 9: Commonly used working substances in ORCs (right [9]), as well as two wet and two dry working substances (left, gaps at critical points, data based on [10])

Working fluid	Symbol	T_{crit} in °C	p_{crit} in bar
Water	R718	373.15	220.64
Ammonia	R717	132.25	113.33
Propane	R290	96.675	42.5
n-Butane	R600	151.98	37.96
Isobutane	R600a	134.7	36.4
n-Pentane	R601	196.6	33.7
Octafluorocyclobutane	R318	115.2	27.78
1,1,1,2-Tetrafluoroethane	R134a	101.03	40.6



The general composition of an ORC plant is shown in Figure 19 on the left. Since the plant parts being examined here represent well-known power plant technology, the technological maturity of individual components will not be discussed further at this point. Potential development possibilities are discussed in section 7.2a).

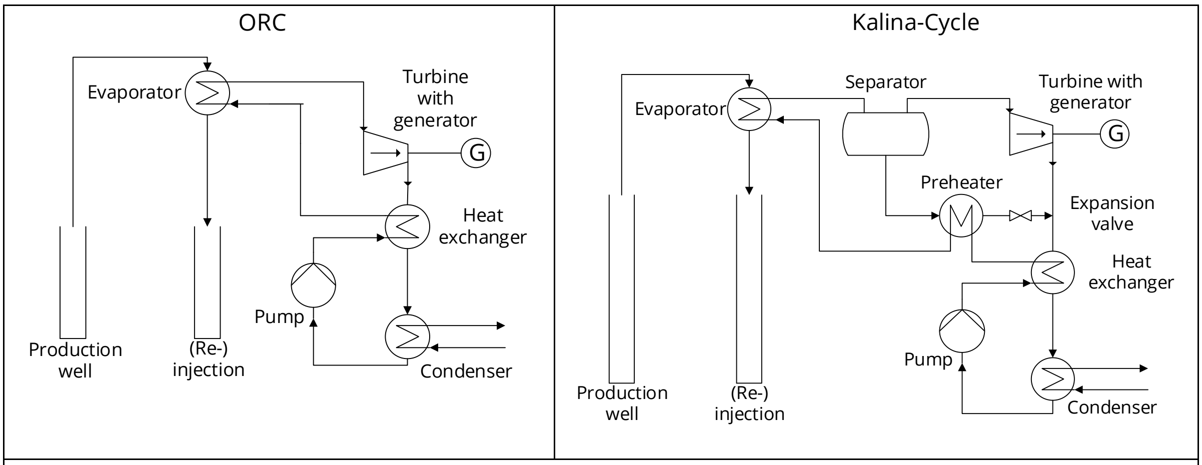


Figure 19: Schematic diagram of the Kalina cycle and ORC based on [11], translated.

Figure 19 also shows the Kalina process. The essential difference from ORC lies in the inorganic, zeotropic ammonia-water mixture. During evaporation, the ammonia boils at lower temperatures resulting in a steam mixture rich in ammonia, which is separated in the separator and re-expanded through a turbine. The boiling temperature shifts during the boiling process, resulting in non-isothermal evaporation. This brings the Kalina process closer to the Carnot process, thereby enabling higher efficiencies in principle. Yet the Kalina process requires more and larger heat exchanging surfaces which need to be protected from the corrosive ammonia-water mixture with coated and high-alloyed steel [9].

7.2. Estimation of potential

a) Technical development potential

As already shown in section 7, the greatest technical development potential for geothermal power generation lies in site exploration and tapping. Due to temperatures of < 200 °C in hydro- and petrothermal reservoirs, only the ORC and the Kalina processes are worth considering in Germany.

For ORC processes operating with ‘wet’ working substances, the same optimization methods generally apply as with conventional power plant processes (superheating, intermediate superheating, cascaded turbines, regenerative pre-heating, etc.). With dry working substances, superheating does not lead to higher levels of efficiency as the working substance is in a superheated, enthalpy-rich state. Here, it makes more sense “to use […] the expanded, but still superheated steam […] to superheat the condensed liquid […]” [9].

[4] mentions further optimization measures, which have nevertheless not yet been implemented on an industrial scale (selection):

- Distribution of the working fluid into several partial flows with different pressure levels, each with adapted turbines (multi-pressure circuit) requiring a large amount of equipment
- Operation in the supercritical range of the working fluid (only possible to a limited extent as a very high temperature is required in the reservoir)
- Use of binary material mixtures, similar to the Kalina process

According to [12], the key areas where adjustments can be made for technical development are the pinch points[13] (connected with larger heat exchanging surfaces), the condensers (reduction of the condensate temperature, handling of large mass flows) as well as the efficiency of the ORC turbine (95%) (larger diameter, large mass flows, multi-stage capability without a transmission).

The use of scroll expanders represents another alternative; however, they are more suitable for smaller output levels and are available commercially up to the two-digit kWel range [13]. Due to the small output level, this branch of technology is not considered further here.

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[13] Point of the lowest temperature difference in a heat exchanger.

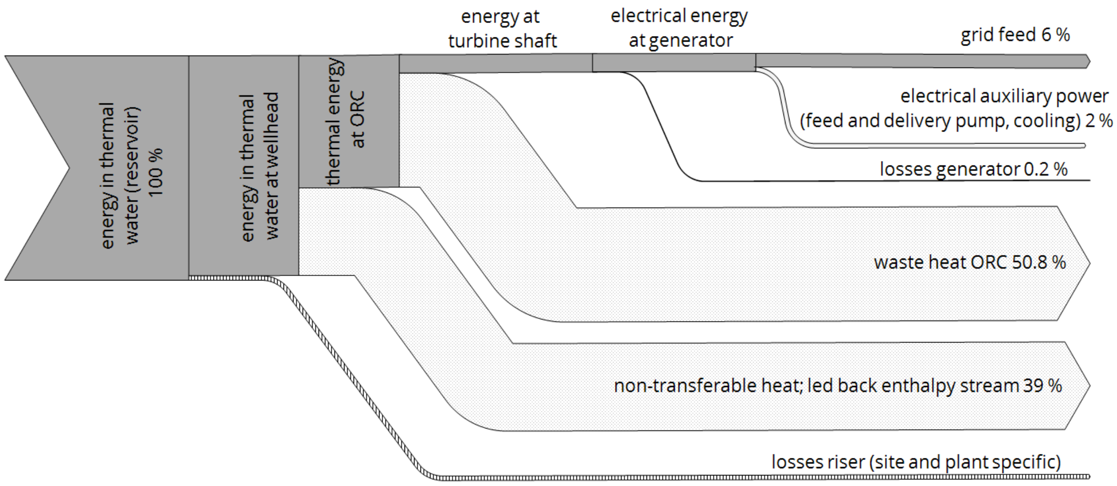

Figure 20: Example energy flow diagram for an ORC process for deep geothermal utilization based on [7], translated.

The previously described disadvantages of the Kalina process (amount of equipment, complexity, protective measures against corrosive working substances) need to be compensated in order to further expand the technology. Corrosion, at least, can be overcome with stainless steel at temperatures below 400°C, according to [14].

Pure power generation from geothermal sources is not productive from an energy standpoint and should take place in CHP operation. For this reason, the German Geothermal Association (BVG) [5] is providing instruction in the following key research areas for power generation, among other subjects:

- Improving turbine and plant efficiencies (esp. for variable CHP operation)
- Optimizing forced-air cooling systems
- Optimizing materials for heat exchangers

In summary, the technical potential is limited by the Carnot efficiency. This limitation is caused by the low temperature differences between the hot and cold sides of the cycle, which are small when compared to conventional plant technology. With a reservoir temperature of 160 °C and an annual mean temperature of 10 °C [15], the Carnot efficiency for a heat engine based on geothermal energy in Germany is, $\eta_{C,Gt} = 32.8\ \%$. Live steam temperatures of 600 °C are being reached in current lignite power plants and the average cooling tower temperature is 18 °C [16]. Thus, the theoretical Carnot efficiency is $\eta_{C,lignite} = 66.6\%$. The gross electrical efficiency reaches $\eta_{el,Gross,lignite} = 45.9\ \%$ [17], i.e. relative to Carnot 68.9 %. If this result is transferred to geothermal power plants, further optimization could make it possible to increase efficiency to approximately $68.9\ \% * 32.8\ \% = 22.6\ \% = \eta_{el,Gross,Gt}$. This would be a near threefold increase compared to the example energy flow diagram in Figure 20 with a gross electrical efficiency of approximately 8%. Technical developments also continue to approach this state. Thus, the net electrical efficiency for binary cycles is quantified at approximately 10-13 % in [18].

b) *Expansion potential*

In order to assess and quantify the energy potentials, numerous assumptions must be made, as the theoretical potential of the accessible depths is dependent on the thermal capacity and subterranean temperatures [3].

Hydrothermal sources in Germany have temperatures of up to approximately 160°C, making them predominantly suitable for supplying low-temperature heat. The petrothermal reservoirs located deep below the surface have higher temperatures. Yet current drilling technology, due to the electronics in the drill head, is limited to approximately 250°C. Flushing coolers can be used to cool the borehole locally and achieve great depths. Alternatively, the borehole can be drilled without electronic aids [3]. Further development of (economically) achievable bore depths could thus significantly expand the geothermal potential shown below.

For example, [19] concludes that thermal water alone with an average electrical power plant efficiency of $\eta_{el,net,Gt}$ ~ 11.3% has a technical total potential of 11.5 PWh_{el} and an economic potential of 8.7 $PWh_{el.}$ In order for the geothermal energy to be used sustainably, the period of tapping should be at least the same or greater than the period of regeneration. Based on this premise, an annual economic potential of 8.7 TWh_{el}/a is given. At the same time, it is emphasized that the hydrothermal potential only represents approximately 5% of the total potential (i.e. 95% is found in petrothermal deposits). Tapping would therefore result in a regenerative, electrical potential of 174 TWh_{el}/a (all other things being equal). Approximately 6500 full load hours per year result in a power plant potential of 26.77 GW_{el}.

[20] gives a scope of 1.9-4.9 GW_{el} (with approximately 6500 full load hours annually) by 2050 in regard to the technical power plant potential. The market potential, in contrast, is quantified at a lower value of 0.7-2.7 GW_{el}.

7.3. Description of the current level of expansion

Today, near-surface geothermal energy in Germany is harnessed using heat pumps. Nine combined heat and power plants with an installed electrical output of 38.19 MW_{el} (thermal output 313.78 MW_{th}) are available in Germany for the cogeneration of power and heat. In 2015, they supplied 0.134 TWh_{el} of electrical power [21]. Two further plants are under construction (P_{el} max. 29 MW) and 38 projects are in the research or planning phase [22]. Table 10 provides an overview of the plants currently operating:

Table 10: Power plants for the generation of geothermal power in Germany based on [8], extended

	Unterhaching	**Taufkirchen**	**Landau**	**Bruchsaal**	**Innsheim**	**Traunreut**	**Dürrnhaar**	**Kirchstockach**	**Oberhaching-Laufzorn**	**Sauerlach**
Technology	Kalina	Kalina	ORC	Kalina	ORC	ORC	ORC	ORC	ORC	ORC
P_{el}	3.36 MW	4.3 MW	3 MW	0.55 MW	4.8 MW	5.5 MW	7 MW	7 MW	4.3 MW	4 MW
P_{th}	38 MW	40 MW	5 MW	5.5 MW	0 MW	12 MW	0 MW	0 MW	40 MW	5 MW
In operation since										
Power	2009	2018	2007	2009	2012	2014	2013	2013	2011	2014
Heat	2007	2013	2007	2009	-	2014	-	-	2014	2014
Working fluid	Water-NH_3	Water-NH_3	Isopentane	Water-NH_3	Isopentane	Propane/ Butane/ Silicone oil mixture	Pentafluoropropane	Pentafluoropropane	Isobutane	Pentafluoropropane
Well	1. 2.									
Depth [m]	3350 3340	1. 3763 2. 4258	4258	2542	3600	4646	3926	3882	3755	4480
Temperature [°C]	122 160	135	160	120	165	113	141	134	127	140
Pumping rate [l/s]	150 70	100-120	70	24	67	143	151	135	132	110

7.4. TRL assessment

The technologies presented for geothermal energy are already in commercial operation. The available output levels for low-temperature Kalina and ORC processes are still limited, but there are ORC plant sizes of up to 139 MW_{el} outside of Germany. The basic physical and technological similarity to conventional plant technology is paving the way for further possible developments. Economical and flexible CHP operation presents a challenge for generating power but is not the main obstacle for additional installations. Further expansion is impeded by insecurity and the high costs for exploration and development of the reservoirs. The TRL classification for the technologies presented is shown below in Table 11.

Table 11: Results of the TRL analysis

Technology	TRL	Supplementary sources
Dry steam	9	[23]
Flash process	9	[23]
Organic Rankine Cycle up to 50 MW_{el}	9	[24], [25]
Kalina process	6	[8]

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8. Hydropower

8.1. Technology description

This section examines the generation of electricity from hydropower. It also looks briefly at ocean energy, first explaining the physical basis and then classifying the available plant sizes.

Technical plants for generating electricity from hydropower primarily use potential energy extracted from the water. If water is already flowing because of differences in elevation, then the kinetic energy is used. This means the amount of energy that can be obtained depends on the usable difference in elevation:

$$\Delta E_{W,th} = m_W \cdot g \cdot \Delta h \tag{6}$$

Or

$$P_{W,th} = \rho_W \cdot g \cdot \dot{q}_W \cdot (h_u - h_l) \tag{7}$$

The German Federal Environment Agency (*Umweltbundesamt*, UBA) classifies hydropower broadly as flowing water, storage or pumped storage power plants based on their mode of operation [1]. Pumped storage power plants are discussed in more detail in the Mechanical storage section 14. Plants are also commonly classified by fall height (as low-pressure plants < 15 m, mid-pressure plants 15 to 50 m, high-pressure plants > 50 m) or by output as large (> 10 MW_{el}) and small hydropower plants (< 10 MW_{el}) [2].

When utilising hydropower, the turbine used is the central hydraulic component in energy conversion; it uses the potential and kinetic energy from the available fall height. Turbines have been developed for various conditions and they represent a mature technology at present. Figure 21 provides an overview of the different types of turbine and where they are used.

A sample selection of the most common types of large turbine is given below in Table12 to classify the sizes of turbine available with state-of-the-art technology:

Table12: Maximum turbine sizes for selected examples

Example [source]	Type	Output
Bieudron power plant, Switzerland [4]	3x Pelton, fall height 1883 m	423 MW_{el} per turbine
Danube power plant, Freudenau, Austria [5]	6 Kaplan pipe turbines	30.3 MW_{el} per turbine
Expansion at Brilliant Dam, Canada [6]	1 Kaplan spiral turbine	120 MW_{el}
Three Gorges Dam, China [7]	32 Francis turbines	700 MW_{el} per turbine

The turbines' high degree of maturity is also evident in the very high levels of efficiency that be maintained even over a wide range of partial loads, depending on the design used (Figure 22).

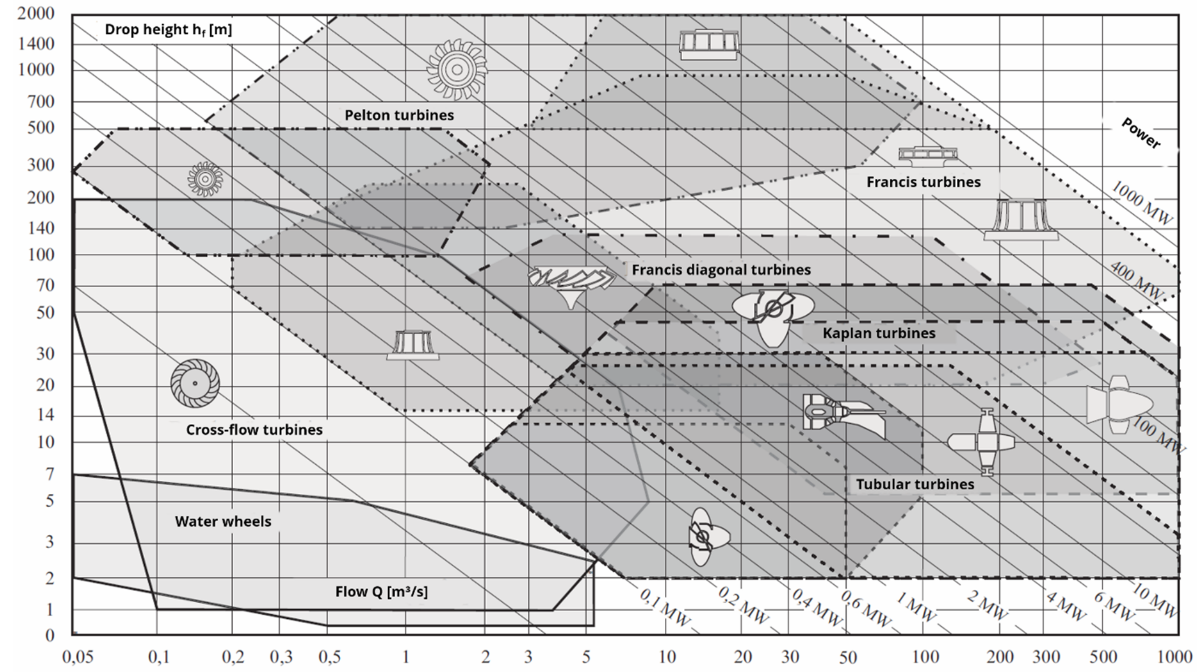

Figure 21: Uses of different types of turbine by fall height and flow rate [3], translated

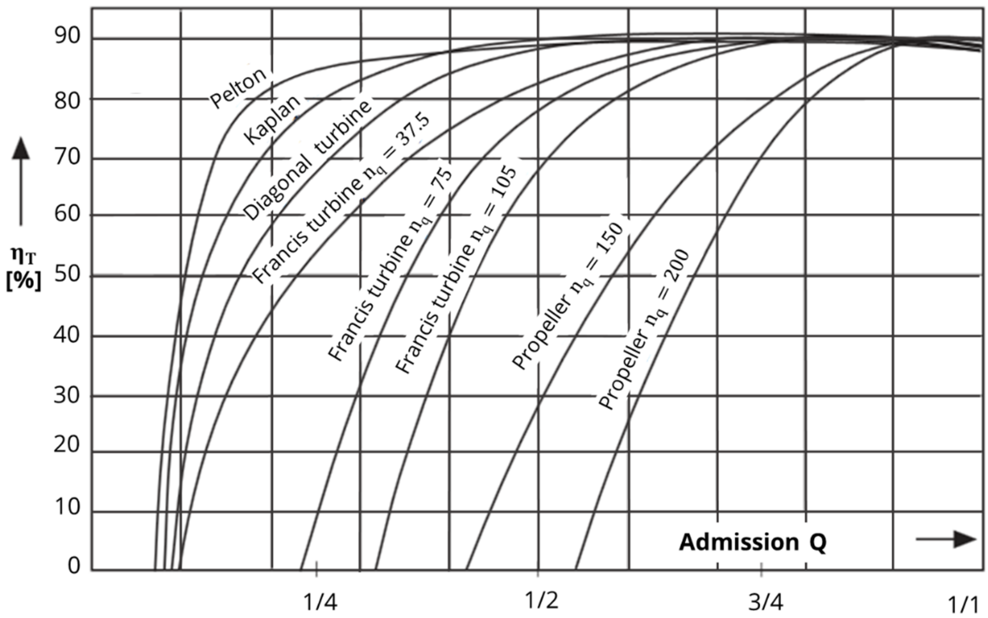

Figure 22: Efficiency curves of different types of turbine [3], translated

According to [2], Francis turbines have limited controllability. With a load of $Q < ½ Q_{max}$, the plants are under excessive load.

The efficiency of modern turbines is usually above 90 % and combinations of gear units, converters, etc. result in only small losses (cf. Figure 23). Significant increases in the seasonal performance factors (i.e. GWh/a) of a hydropower plant can be achieved by reducing hydraulic losses before the water enters the turbines.

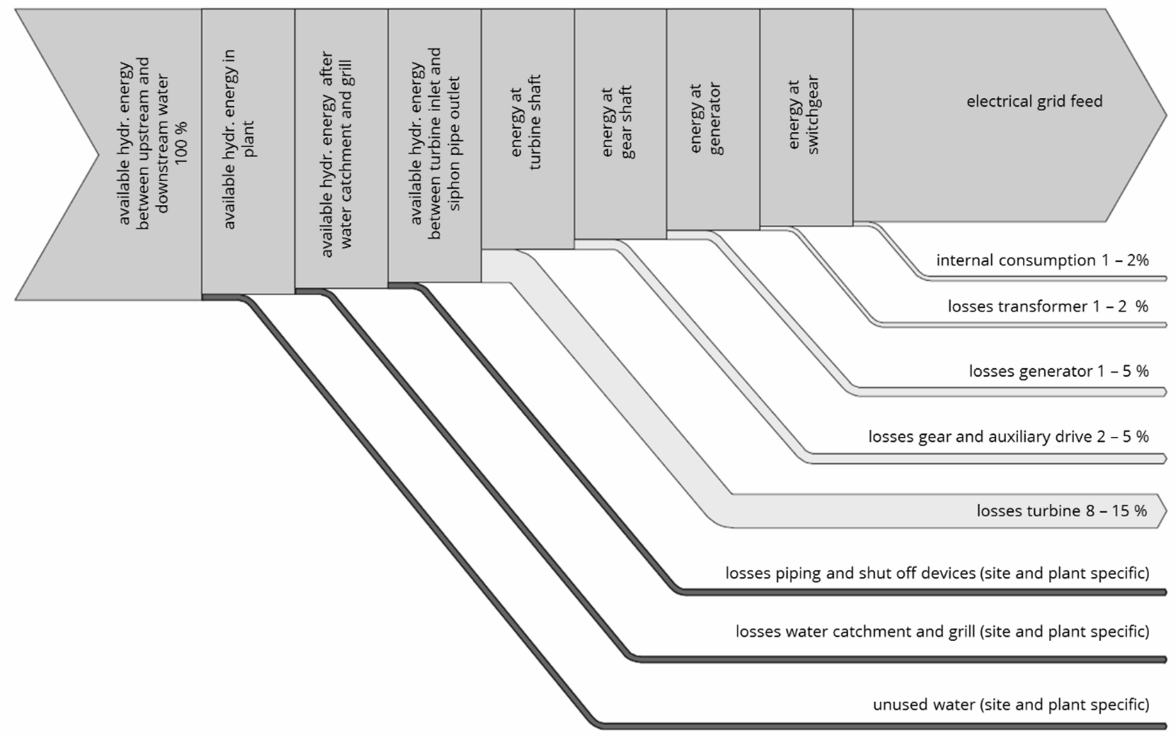

Figure 23: Sankey diagram of a hydropower plant [8], translated

In addition to classic turbine designs, there are alternative technical approaches in development that mostly apply to the utilization of ocean energy. These are divided into three categories: those that use tides (the largest tidal plant is in the Rance river estuary, France, 240 MW_{el}), those that use ocean currents and those that use waves [1]. The development of ocean energy and small hydropower plants (< 10 MW_{el}; < 1 MW very small hydropower plants) will not be explored in great detail here. This is because the expansion potential for this type of hydropower is very limited in Germany (see section 8.2b)). Other exceptions that are not explored here are gradient power plants with energy conversion based either on temperature differences at different water depths or differences in salt concentration between fresh and salt water (osmotic power plants). Water wheels are also mentioned only occasionally (especially those with low fall heights) [9].

8.2. Estimation of potential

The estimation of potential is divided into a) the technical development potential and b) the expansion potential for Germany. Part a) describes the technical developments. Part b) focuses on the energetic potential, because this limits the possible increase in output.

a) Technical development potential

Hydropower as used to generate electricity is, as described above, a very mature technology and the current focus is on the optimization of individual aspects and details of the processes involved. The fall height (equations (6), (7)) can rarely be altered, so potential improvements can only be achieved by minimising hydraulic, mechanical and electrical losses that occur during use of the plant. This requires optimising the plant design and layout.

A comprehensive overview of the development of mostly small hydropower plants is given in [9]. Because of the generally high level of maturity of these technologies, the approaches being considered are usually not energetic (e.g. the development of fish-friendly turbines and turbine resistance to debris and fish); instead, these improvements aim at making plants more environmentally friendly. Some of the approaches described in [9] can be easily carried over to the modernization of larger plants:

Optimization of flow management: The development of computer-assisted flow simulations can minimize flow losses, improve behaviour under partial load, reduce wear and therefore improve seasonal performance (+2 to 4 %).

Improved operation management: If several turbines are used in one hydropower plant, the individual turbines can be used at maximum efficiency at low flow rates (cf. Figure 22). This is accompanied by an increase in seasonal performance, which, in combination with optimized impellers, significantly increases annual yield. At the Meitingen hydropower plant, the seasonal performance was increased by 14 % in this way [10].

Optimising water catchment/cleaning programmes: Dirt, debris and driftwood in the grills can quickly lead to significant reductions in output in hydropower plants. The rinsing and cleaning measures used are not yet widely automated, and gaps in monitoring result in seasonal performance losses. Alternatively, grill contamination can be reduced by means of design modifications, for example by using Coanda grills or by not positioning the grills perpendicular to the direction of flow in shaft power plants. Tightening up the spacing of the rods in the grills improves fish-friendliness but increases flow resistance and reduces seasonal performance.

Use of modern generator technology: The continuing development of converter technology in PV and wind power plants is producing more potential uses for hydropower plants. Francis pump turbines in particular can be operated cost-efficiently at variable speeds using frequency converters, which significantly increases their performance under partial load [9] and allows a more flexible reaction to grid fluctuations. They can also operate without a gear unit (direct coupling to the generator reduces the cost of maintenance and efficiency losses). According to [2], the selection of converter, transmission and generator technology is a case-by-case decision that needs to be looked at in detail.

The approaches mentioned modernize the utilization of hydropower technology without fundamentally altering it. They are commercially available and some can be integrated without large retrofitting operations.

b) Expansion potential

The hydropower potential in Germany that is technically feasible to utilize is estimated at about 33.2 to 42.1 TWh_{el}/a in various sources [11]. Of this, 3 TWh_{el}/a or 968 MW_{el} is considered possible to develop further in view of ecological considerations. 2.5 TWh_{el} is attributed to larger rivers; the rest to small and medium rivers [9]. This additional output is based on the expansion and optimization of existing plants, since building new plants was not permitted in the studies mentioned.

In [12], with regard to the utilization of ocean energy, the technical potential energy from waves is estimated at 1200 TWh_{el}/a and the usable ocean current energy at 150 TWh_{el}/a. Only a fraction of this is available to Germany, so according to [12], the potential for Germany is just a few TWh. The potential for osmotic power plants for Germany is estimated at about 40 MW_{el} and approximately 330 GWh_{el}/a [13]. This means that with today's technology, ocean energy cannot contribute substantially to the energy revolution.

8.3. Description of the current level of development

Hydropower plants are currently installed in Germany with a total output of 5.6 GW_{el} [14], and they have supplied an average of 20.3 TWh_{el} of electricity in the past 10 years. The fluctuation in full load hours is thanks to the variation in outflows caused by the weather and the fluctuating demand in combination with base load power plants [2] (cf. Figure 24).

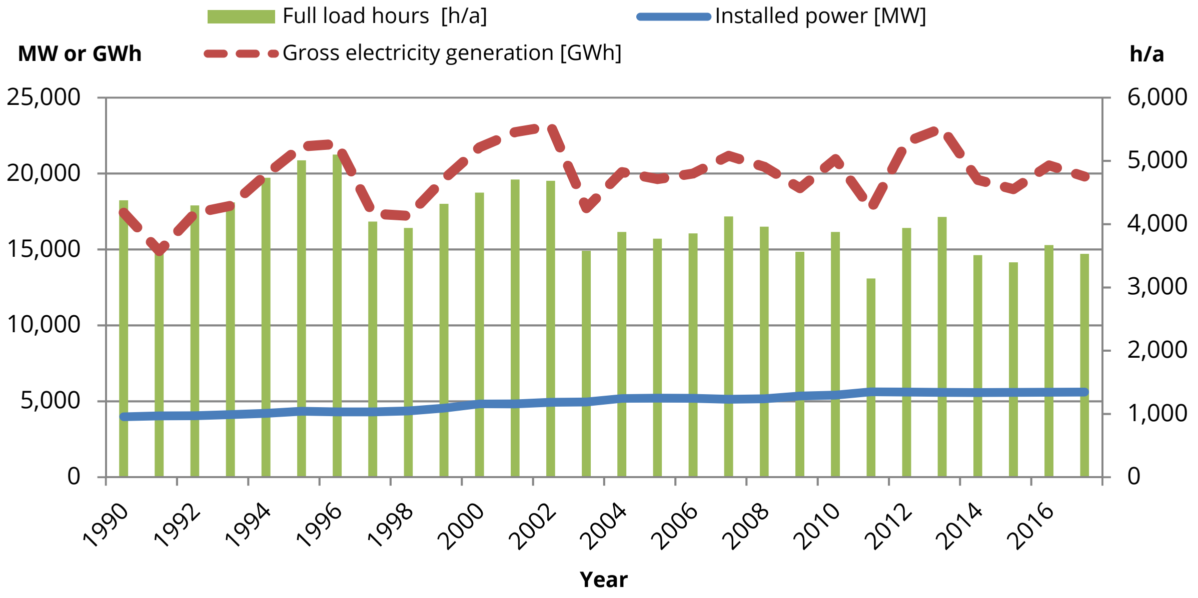

Figure 24: Development of output and generation of electrical energy from hydropower, data basis [14]

Here it is worth noting the structure of the plant sizes, as depicted in Table 13 [9].

Table 13: Hydropower in Germany as of 2013 [9]

	All hydro plants	Hydro plants with P > 1 MW	Pumped storage power plants with natural inflows
Number of plants	7,330	436	11
Installed output [GW]	5.6	3.8	1.16
Seasonal performance [TWh]	20.8	18.05	0.6

---

[14] Flowing water, storage and pumped storage power plants with natural inflow

This shows plainly that a few large plants (6 %, > 1 MW_{el}) provide approximately 87 % of the seasonal performance. So it is clear why hydropower plants on large rivers in section 8.2b) represent the majority of the potential for ecological development. Smaller hydropower plants will have a smaller role in the Germany energy revolution. The limited decentralized potential compared to photovoltaic plants will not allow for a significant energetic contribution.

The modernization of existing hydropower plants was investigated in [9] using an operator questionnaire for 48 hydropower plants > 1 MW_{el}; it showed a cluster starting in 2000. The study indicated that modernization was generally undertaken for technical reasons. To be granted higher compensation under the German Renewable Energy Sources Act (EEG) for the additional seasonal performance resulting from modernization measures, annual generation must be increased by at least 10 % [10].

8.4. TRL assessment

Overall, the technological maturity for the utilization of hydropower must be regarded as highly mature. There is almost no potential for improvement in the use of flowing water and storage power plants from an energetic standpoint, so the technology readiness level must be assessed as TRL 9.

The technology to utilize ocean energy, however, presents technical challenges. Many approaches in this area are still in the development phase (demonstration and pilot projects, i.e. TRL 6-8). However, despite the technical potential here, there is a lack of energetic potential for Germany according to the current state of knowledge.

8.5. References

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9. Biomass

9.1. Technology description

This chapter examines the production of energy from biomass. First the term is defined and then the possible conversion paths for biomass are presented. The present study focuses on power generation.

A possible definition of biomass is given in [1]:

“The term biomass refers to all substances of organic origin (i.e. carbonaceous matter). Biomass thus includes

- the phytomass and zoomass (plants and animals) living in nature;
- the resulting residues (e.g. animal excrements);
- dead (but not yet fossilized) phytomass and zoomass (e.g. straw); and
- in the broader sense, all substances that have been produced or that occur as a result of technical transformation and/or material use (e.g. black liquor, paper and cellulose, slaughterhouse waste, organic household waste fraction, vegetable oil, alcohol).”

Furthermore, in [1], biomass is differentiated into primary biomass (through direct photosynthetic use of solar energy), secondary biomass (through degradation/conversion of organic matter) and tertiary biomass (through process-related transformation of primary and secondary biomass).

Biomass can be converted into final energy in a variety of ways. Processing steps that come into play after provision, preparation and transport are thermochemical (pyrolysis, gasification), physiochemical (pressing, extraction, transesterification) and biochemical (alcoholic or anaerobic fermentation, aerobic degradation) conversion. These processes usually produce solid, liquid and gaseous fuels, which in turn are used for energy recovery in redox reactions (e.g. combustion and fuel cells).

The entire spectrum of sophisticated, conventional power plant technology is used for the combustion of biogenic fuels, so reference must be made here to the basic literature, such as [1], [2], [3], gasification and pyrolysis [4], and biofuels [5].

Biomass in itself acts as an energy store for solar energy. Because of its availability, biomass is usually assigned a balancing function in the provision of energy [7]. Biomass is in principle suitable as a basis for any form of useful energy (e.g. heat, electricity, mobility and light), and the variety of processes described above is based precisely on this. In the end, however, the entire regenerative biomass potential in Germany is far from enough to cover the total energy demand (see also section 8.2b)), and so it is “an important task of energy technology and the energy industry to select and implement the processes that have the best possible energy exchange ratio when replacing fossil fuels” [8]. This does not necessarily depend solely on the overall efficiency of a process chain but rather on the substitution of an efficient biomass process for a (relatively) inefficient fossil process.

An example of this is also given in [8] and the energy exchange ratio is discussed in detail in [9]. This approach remains valid as long as fossil resources are used to meet energy needs. However, as substitution progresses, the focus will continuously shift.

The current state of the use paths therefore depends less on technical maturity than on which biomass is processed and how (because there are processes and means for all paths) and for which purpose or target energy the biomass is used. The use scenarios are therefore the link to be optimized. Sterner [7] compiled a series of efficiency chains, for example, and concluded that pure heat supply or CHP concepts achieve the highest overall efficiencies. For power supply, the highest efficiencies are achieved in the co-firing of suitable biomass (here: wood pellets in coal-fired power plants) followed by CHP plants and fermentation concepts. Because of the lower mass-specific energy density compared with hard coal, crude oil, natural gas, etc., biomass is usually only harvested, processed and used regionally for energy purposes. Therefore, as far as possible, the technical plants are designed for one fuel or biomass (the significance of the fuel-adequate design is explained, for example, in [10]), and even average plants achieve full load hours > 6000 h (cf. section 8.3).

In the further course of this chapter, the focus will again be on the provision of electrical energy. The following process routes starting from solid biomass have been classified as technically relevant in [11]:

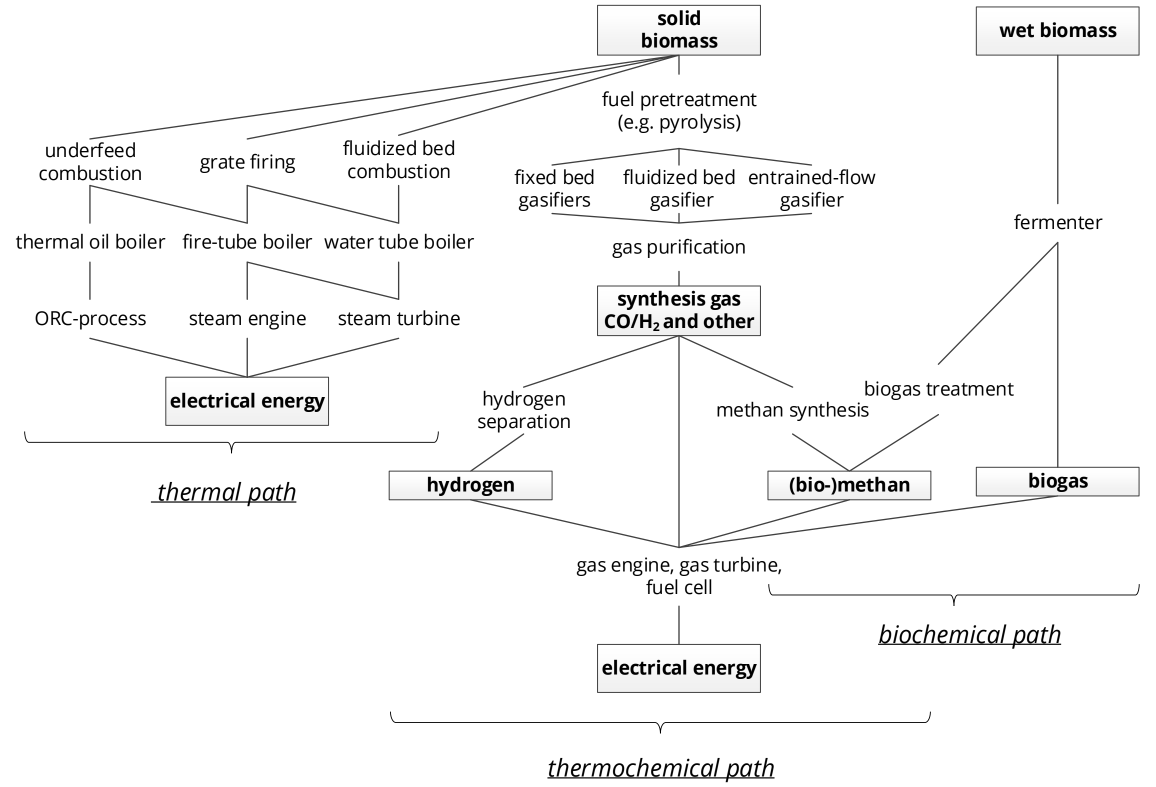

Figure 25: Generation of electrical energy from biomass, based on [11]

In Figure 25 (left), biomass is first converted into thermal energy by combustion followed by a conventional cyclic process (e.g. water vapour power process, ORC process). In Figure 25 (right), the solid biomass is first converted into gaseous fuel by pyrolysis and/or gasification and only then converted in the subsequent cyclic process (e.g. gas engine, gas turbine). Biomasses with high water content (e.g. manure, organic waste and sewage sludge) are well suited for anaerobic degradation in biogas plants because of the aqueous environment, and they also produce a gaseous fuel (biogas). The biomass is decomposed by various microorganisms in a multi-stage process. Dry or wet fermentation is generally used. Wet fermenters represent approximately 90 % of all plants (especially for agricultural substrates, e.g. slurry, solid manure, renewable raw materials), whilst dry fermenters are primarily used for solid fermentation in the continuous plug-flow process (e.g. domestic biowaste) [12]. The gas generated is mainly collected in a single- or double-shell gas storage roof and can then be further processed. The processing includes:

- Desulphurization: Removal of hydrogen sulphide (H_2S); mostly aerobically as biological desulphurization by bacteria for cost reasons or via desulphurization filters (steel wool, regeneration by heating) and finally via activated carbon filters for high gas quality requirements
- Gas drying: Condensation of the water vapour in the biogas by passive cooling in the gas line or actively by means of compression chillers
- According to [12], carbon dioxide separation is performed in n = 187 plants via pressure water washing (30 %), amine washing (29 %), pressure swing adsorption (20 %), membrane separation process (9 %), polyglycol washing (9 %) or membrane and cryogenic separation process (1 plant)

The biogas or biomethane is mainly used in conventional CHP plants [12]. In Germany, there are currently > 9300 biogas plants with a gross installed electric output of approximately 4500 MW_{el} [13]. The system sizes vary from a few kW_{el} up to the MW_{el} range [12]. Areas with large biomass potential can support the operation of very large plants, such as the biogas plant in Berlin Ruhleben. This plant converts approximately 60,000 t of biowaste into 29 GWh_{chem} of biomethane per year [14]. The resulting rated heat output is approximately 3.3 MW_{th}.

Of the technical processes listed in Figure 25, most belong to conventional, mature technology (firing technologies, boilers, steam engines, steam turbines, piston combustion engines, gas turbines) or have already been dealt with separately in other chapters (for ORC process, see Geothermics; for fuel cells, see Chemicals to Power). The development status of the gasification technologies and biogas plants will be discussed in more detail in section 9.2a).

9.2. Estimation of potential

The estimation of potential is divided into a) the technical development potential and b) the expansion potential for Germany. Part a) describes the technical developments and the technically foreseeable potential. Part b) focuses on the primary energy biomass potential, because this limits the possible increase in output.

a) Technical development potential

Advanced technical development of existing, implemented and mature processes focuses on optimization (i.e. the improvement of individual aspects or of a process detail). A presentation of the numerous detailed improvements would be unreasonably extensive. Therefore, only the most significant advances and research approaches are listed below:

- Increased efficiency (consistent use of CHP, co-firing), process stability (especially in bio-chemical processes – anaerobic fermentation)
- Avoidance or reduction of emissions (fuel preparation, gas cleaning, plant management)
- Extension of service life by corrosion prevention or reduction (e.g. by fuel additives or constructive protection – cladding)
- Flexibilization with regard to fuel use (e.g. fluidized bed furnaces, large plants up to 190 MW_{el} in operation; up to 299 MW_{el} in planning [15]) and operation.

As already mentioned in section 9, technical maturation potential exists above all for gasification technologies using biomass. The resulting gases can be used in many ways (fuel gas for power/heat supply, synthesis gas for various syntheses, and hydrogenation processes or reducing gas in metallurgy). "Gasification is a thermochemical mass conversion process in which a combustible gas is normally produced from carbonaceous energy carriers with the aid of a reaction partner [oxygen (air), hydrogen, water vapour, carbon dioxide] at temperatures above 700 °C" [16]. The oxygen is usually supplied sub-stoichiometrically (lambda 0.4 to 0.6). DC or counter-current fixed beds, fluidized beds, and the entrained-flow process are used as process principles. There is extensive experience in gasification using brown or hard coal as gasification material. The difficulty in using biomass lies in the interfering by-products of gasification (higher hydrocarbons or tars), which make its use in internal combustion engines or fuel cells considerably more difficult. The higher hydrocarbons condense during the necessary cooling for gas cleaning and lead to system failure within a very short time [17]. Entrained-flow gasification is most suitable for biomass mass gasification because it has a high carbon conversion at temperatures > 1,000 °C, and the synthesis gas is virtually free of hydrocarbons. However, experiments have shown that the biomass (straw) remains and must first be processed [16]. In Figure 26, this also results in the structure of the following two recent processes for biomass gasification and further synthesis:

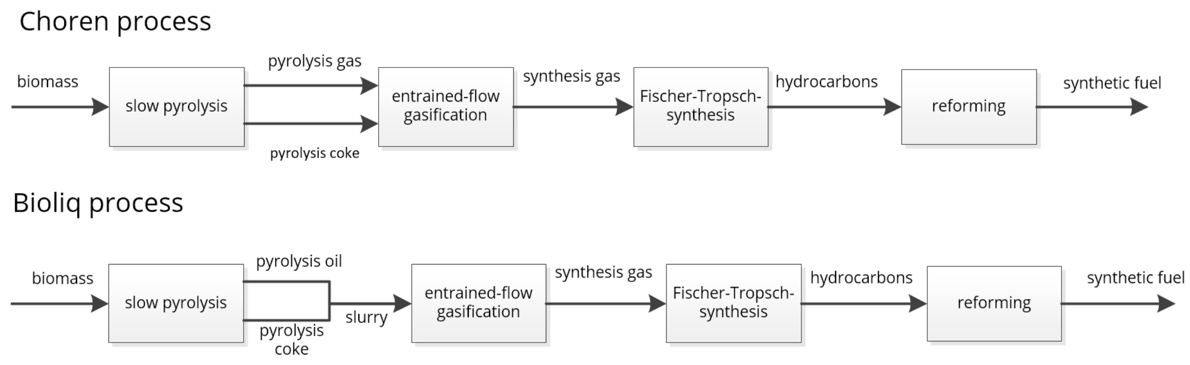

Figure 26: Two processes for the production of liquid fuels from biomass using gasification technologies according to [18], [19].

A wide variety of different biomasses can therefore be used (high fuel flexibility). The product gas obtained in this way can be processed into synthesis gas (gas purification, adjustment of the composition) and even synthetic fuels via Fischer-Tropsch synthesis (FTS). Both of the above processes are primarily aimed at producing fuels and are not yet commercially mature (liquid fuels are not considered here because they should not be used for power/heat applications). There are also a number of small, decentralized gasification plants that are used commercially in CHP operation. However, these only reach sizes in the low, single-digit MW range for the rated heat output (RHO) and must be operated with high-quality, processed fuels (wood pellets or wood chips) [20]. Large plants such as in Güssing (pilot plant, circulating fluidized bed gasification with steam, 8 MW_{RHO}) [21] have not yet been able to establish themselves [22].

The size of biogas plants is also limited by local substrate availability. By combining the above-mentioned processes in dry-wet simultaneous fermentation (former DWS process), substrates with different dry substance contents can be converted in one plant. The process diagram is shown in Figure 27.

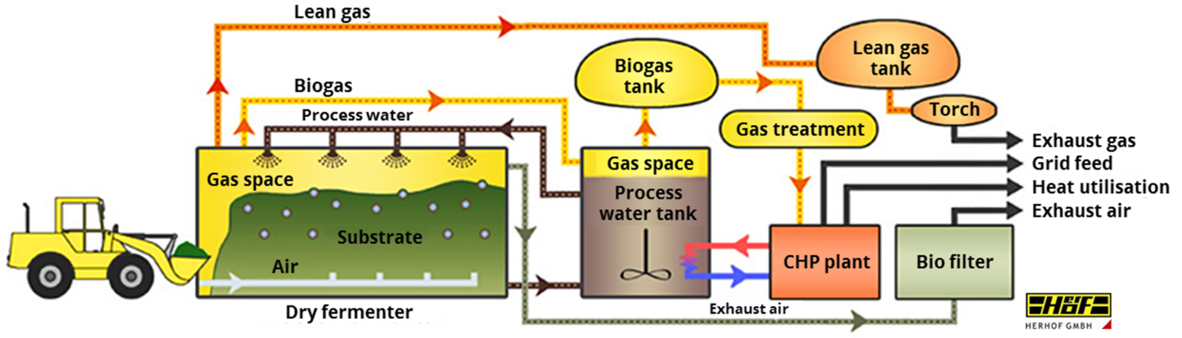

Figure 27: Schematic diagram for dry-wet simultaneous fermentation [23], translated

Several dry fermenters run in batch operation. The substrate is sprinkled with process water and moistened. The percolate (leaking process water) is then fed into the process water storage tank, in which biogas is also produced through the decomposition of organic substances and acids. Compared to conventional dry fermentation, the process stability is increased (no over-acidification because of continuous removal) with lower process energy and water consumption [23]. Several plants (e.g. biowaste treatment plants Heppenheim, Dörpen, Schkopau) have already been constructed according to this principle.

Another development in connection with biogas plants is biological methanation. Instead of separating the CO_2 in the biogas by physiochemical processes, H_2 is added

a) to induce chemo-autotrophic conversion to methane CH_4 by means of methanogenic bacteria[15]; or
b) to induce photo-autotrophic conversion to methane by means of various types of microalgae.

In chemo-autotrophic processes, a basic distinction is made according to the point in the process at which methanation takes place. It can take place either in situ or ex situ, i.e. in a separate reactor with specially designed basic conditions (e.g. temperature, pressure and composition). Ex situ processes therefore ensure better process stability – both for the fermentation process and for the methanation. However, according to [24], both process variants were successfully applied experimentally on a laboratory or demonstration scale. The main obstacles to further scaling of these processes are the low solubility of hydrogen in water as well as the lack of understanding of the process flow [25].

For the photo-autotrophic processes, the most suitable types of algae are still being investigated in the laboratory or, at best, demonstration plants [24].

b) Expansion potential

In this section, the primary energy potential will be used to assess the expansion potential. In contrast to the theoretical, technical, economic or sustainable potentials described in [1], the applied processing chain is left out of the equation. However, the reliability and informative value of the potential studies is limited because according to [26], there are no harmonized, consistently applied quantity or minimum requirements for the calculation of biomass potentials. Several studies on biomass potential have been conducted in Germany with support from the Agency for Renewable Resources (*Fachagentur Nachwachsende Rohstoffe e. V.*, FNR): some by the Agency for Renewable Energies (*Agentur für Erneuerbare Energien e.V.*, AEE) [27] and some by the German Biomass Research Centre (*Deutsches Biomasseforschungszentrum*, DBFZ) [28]. In [27], the primary energy biomass potential is estimated at 1436 PJ. The composition is presented in Figure 28. Another study [28] came to a comparable value of 1433 PJ. The composition is also presented in Figure 29. The FNR itself cites a primary energy biomass potential of 1819 PJ by 2050 (consisting of 988 PJ from agriculture, 697 PJ from the wood industry, and 134 PJ from waste) [29]. If all the above potentials are exploited, 10.6% to 13.5% of the primary energy requirement (currently approximately 13,500 PJ) could be covered by biomass.

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[15] Via the endothermic reaction $CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$

Current development and research focuses on how and with what methods this should be done.

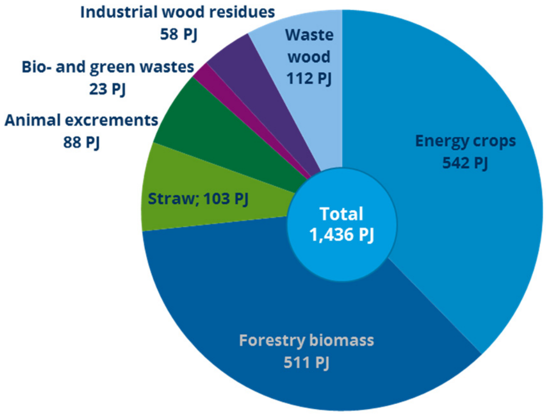

Figure 28: Biomass potentials in Germany according to [27], translated

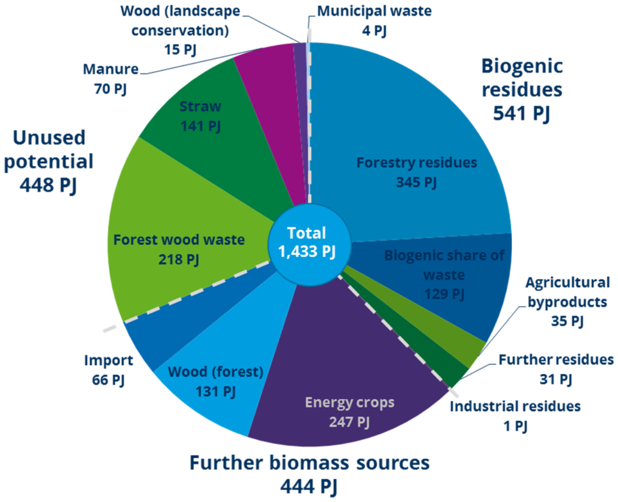

Figure 29: Biomass potentials in Germany according to [28], translated

9.3. Representation of the achieved state of expansion

With approximately 8 GW_{el} installed output and 51.4 TWh_{el} or 7.8% share of German gross electricity generation, biomass is also one of the most important renewable energies of the energy revolution. In purely arithmetical terms, the annual full load hours for the generating plants are far in excess of 6,000 h/a. Because of its constant availability, biomass can make a considerable contribution with comparatively small output capacities.

Figure 24 shows a slight, but steady increase in installed output. Since the German Renewable Energy Sources Act of 2000, the number of biogas plants has been increasing continuously. Biogas plants were given a special impetus in 2004 and 2009 because of new versions of the Renewable Energy Sources Act. However, since the amendments in 2012 and the new version in 2014 of the Renewable Energy Sources Act, the increase in output has declined and can mainly be limited to plant expansions [30]. In addition, since the amendment of the Renewable Energy Sources Act in 2016, the annual expansion for energy from biomass has been limited to 150 MW_{el}, and starting in 2020 it will be limited to 200 MW_{el} [31].

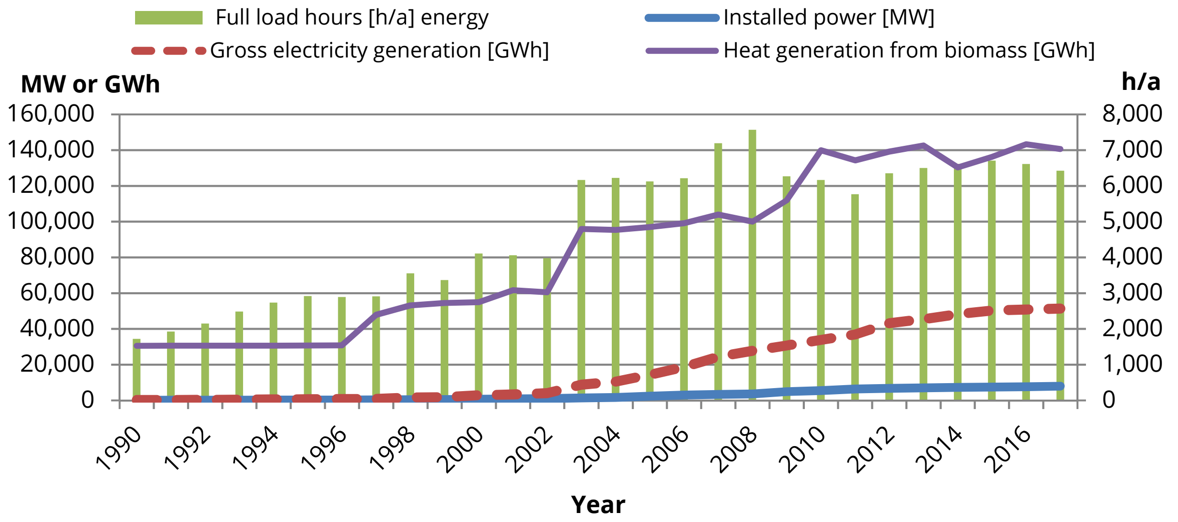

Figure 30: Development of output and generation of electrical energy from biomass, data based on [32]

9.4. TRL assessment

Overall, the technological maturity for the use of biomass for power generation must be regarded as highly mature. The conventional route via furnace, boiler and subsequent cyclic process (conversion of chemical energy to thermal to mechanical to electrical energy) is rather limited by the local availability of biomass. The high flexibility of the biomass undoubtedly ensures long-term application possibilities, which should be selected according to optimal energy exchange conditions. The thermochemical conversion of various biomasses into versatile product gases via gasification processes is technically challenging. Depending on the approach and rated heat output, many projects are still in the development phase (demonstration or pilot projects, i.e. TRL 6-8).

Table 14: Summary of TRL biomass

Technology	TRL	Supplementary sources
Conventional combustion technologies for power generation from solid biomass and gaseous secondary fuels • **Firing (cf. Figure 25)** • **Boiler (also Figure 25)** • **Cyclic processes (gas turbines, gas engines Figure 25)** • **Steam turbines, steam engines**	9	
Fuel cells	See Chemicals to Power	
ORC processes	See Geothermal energy section	
Gasification processes for biomass		
Fixed-bed gasifier	Up to 0.9 MW_{RHO}: 9	[20]
	Up to 7 MW_{RHO}: 7	[33]
Fluidized-bed gasifier	Up to 8 MW_{RHO}: 8	[33]
Entrained-flow gasifier	Up to 5 MW_{RHO}: 6	[34]
Anaerobic fermentation for biogas production:		
Wet fermentation	9	
Dry fermentation	9	
Dry-wet simultaneous fermentation	8	[23]
Biogas treatment (physiochemical process)	9	
Biological methanation		
Chemo-autotrophic process		
In situ	4	[35]
Ex situ	6	[35]
Photo-autotrophic process	4	[35]

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10. Transmission and distribution grids

10.1. Technology description

The technologies for transmitting and distributing electrical energy can be divided roughly into primary and secondary technologies. Primary technology encompasses operational equipment such as cables, switchgear and transformers, while secondary technology comprises components for monitoring, regulating, controlling and protecting the operational equipment [1]. The physical components or hardware used (sensors, actuators) are of less importance in secondary technology than in primary technology. Complete digitalization and remote switching on all grid levels represent a major step for the improvement of secondary technology. On this basis, grids can be expanded to form smart grids through a process of intelligent use and optimization. The importance of smart grid components such as smart controllers, smart meters, etc. has been established beyond all doubt. The present paper shows that smart grids are a good example of a technology whose main obstacle is not the underlying electronic components (most electronic components are TRL 9 and commercially available), but rather the intelligent interconnection and programming of these parts. Further development will require more time for system integration, but the core problem is not caused by the technical maturity of the physical components.

It should be noted here that the field of the transmission of electrical energy is so broad from a scientific and technical standpoint that only a small selection of the primary technologies for transmission and distribution grids can be examined (the classification of the grids is illustrated in Figure 34).

Transmission grids

The expansion of the transmission grid required for the energy revolution is proceeding in accordance with the NOVA principle (German acronym for “grid optimization before reinforcement and expansion”). The corresponding technologies are shown in Table 15 (based on [2]):

Table 15: Measures and technologies for grid expansion based on [2]

Measure	Technologies
Optimization:	Overhead line monitoring
	Load flow control
Reinforcement:	High-temperature low-sag conductors (HTLS)
	More electric circuits required, conductors with a higher cross-section
Expansion:	Overhead lines (use of stronger cables)
	Cables (including high voltage direct current transmission)
	Use of new pylons

The following will examine the technological maturity of these expansion measures. Administrative and contractual arrangements to secure grid stability (e.g. re-dispatch, cascading, feed-in management, interruptible loads, introduction of smart grids, etc.) are not considered here, as their implementation is largely determined by the further development of the secondary technology.

Grid optimization

One option for the optimization of existing grids is the use of overhead line monitoring (OLM). The transmission capacity of overhead lines is significantly limited by their temperature. They are designed in accordance with DIN EN 50182, which states that the conductor temperature must not exceed 80 °C. In favourable weather conditions (low external temperatures, strong winds, rain), there is better cooling of the conductors, allowing them to carry heavier loads than in the statistical worst-case scenario (ambient temperature 35 °C 900 W/m² solar radiation, 0.6 m/s wind according to DIN EN 50182:2001-12). With OLM, the temperature and sag of the conductor is measured and the load increased where applicable. The measurements are taken via fibre optic cables, thermocouples, load cells, acoustic surface wave sensors, thermography or by measuring the ground clearance using lasers or ultrasound. Overhead line monitoring is already being used selectively and, in some cases, over large areas by transmission system operators (TSO) (e.g. at Tennet, end of 2017, approximately 4,300 km [3]) and thus should be considered technically mature.

Grid reinforcement

As mentioned above, conventional aluminium/steel conductors are designed for a constant temperature of 80 °C. The existing conductors can be replaced with high-temperature low-sag conductors (HTLS) and then operated at higher temperatures to yield greater transmission performance. The temperature stability depends on the material, reaching 150 °C with thermal-resistant aluminium (TAL in accordance with DIN EN 62004, or with the addition of zircon ZTAL) or up to 210 °C (commercially available, e.g. [4], [5]). Alternatively, ACCR (aluminium conductor composite reinforced) conductors can be used, which have a smaller sag at 210 °C compared to (Z)TAL cables, according to [6]. Thus, the transmission performance of conventional conductors can be doubled with existing pylons [7]. The technologies mentioned are fully state of the art and are sold commercially.

Grid expansion

When expanding the grid, there is room for improvement in conventional line construction components, such as by reinforcing the conductor cross-section of aluminium-steel cables or using a four-conductor bundle instead of the normal three. These options are state of the art (TRL = 9) and will not be examined further, as social acceptance is an important requirement in further grid expansion and is better fulfilled by more recent technological concepts. These include, in particular, modern pylon structures and the use of extra-high voltage cables installed underground.

Underground cables

Underground cables for the transmission of power are state of the art and standard in distribution grid systems up to 110 kV (TRL = 9). Overhead lines are preferred over cables for the transmission of extra-high voltage alternating current (HVAC) for the following reasons (according to [8])

- The lines are cooled by the air (heat dissipation in the earth is lower)
- The air acts as insulation and is “self-repairing”
- Repairs can be undertaken quickly/inexpensively due to good accessibility
- Less effort is required for reactive power compensation

However, according to [9], underground cables have the following advantages

- They are better protected (e.g. against lighting strikes)
- The electrical field is practically eliminated
- The magnetic field strength drops quickly

The above-mentioned benefits of overhead lines can be compensated for in part with cables by using high voltage direct current transmission (HVDC). The transmission of direct current is normally implemented as a point-to-point connection (no networking) and inverters are used at junction points. In state-of-the-art technology, the converters are commutated “by the grid” or externally (line-commutated converter – LCC) and the current flows in one direction only. Reversing the direction of the flow is technically complex and time consuming (slowly decreasing space charges in the dielectric). HVDC lines with thyristor-based converters are state of the art and have proven themselves onshore and offshore (e.g. NorNed, 580 km cable though the North Sea, 700 MW transmission performance) [10]. On the other hand, the latest developments include self-commutated HVDC lines (voltage-sourced converter – VSC), made possible due to the developments in insulated-gate bipolar transistors (IGBT) and cable materials [10]. The direction of the power flow of VSC HVDCs is freely adjustable. The systems are marketed, for example, as HVDC Light (ABB) and HVDC Plus (Siemens) and several HVDC connections have already been installed worldwide (e.g. East-West Interconnector Ireland/GB, 130 km, 500 MW; HVDC Zhoushan in Zhejiang, China, 134 km, 400 MW; NordBalt Sweden/Lithuania, 450 km, 700 MW) (TRL = 9).

Grid connection of offshore wind turbines

The transmission system operators are responsible for connecting offshore wind turbines. In the past, there have been delays in erecting offshore wind farms [11]. The associated grid connection is therefore briefly considered below. The circumstances of offshore wind turbines necessitate a cable connection, and the distances to reach a grid junction are much greater than on land (see also chapter 5). Several offshore wind turbines are connected to a substation (star, ring or radial configuration of the cabling [12]) and the electricity is transmitted onshore via high-voltage cable. The marine cables used are plastic coated and buried approximately 1.5 m in the sea bed [13]. The energy is transmitted in the form of alternating, three-phase or direct current. The technologies are selected depending on factors such as the distance to the shore, since transmission of three-phase alternating current by cable results in losses over large distances and requires systems for reactive power compensation (capacitive compensation by capacitors, for example). According to [11], conventional technology for the transmission of alternating current is feasible for distances of up to 80 km, while HVDC technology is favourable from 60 km. The components (cables, converters, transformers, reactive power compensators [16]) required for the different concepts are state-of-the-art technology and are available on large and industrial scales. There have been problems in the past, in particular when erecting converter platforms, which support the high-voltage direct current converters and form the connection point for the wind farm. The platforms (e.g. SylWin platform of the Dantysk wind farm; HelWin, BorWin) were pilot projects in which converters had to be built more compactly than conventional technology due to limited space on the platforms. One solution for this is gas-insulated switchgear (GIS), in which the circuitry can be implemented in smaller spaces [11]. Siemens reports that it has already installed more than 36,000 GIS in the voltage range of 550 kV worldwide [15].

Distribution grids

The previous section individually addressed technologies that can also be used, or are already being used, on a distribution grid level. Therefore, they will not be revisited below.

Grid optimization

According to DIN EN 60038, the voltage in medium and low voltage grids must be kept in a range of +/- 10%. Since conventional transformer stations on a local grid do not have a control system, the voltage range is divided into medium and low voltage levels. An increased supply in the low voltage grid (decentralized PV systems) can quickly damage this voltage range, leaving distribution system operators no option but to undertake cost-intensive grid expansion. So the transformers are upgraded to regulated local grid transformers (RLGT). The conventional transformers in principle have a constant transmission ratio due to the two iron-core coils. If a coil is then fitted with several junctions (i.e. the winding number is variable), the output voltage can be dynamically regulated with an on-load tap changer. The medium voltage grid is therefore decoupled from the low voltage grid and the entire voltage range is available in the low voltage. RLGTs have been in use by grid operators since 2011 and can increase the integration capacity for renewable energy sources by a factor of between 2 and 8, depending on the grid structure [16]. Line voltage regulators represent an alternative for integrating more renewable energy sources in medium voltage grids. Medium voltage, low load grids with high supply peaks from renewable energy sources experience voltage fluctuations that have to be resolved by conventional grid expansion. However, RLGTs need to be used in

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[16] MSCDN (mechanically switched capacitor with damping network), e.g. by Alstom with 300 Mvar at the substation in Karben (Frankfurt/Main) [14]

several places [17]. Line voltage regulators (LVR) can also be used to comply with the voltage limits in medium and low voltage grids. In 2014/2015, both Siemens and ABB unveiled reference systems for line voltage regulators in medium voltage grids ([17], [18]). Therefore, a TRL classification of TRL 8 can be assumed based on the production-ready systems in commercial demonstration operation.

The further development of *converters* is another important component of grid optimization worth mentioning. Converters play a particularly important role in coupling wind farms and PV systems to the electricity grid. The basic block diagram is shown in Figure 31 and Figure 32:

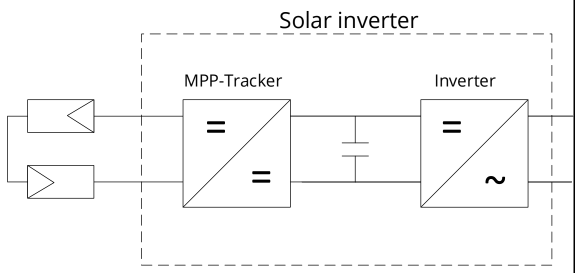

Figure 31: Block diagram of solar inverter [19], translated

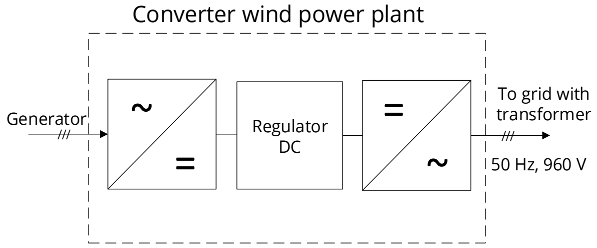

Figure 32: Block diagram of wind turbine converter according to [20], translated

In PV systems, the MPP[17] tracker is a DC chopper. The inverter is connected to this (with a transformer if needed) to ensure the connection to the grid. In modern wind turbines with variable speed rotors, the generator supplies variable frequencies and voltages. The generator output is completely separated from the grid via a direct-current circuit with a DC chopper and an additional inverter so it can be fully adjusted to meet the requirements of the grid [20]. The installed electronic components (power MOSFETs, bipolar transistors with insulated-gate electrode – IGBTs) are standard components and are therefore rated TRL 9. Nonetheless, the components are vulnerable, for example, due to the intermittent operation on wind farms or environmental influences, such as the thermal load in PV inverters, which may result in system failure [21].

FACTS

FACTS systems encompass an entire family of primary technology innovations, which according to [22] are defined as “alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability”. The systems are based on power electronics components, enabling quick and flexible control, and are used to control voltage and power flow [23]. FACTS systems include the following (based on [24], [25]):

- Static var compensator (SVC) and static synchronous compensator (STATCOM) based on voltage source converter (VSC) technology

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[17] Maximum power point tracker – regulates the voltage of the PV module so that maximum power is delivered.

- Static frequency converters (SFC)
- Series compensation (SC) with series capacitors (fixed series compensation (FSC) and thyristor-controlled series compensation (TCSC).

According to [23], they are being field tested and are already being sold by Siemens and ABB (TRL 8). They can reduce conventional grid expansion and ensure stability in systems with low-rotating masses.

Gas-insulated lines

Gas-insulated transmission lines provide an additional solution. They are used in the high and extra-high voltage range in confined conditions. The basic structure is shown in Figure 33:

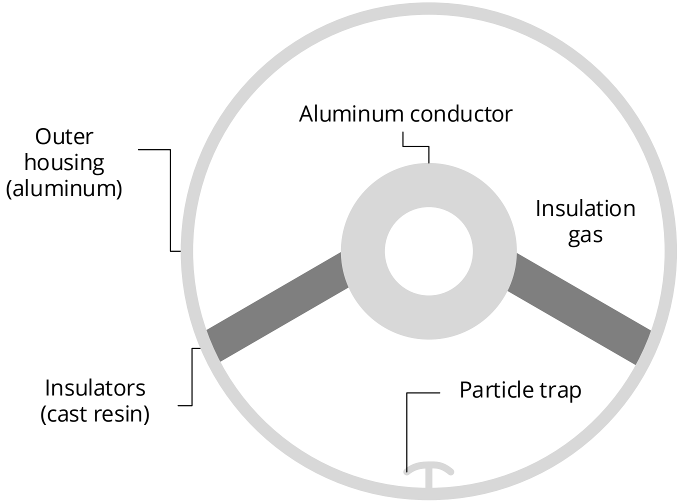

Figure 33: Structure of a gas-isolated line (GIL) based on [26]

The gas-tight welded and flanged pipes are filled with sulphur hexafluoride (SF_6) at a pressure of approximately 5 bar (due to cost and environmental reasons[18] in part also 80% N_2, 20 % SF_6). "The breakdown voltage of SF_6 is approximately three times greater than air. This is further increased at excess pressure, reducing the space requirement for these systems by one fifth of the original value needed in conventional technology" [28]. Due to the design ("line-in-a-can" [29]), the magnetic fields around the conductor are only marginal and powers of up to 3700 MVA can be transmitted at a voltage of 550 kV [30]. Should a short circuit occur, the insulation (the gas) is self-repairing and fireproof. The technology was developed in response to the increasing electricity demand and a simultaneous shortage of space in metropolitan areas in the 1970s, resulting in gas-isolated switchgear [28]. GILs are used around the world (e.g. first GIL route was the underground power station in Wehr, Germany in 1975; Xiluodu Dam, China 2013, grid length 1275 km; Frankfurt, landing corridor, grid length 5.4 km [26]) and can therefore be assessed as TRL 9.

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[18] SF_6 is a greenhouse gas with a global warming potential (GWP) of 23,900 in relation to 100 years, according to [27].

10.2. Estimation of potential

The estimation of potential is divided into a) the technical development potential and b) the expansion potential for Germany. Part a) describes the technical advancements and the current technically foreseeable potential. Part b) focuses on the potential expansion of transmission lines in Germany.

a) Technical development potential

The approach of circuit isolation via AC-DC-AC converters, which has already been largely pursued in wind turbine converters, can also be used with local grid transformers. Solid state transformers (SST) fully decouple voltage levels with regard to voltage, reactive power and frequency and can make a substantial contribution to local integration of renewable energy sources and high loads (e.g. charging electric vehicles) [31]. Compared to regulated local grid transformers, standardized electronic components are used in SSTs, resulting in smaller system sizes. Further development must be made in terms of the service life and reliability [32] and also regarding the complementary secondary technology for integration into smart grids.

Pylon construction is also considered a component for grid expansion with overhead lines. Overhead line pylons are technically mature and are used around the world by the thousands. Further development is being made primarily in the area of design, which should increase visual acceptance. This can be achieved by using more appealing shapes, lower pylon heights and narrower route widths. The height of the pylons is primarily determined by the sag of the cables [33]. It is in this context that 50Hertz, among others, has developed an overhead line variant under the project name “compactLine”. In this project, additional carrier cables are tensioned between the pylons upon which the line conductors are suspended every 20 m. The distance between pylons remains constant at approximately 400 m, but compared to conventional “Danube” pylons the height is reduced from 50–60 m to 30–36 m and the route width from 72 m to 55–60 m [34]. The line concept has been in construction since September 2017 as a pilot project at the substation Jessen/Nord [35]. The project will attain TRL 6 (pilot system with final system fidelity and use in operational environment) in the 3rd quarter, when it is planned to be put into operation.

As shown in section 84, HVDC technology has achieved technical maturity in point-to-point connections. The challenges facing the development of HVDC grids (VSC HVDC) are mainly the construction of suitable circuit breakers [36]. Purely mechanical circuit breakers cannot be used, as separating the high voltage will always produce an electric arc that does not extinguish, due to the DC voltage [19], and that would result in significant thermal loads. Hybrid DC circuit breakers are therefore in development, which rely on a combination of mechanical and power electronics switches [37]. According to [38], these

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[19] In the case of alternating voltage, the electric arc extinguishes at zero crossing and is prevented from re-forming by the insulating filler in the switch (e.g. transformer oil, SF_6).

hybrid DC circuit breakers have been available since 2011 as “commercial prototypes” and are undergoing continuous further development. Likewise, [38] mentions three examples for HVDC grids planned and currently under construction (all in China), meaning that in the near future pilot projects for DC grids will also go on line.

The GILs shown in section 84 have so far been used for alternating current. A consortium is currently working on a GIL DC transmission system (DC CTL – compact transmission line for direct current). This type of line could be used in densely built-up regions for the laying of space-saving underground HVDC lines. Alongside the basic implementation, the main focus of study is to ensure long-term stability (new welding methods, mechanical and thermal loads, ageing of the components) [39]. To this end, a demonstration route was installed between Griesheim and Darmstadt (underground, tunnel and open air lines) and tested in 2017 (maximum 5 GW/system; 500 kV; up to 5000 A) [40].

The project “AmpaCity“ is pursuing a similar space-saving method. A 1 km-long test cable was laid between two substations in Essen in 2014, functioning as a high-temperature superconducting cable [41]. When ceramic conductor is used (BSCCO (bismuth strontium calcium copper oxide) or YBCO (yttrium barium copper oxide) [42]), the internal resistance of the conductor drops to zero at -200 °C. The cable is integrated into actual grid operations as a 10 kV cable that replaces a conventional 110 kV line and is currently in the test phase [43].

b) Expansion potential

The power grid on land must be expanded on several grid levels. Expansion must be restricted to what is necessary due to the considerable costs, which fall to the general public. The quantification of this necessity is currently determined on the transmission grid level by the grid development plan [44]. In it, the associated expansion requirements are calculated using possible scenarios for supply and consumption. These scenarios are subject to many influencing factors [20], and thus it is only possible to forecast expansion for a limited period in a limited space. Currently, the grid development plan specifies grid additions and expansion until 2030 at best. In transformation scenario B 2030 (moderate addition of renewable energy sources), there are plans to make additions to the transmission grid in the amount of 600 km HVAC and 2200 km HVDC. The existing AC and DC power routes must also be reinforced (AC: 2800 km additional cabling/re-cabling, 4000 km new construction in the existing stock, DC: 300 km additional cabling/re-cabling, 40 km new construction in the existing stock [21]). In total, 9900 km kilometres of grid need to be expanded or newly built by 2030, according to the most recent grid development plan. Compared to scenarios A (little addition of renewable energy sources) and C (more

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[20] Examples of such conditions include power, capacity, energy flows, positions, behaviours, etc. of the consumers, storage systems and energy provision systems and are constantly changing.

[21] The current grid (starter grid) does not yet have an HVDC route, making it clear that previously planned measures need to be extended.

addition of renewable energy sources), the deviations are clear at 9300 km and 10,200 km. A prediction extending to 2050 is not worthwhile in this context, as the boundary conditions of possible scenarios cannot be foreseen.

In addition to the above-mentioned expansion, the grid development plan includes the offshore grid development plan 2030. This contains plans to connect 15 GW_{el} of offshore wind turbines to the grid (target scenario B 2030). The offshore grid to be added is determined to be 2277 km long with a total transmission capacity of 7.4 GW [44]. DC grids are favoured in planning for the North Sea, while AC grids dominate the Baltic Sea.

Yet transmission grids constitute less than 2 % of the power lines (in relation to total length) in Germany. The vast majority are found in the distribution grid and are maintained by approximately 880 distribution system operators [45] [2]. According to [2], "[...] no universally valid procedure exists for determining expansion requirements in the distribution grid. Instead, grid expansion is planned according to regional conditions and requirements (consumers, load profiles, installed generation capacity and type, etc.) and independently by the responsible grid operators". An estimation of the expansion requirements in the distribution grid is therefore unreliable, especially when the influence of decentralized PV generation and the increase in electric mobility (both on the low voltage level) would have to be taken into account. The range of evaluations is clearly visible in Table 16 below [2]:

Table 16: Grid expansion requirement in the distribution grid according to grid levels in km [2]

Study	Year	High voltage	Medium voltage	Low voltage	Total	Reference year
German Federal Ministry for Economic Affairs and Energy (BMWi) distribution grid study (German Renewable Energy Sources Act (EEG) 2014)	2014	10,820	70,104	50,393	131,317	2032
BMWi distribution grid study (Grid development plan 2013, B)	2014	12,760	58,552	73,852	165,885	2032
BMWi distribution grid study (German federal states)	2014	22,391	138,436	118,488	279,315	2032
dena distribution grid study (Grid development plan 2011, B)	2012	35,610	72,051	51,563	159,224	2030
dena distribution grid study (Federal states scenario)	2012	39,544	117,227	57,229	214,000	2030
German Federal Association of Energy and Water Industries (BDEW) (energy concept 2020)	2011	350	55,000	140,000	195,350	2020
BDEW (German Federal Ministry for the Environment (BMU) lead scenario 2020)	2011	650	140,000	240,000	380,650	2020

Recent studies arrive at low expansion figures, yet the scope of over 380,000 km to 130,000 km is substantial, indicating little transparency in this issue. In fact "operators of electricity distribution grids [...] in accordance with Section 14 (1a) of the German Energy Industry Act (EnWG), must draw up and submit a report on the state of the grid and plan for grid expansion upon request of the regulatory authority" [46], yet the monitoring report by the Germany Federal Network Agency (BNetzA) only indicated the required investment volumes for the next ten years.

One difficulty in determining the local expansion requirement is the possible concepts of decentralization and regionalization of the electricity grids. Study [47] acts as a meta study in looking at this approach, and it comes to the following conclusions:

- Decentralization concepts are usually vague and restrict themselves to rough narratives.
- Actual physical proximity between producers and consumers alone does not lead to smaller grid expansion, as the flexibility options on both sides must also be regulated by suitable market and incentive models (pricing in liberalized markets).
- "Lower electricity grid requirements can only be reliably assumed if close-to-consumption generation and flexibility options are merged into private consumption solutions or if regionally adapted cellular regulation methods take effect. [47]
- The lager the selected cells/regions are, the more effective the diversification of flexibility options (portfolio expansion).
- Available studies give no clear answer regarding the scope for reducing the grid expansion requirement. The expansion needed is expected to decrease by approximately 10-20%.

Study [48] also illustrates how new electricity applications (heat pumps, electric mobility) and their behaviour influence grid expansion requirements in distribution grids. It is clear that a high degree of concurrency can occur with greater market orientation, which requires increased grid expansion for flexible operating behaviour compared to today's demand-orientated operation. According to [49], grid expansion requirements can be substantially reduced by lowering the concurrency of low voltage applications.

10.3. Representation of the achieved state of expansion

The current stock of the German electricity grids is shown in Figure 34, based on [50]:

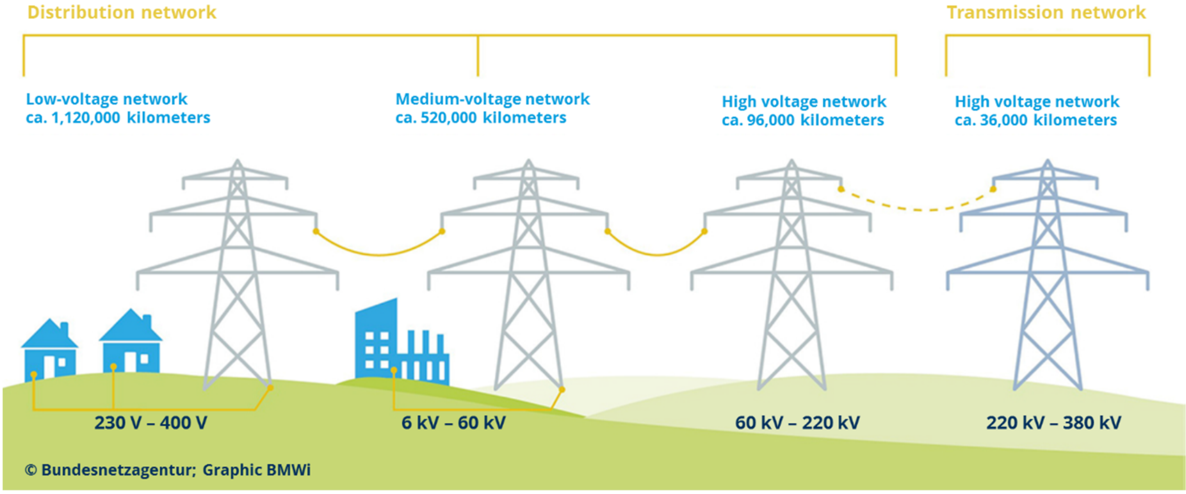

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Figure 34: Structure of the German electricity grid and voltage levels [50], translated

The total length of the grid is thus approximately 1,740,000 km. According to the current grid development plan 2,030 [44], the planned expansion and additions in the amount of approximately 10,000 km pertain to 0.53 % of the existing lines or 28.5 % of the transmission grid.

The grid expansion that is immediately needed in the onshore transmission grid was quantified and supported as early as 2009 by the German Energy Line Extension Act (EnLAG). The act stipulates measures for approximately 1,800 km of 380 kV three-phase AC extra-high voltage lines. Based on current information in [46], around 1,000 km are approved, of which 750 km have been realized and a further 600 km are in ongoing regional planning and plan approval proceedings. The lines are primarily designed as overhead lines; underground cables are used in sections in only six of the 22 measures, but “none of the projects with pilot routes for underground cables […] are fully operative yet” [51].

The German Federal Requirement Plan Act (BBPIG) represents an actual expansion of the EnLAG. It defines the extra-high voltage lines that are to be developed primarily for the “integration of electricity from renewable energy sources, for interoperability of the electricity grids within the European Union, for linking new power stations or avoiding structural bottlenecks in the transmission grid […]” [52]. Eight of the 43 planned measures are intended as HVDC lines and five of those with underground cable in parts. “The total length of the lines resulting from the Federal Requirement Plan Act is currently around 5,900 km. Roughly 3050 km of this is categorized as grid reinforcement in the grid development plan. […] With regard to the third quarter of 2017, a total of approximately 450 km is approved, of which 150 km has been realized.” [46]. This Federal Requirement Plan is regularly amended and reviewed using the grid development plan.

10.4. TRL assessment

In summary, the presented primary components in electricity grids are predominantly classified as mature. A broad range of technical solutions is available for electricity transmission and distribution, which can be used even in difficult conditions (lack of space, dense construction, safety requirements (electrical, magnetic fields, fire safety), in the sea). Transmission by means of HVDC lines in point-to-point connections is also state of the art. Research and development is focusing on approaches that improve social acceptance of the technologies by making them less obtrusive (more compact, underground). The design of HVDC grids and the necessary circuit breakers are not yet technically mature but are being investigated and developed further in pilot projects worldwide.

This chapter deliberately ignores developments taking place in secondary technology, such as the measuring, regulation and control of the current flow. Here, substantial research must be done in future to link existing technologies skilfully and “smartly”. They will be a key element for improving the efficiency of the primary components [49].

The TRLs of the technologies presented for the optimization and expansion of electrical grids are listed in the following Table 17.

Table 17: Summary of TRLs of electrical energy grids

Technology	TRL	Supplementary sources
Overhead line monitoring	9	[3]
High-temperature low-sag conductors (HTLS)	9	[4], [5]
Regulated local grid transformers (RLGT)	9	[4]
FACTS	8	
High voltage direct current transmission (HVDC)	9	[10]
Gas-isolated transmission lines (GIL)	9	[26]
GIL HVDC	6	[40]
HVDC grids	6	[38]
Circuit breakers for HVDC connections	8	[38]
Superconducting HVDC	6	[53]
“compactLine” overhead line pylons	6	[35]

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11. Power-to-heat

11.1. Technology description[22]

Power-to-heat (PtH) refers in general to the use of electrical energy to generate heat. The use of electricity in the heating sector is well known (cf. Table 18) and has recently become widespread.

Table 18: Overview of power-to-heat technologies according to [1]

Power-to-heat technologies	
Households and businesses	Industry and process heat
- Resistance heat systems o Heating elements (flow heaters) o Underfloor heating systems o Infrared radiators - Electrode boilers (commercial) - Electric heat pumps - Bivalent (hybrid) heating systems	- Processes and procedures o Conductive resistance heating o Inductive heating o High-frequency heating o Magnetic direct-current heating o Electric infrared heating - Electrode boilers, heating elements (some with CHP) - Electric heat pumps
Heat accumulators	District heating
- Sensible heat accumulators - Latent heat accumulators - Thermo-chemical heat accumulators	- Large-scale electric heat pumps - Bivalent (hybrid) heating systems - e.g. CHP and electrode boilers

On an industrial scale, large power-to-heat systems are already used in metallurgy (e.g. steelworks, aluminium smelters). The best-known examples are probably electric arc furnaces and the Hall-Héroult process, in which conductive heat is used for smelting. Equally well known are electrode boilers, which are used for water heating or steam supply. In households and businesses, night storage heaters are well-known, mature technologies used for resistance heating systems, heating elements and heat pumps.

To rein in the vast scope of the topic of power-to-heat, the focus here will be limited to large-scale, centralized systems to convert electrical energy into heat for heat supply. Power-to-heat systems have so far not been used on their own, but instead as part of a generating park that ideally includes renewable (biomass-based) or fossil-fuel combined heat and power plants. The key technologies here are electrical flow heaters, electrode boilers and large heat pumps. Heat accumulator technologies are an excellent way of supplementing and simplifying the operation of these plants and are integrated in nearly all known PtH projects; however, they are not power-to-heat converters in themselves.

According to [2], the biggest advantages of power-to-heat technologies are:

- Their energy efficiency

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[22] The following is partially based on earlier articles by the authors:
C. Pieper, S. Unz, M. Beckmann: Operation of power-to-heat plants and opportunities for marketing, Berlin Waste and Energy Conference, Berlin 2018. Contents have been transferred verbatim without further acknowledgement.

- Their high load change rates (limited for heat pumps)
- Their resultant ability to utilize short-term grid overloads
- Their high technological maturity at low investment costs (limited for heat pumps)

Conversely, their main disadvantages are:

- The high power requirements, often all at the same time within one region (which leads in turn to high load on the distribution grid when they are used en masse, e.g. in households)
- The high price of the energy source “electricity” (including levies, taxes, fees; this makes it more difficult to use these economically as base load, so they tend to be used more to cover peak load requirements) [3].

If excess power were the only issue for the energy sources needed for the technologies, the advantages concerning this would be:

- Cost-effective use of widely available renewable energy that otherwise cannot be used
- Substitution of fossil input energy by renewables and therefore no emissions (i.e. CO_2, NO_x) at the point of use
- Grid usefulness
- In future, high levels of renewable use in the electricity mix used for heat generation because of dynamic development of renewables

The current state of the technologies mentioned above and their level of development in Germany is discussed below (section 7.3).

Electric process heaters:

The electric process heater is a special form of resistance heating system consisting of several heating elements across which fluids can flow both lengthwise and crosswise. Heating systems with lengthwise flow have no baffle plates and therefore exhibit little pressure loss. They are usually used for oil. Other designs include heating wire bundles that can be used as trace heating or can be immersed in containers and even operated under pressure [3].

Electric process heaters with crosswise flow increase the temperature of the water flowing through them by means of an integrated electrical resistors. The efficiency level is around 99 %. Electric process heaters are widely available and can be operated dynamically because they can be controlled quickly and easily. This means electrical energy is converted into thermal energy almost without loss. The structure of an electric process heater is represented schematically in Figure 35.

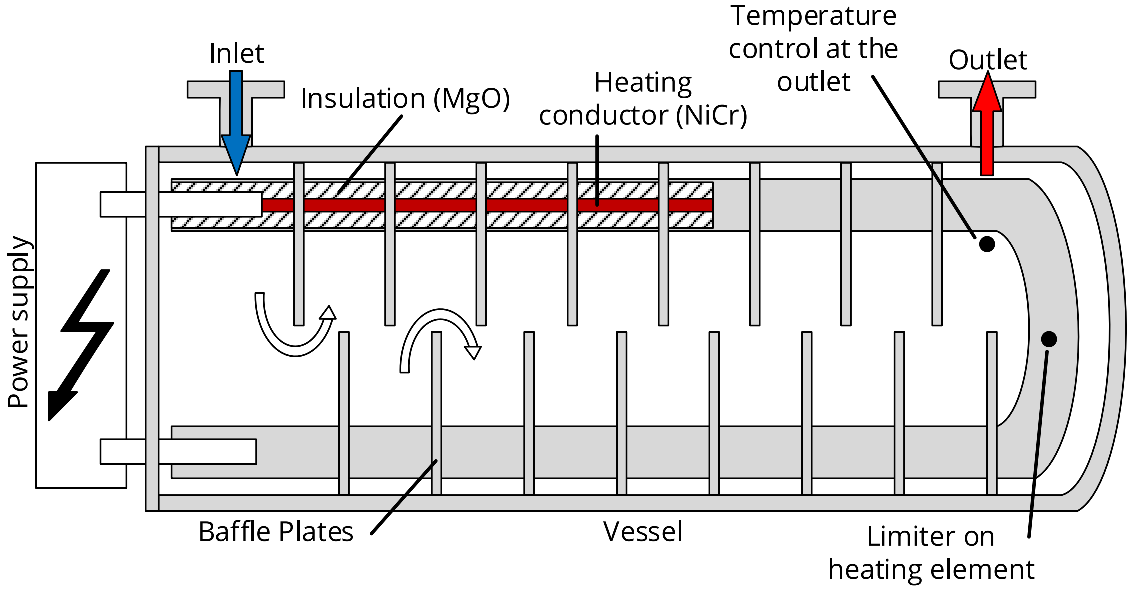

Figure 35: Schematic structure of an electric process heater, based on [4]

The cold medium is conducted through the inlet into the container and flows around a bundle of heating elements. The heating elements consist of a central heating wire (e.g. NiCr 80/20, melting temperature ~ 1,400 °C [5]) clad with high-temperature insulation (in this case, compacted magnesium oxide – MgO, melting temperature > 2,800 °C) and a metal pipe. The heater is connected to the low-voltage grid because of the insulation required. The heating elements can be controlled individually and by percentage (using thyristor control) allowing low partial loads and infinitely variable control [6]. The maximum positive load change rate is braked in practice by the surrounding system (e.g. thermal stresses in cold boilers). The heating elements are cooled in operation by an elegant flow control (baffles), which avoids hot spots and low-flow areas.

According to manufacturers, the systems can be operated under pressure (up to ~ 160 bar) and at temperatures up to 600°C depending on requirements [7]. The output range is from 150 kW_{el} to 10 MW_{el}. For larger stand-alone systems, the flow control and the density of connections become a challenge, resulting in the use of several units or electrode boilers.

Electrode boilers:

In contrast to electric process heaters, electrode boilers use an electrode system to directly heat the conductive water in a container instead of indirectly heating it by means of heating wires. Phase electrodes and (with some manufacturers) zero-point electrodes are integrated in the container and surrounded by water. The boiler is controlled via control screens (which can be used to adjust the exposed contact surfaces of the phase electrodes) or via an adjustable water level (which changes the contact surface between water and electrodes). With district heating, the heat is indirectly output through a heat exchanger because the system has different requirements for the water quality (cf. Figure 36) [6].

Even here, the efficiency is approximately 99%. Electrode boilers are very scalable; boilers up to 50 MW_{el}, systems up to approximately 120 MW and pressures up to 50 bar (including steam) are possible [8], [9], [10]. “Higher output classes are theoretically feasible, but the manufacturing costs increase sharply at higher outputs and higher pressures. For this reason, a modular combination of smaller boilers is more economical.” [9] “The electrode boiler can be brought to full output within 15 minutes from a cold start and if started warm, within 30 seconds. The minimum load to keep the boiler hot is extremely low, less than 1 % of the rated output.” [9] For this reason, electrode boilers are also used as a finely controllable load to start up power plants.

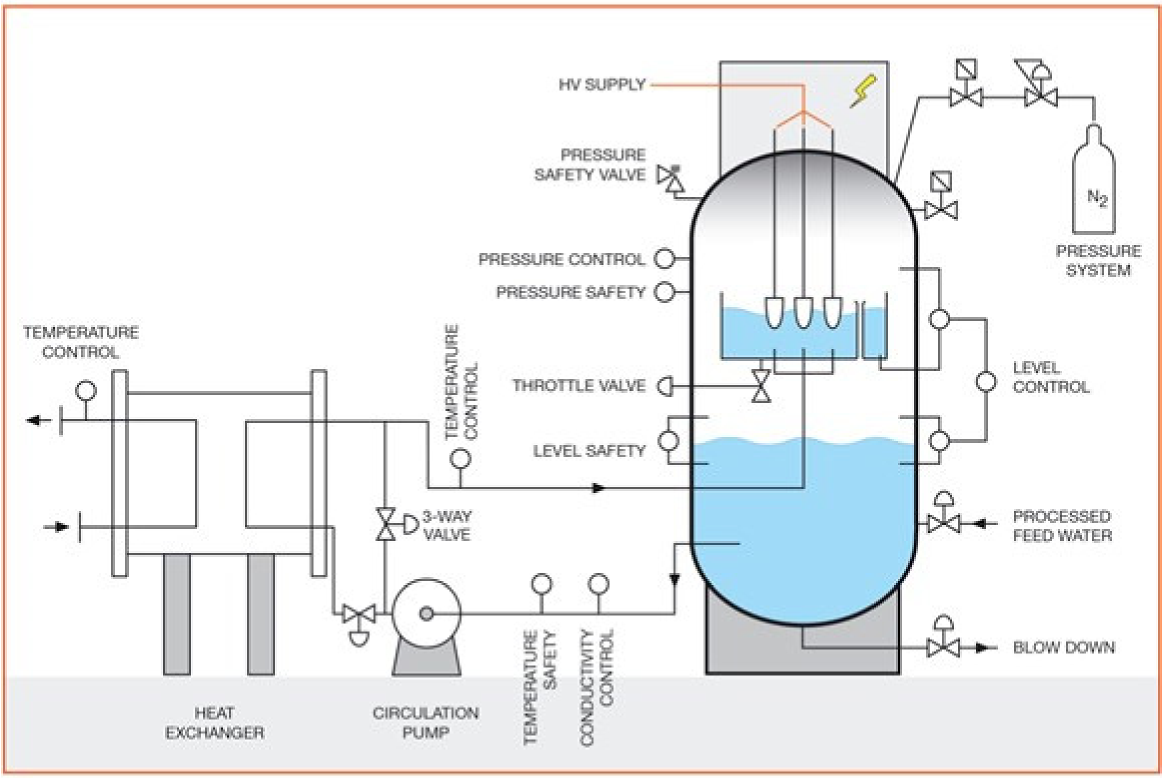

Figure 36: Structure of an electrode boiler for hot water generation. During steam generation, the steam is extracted at the tank cover. [11]

Large heat pumps:

Heat pumps use energy to move heat from a lower-temperature reservoir to a higher-temperature reservoir. Compression heat pumps use primarily electrical energy to operate a compressor, while adsorption and absorption pumps usually require heat at an even higher temperature to operate. Because the use of electrical energy is crucial for this system, further designs are limited to compression heat pumps, whose schematic structure is shown in Figure 37.

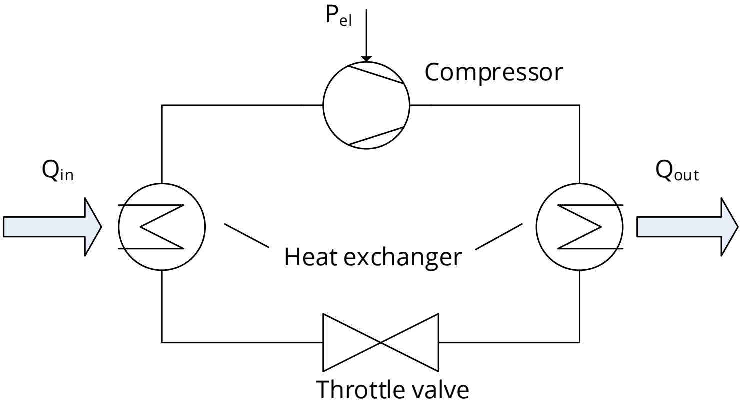

Figure 37: Compression heat pump schematic

The basic operating principle is familiar from the common household refrigerator, so extensive detail is not required here. Heat sources include the earth, air, water or collected waste heat flows (from coolant, thermal oil, waste water, etc.). The smaller the temperature spread between the two heat reservoirs, the more efficient the process. Therefore, when using large heat pumps it usually makes the most sense to increase process return temperatures and to reach the final target temperature using other heating methods (e.g. using electricity or fossil fuels). If the heat supply is also used to cool the process water, for example, then the ratio of heat (or cold) output to electrical energy input increases further and maximises the coefficient of performance (COP), which can be up to 7 [9][23]. It is worth mentioning here an example of the technological state of the art, such as the large heat pumps manufactured by Friotherm. The systems are in the output range of 1 to 20 MW_{th} [12] and some have a multi-stage design. "The possible flow temperatures for these types are in the range of 80 – 90 °C at source temperatures from 10 – 15 °C and, depending on return temperatures and number of compressors, can be increased to 120 °C. Even in this last example, the COP would remain above 2.7, up to around 3." [9].

Although heat pumps at partial load can be controlled on a continuous scale between 10 – 100 % [12], heat pumps have relatively poor dynamic behaviour, which makes dealing with peak current more difficult. For this reason, it is only economical to work with base loads, which is counter to the idea of using excess power.

11.2. Estimation of potential

a) Technical development potential

For the electric process heaters and electrode boilers mentioned above, the technical potential is exhausted at an efficiency > 99 %. There is room for further development in

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[23] The technical parameters for a heat pump (temperatures and pressures) are highly dependent on the technology used, the working fluid and the heat reservoir. An extensive overview of performance data for air/water, brine/water, water/water and used water heat pumps can be found in [13]. The pumps are usually used to produce heated water up to 60°C. Industrial CO_2 heat pumps work in the transcritical range at pressures > 80 bar and up to 135°C [14].

the area of plant sizes. However, from the standpoint of capacity, the two technologies complement each other well. Electric process heaters are available up to 10 MW_{el} and can be expanded on a modular basis. In the case of higher output requirements, electrode boilers are more economical and can be built with a capacity of up to 50 MW_{el} per unit. In view of this, there is little incentive for further development. According to [10], the development work with electrode boilers is focusing on simplified modularization, which aims to reduce investment and maintenance costs. Making the boilers smaller allows better integration into existing structures. Another development goal is even-higher load change rates, aiming to reach 100% load within 30 seconds when started warm. This means electrode boilers could even be used for primary control output. The key challenge related to materials is the ceramic components in the insulators.

There is more potential for the heat pumps. The theoretical maximum COP of a heat pump is the inverse of the associated Carnot efficiency value and is therefore determined by the temperatures of the source and sink. This limit is shown for a source temperature of 70°C in Figure 38 as an example.

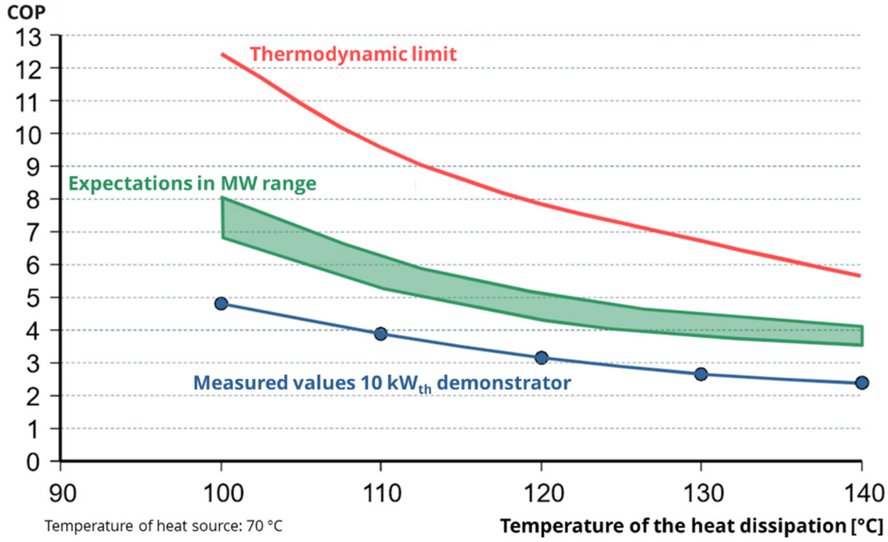

Figure 38: Estimation of potential for high-temperature heat pumps at a source temperature of 70°C, translated [15]

The possible output range for heat pumps is shown in the MW range as expected from [15]. It is clear from the currently common COP values of 3-4 that there is still room for optimization. Because this is a cyclic process, the optimization approaches used here can be similar to those used for conventional power plant technology. This includes internal recuperation, the introduction of multi-stage compressors (esp. scroll compressors) and, where possible, separation into several coolant circuits to optimise the temperature spectrum [16]. The possibilities of cascaded hybrid heat pumps consisting of compression and adsorption circuits are discussed in [17].

Heat pump development is focused on performance optimization as well as expansion of the usable temperature spectrum, which is determined by the coolant used.

“Temperatures of approximately 90 °C appear realistic in tests with R227ea, for example, or 140 °C with R245fa.” [9] The use of CO_2 as a coolant is another possibility. This means that flow temperatures of up to 110°C are possible. Large plants have a heat output of up to 2.2 MW_{th} [18]. The efficiency of the heat pumps increases when heat sources with high temperatures are used; however, this leads to higher requirements for the compressors (motor cooling, temperature-resistant materials for seals, lubrication, etc.) [19]. Heat pumps that reach a target COP of 3 at temperature spreads of 90/150 °C are already in close-to-industrial development [20]. At 200 kW_{th}, the output is still limited. A further overview of key research areas is presented in detail in [18]. “The highest flow temperature of 160 °C was reached with the laboratory system at the Austrian Institute of Technology (AIT) with the hydrofluoroolefin (HFO) coolant R1336mzz(Z) in a 1-stage circuit with IHX. A COP of 2.7 was measured with a temperature difference of 45 K. At 150 °C, a COP of 2.4 was achieved with a significant temperature difference of 70 K.” [18]. Another large heat pump made by Kobelco (SGH 165) enables flow temperatures of up to 165°C according to its data sheet, but it is a hybrid system in which a heat pump generates steam at up to 120 °C, which then reaches the end temperature via a vapour compressor (COP ~ 2.5 at a difference of 70 °C to 165 °C, 660 kW_{th}) [18].

b) Expansion potential

Quantifying the economic expansion potential of central PtH plants in the general heat supply depends strongly on the future expansion of the district heating network. For this reason, it is assumed from the outset that the existing district heating network cannot be retrofitted or removed. Nevertheless, ongoing modernization of existing structures means that the future heat requirement will be reduced unless gains in efficiency are negated due to rebound effects.

In 2010, the seasonal heat output for general supply was 100.9 TWh_{th}. Of this, 52.2 TWh_{th} came from CHP systems, which usually cover the base and mid-load range of the district heating supply [6]. Data provided by AGEB e.V. indicates that in 2016, approximately 408 PJ or 113.3 TWh_{th} of the end energy requirement was covered by district heating [21]. If the base and mid-load is covered by large heat pumps, then the potential is at least 52.2 TWh_{th}, which corresponds to an electrical energy requirement of 17.4 TWh_{el} with an average COP of ~ 3. The remaining peak load can be covered by more PtH plants with efficiency levels of ~ 1, adding a further 60 TWh_{el}.

Heat pumps can also provide a majority of decentralized space heating and hot water supply in households, commerce, trade and services and industry, since the temperatures required are usually < 100°C. According to [22], this results in a total heat potential of 2818 PJ_{th} or 783 TWh_{th} for 2015. With a seasonal performance factor (SPF) of 3 or 4 (i.e. the average COP over the year), the electrical energy requirement would then be approximately 196 to 261 TWh_{el}. According to [9], however, only approximately 80 % of the heat requirement for households and 90 % in the commerce, trade and services sector could be covered using heat pumps. The technical generation potential is far above the potential demand, thanks to deep geothermal probes, near-surface geothermal energy and industrial waste heat [23].

11.3. Representation of the achieved state of expansion

In recent years, PtH projects have been implemented precisely in municipal energy supply companies with an appropriate district heating connection. A small overview in 2015 in [24] showed approximately 250 MW_{el} of installed PtH output, while the AGFW[24] association assumed in 2017 in [25] that approximately 343 MW_{el} PtH output was in municipal hands. In [26], the BDEW[25] anticipates “at least 35 larger power-to-heat plants with a total output of almost 540 MW”. Despite this development, the ratios in Figure 39 show that PtH still has a subordinate role in grid-bound heat provision.

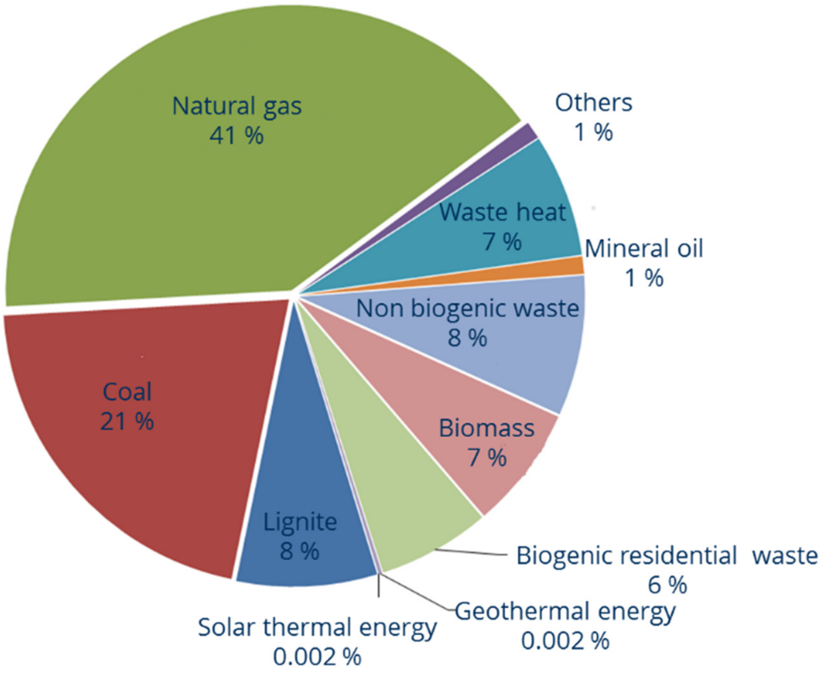

Figure 39: Net heat generation for grid-bound heat provision in 2016 (137 TWh_{th} = 100%), data based on [26]

This shows that the penetration of PtH in the German district heating industry is by no means substantial (in Figure 39 under “Other”). According to [27], a total of 800,000 heat pumps (as of 2016, 39% geothermal, 61% environmental heat (air, groundwater)) are already in operation in Germany.

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[24] AGFW – Energy Efficiency Association for heating, cooling and CHP

[25] BDEW – German Federal Association of Energy and Water Industries

11.4. TRL assessment

The PtH technologies mentioned above are already in use commercially. Only the outputs are still relatively limited for heat pumps. For decentralized applications in households and businesses, there is no doubt that the technology is mature. Large heat pumps are also technically and commercially available. Their lack of widespread adoption is a result of high investment costs and the additional cost of using geothermal heat (e.g. drilling costs). The TRL classification for the development potentials mentioned above is shown below in Table 19.

Table 19: Results of the TRL analysis

Technology	TRL	Supplementary sources
Electric process heaters/heating elements	9	
Electrode boilers	9	
Large heat pumps for district heating (up to 90°C), multi-stage compressors and circuits	9	
High-temperature heat pumps up to 110°C, 2MW$_{th}$, R744 (CO_2)	8	
High-temperature heat pumps up to 150°C, 0.2 MW$_{th}$	6	
High-temperature heat pumps up to 160°C	3	
Cascaded hybrid systems	4	

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12. Power-to-cold

12.1. Technology description

Power-to-cold describes the use of electrical power to cool down a medium. The cooling of material flows generally takes place using chillers, which utilize energy to displace heat in a manner similar to heat pumps. Chillers transfer thermal energy from a medium with a lower temperature to a medium with a higher temperature. The technical work necessary for this process can be provided by thermal energy or electrical power.

Various concepts are used for chillers:

- Vapour-compression chiller
- Adsorption chiller
- Absorption chiller
- Resorption chiller
- Steam jet cooling system
- Thermoelectric cooler (TEC) based on the Peltier effect

Adsorption, resorption and absorption chillers primarily use thermal energy to maintain the respective cyclic process and therefore only represent a limited potential for the use of electrical energy. By using waste heat they can take the place of vapour-compression chillers and thus contribute to saving electrical energy. Steam jet cooling systems primarily use thermal energy as well, driven by a steam jet vacuum pump. Cooling output can be supplied de-centrally or centrally and transported to the consumer by means of a district cooling network.

In a TEC, current flowing through certain pairs of semiconductors, which are electrically in series and thermally in parallel, leads to a temperature difference on both sides of an element, which is usually cuboid in shape. The efficiency of today's TECs is very low (coefficient of power < 1) and the cooling output is limited to a few watts [1]. Therefore, TECs have only been considered so far for niche applications (e.g. cool boxes for medicine or food) in which their advantages (small size, no moving components, gases or liquids) can be exploited. They are not relevant for the energy revolution and therefore will not be covered in any further depth [2].

Vapour-compression chillers

The composition and operation of vapour-compression chillers has already been dealt with in the chapter 11, regarding heat pumps. They are technically mature and commercially available in a wide spectrum ranging from a few kW_{th} up to MW_{th} (e.g. [3]). Further developments are described in section 12.2a).

Sorption chillers

The sorptive process uses continuous working systems (absorption of refrigerant vapour in a salt solution) as well as cyclic working systems (adsorption of the refrigerant vapour to solid matter) [4].

Adsorption chillers operate in two separate stages. First, the working fluid/sorbate evaporates (at a low pressure, if necessary), as it is adsorbed by the dry and unloaded sorbent. Due to the evaporation enthalpy emitted, the working fluid cools down. In the second stage, heat is applied to the wet/loaded sorbent, whereby the working fluid is desorbed and thus the adsorber is regenerated [5]. The common refrigerants for adsorption chillers are water, methanol and ammonia. The sorbents are activated carbon, zeolite and silica gel. “Driving temperatures between 60 °C and 90 °C are required for the working pairs water/silica gel and water/zeolite. The achievable heat ratios are between 0.4 and 0.7”[26] [4].

In absorption chillers, a (gaseous) refrigerant is dissolved in a solvent cycle (absorbed at a low temperature) and desorbed when heated at a higher temperature. The desorbed refrigerant is cooled (a heat sink is required) and liquefied. Afterwards, the liquefied refrigerant is sprayed onto a heat exchanger in the evaporator; it then evaporates and absorbs the heat from the material flow to be cooled. Water/lithium bromide or ammonia/water are normally used as working pairs. “The achievable heat ratio of single-stage processes are roughly 0.6 to 0.8 and are dependent on the cold, cooling and hot water temperatures, and the selected solution cycle[.]” [4]. With ammonia/water, the heat ratios are 0.5 to 0.7.

An overview of the commercially available performance capacities for ad/absorption chillers is shown in Figure 40.

The resorption systems are not shown in Figure 40, as, according to current research, commercial systems are still not available. The basic principle rests on the sorption of gas to solid matter and, according to [6], an application for heat pumps/chillers was first presented in literature around 1990. The systems take advantage of the release and absorption of thermal energy during the interaction between solid and gas in order to heat or cool. Two solvent cycles operate in a resorption system. “Compared to a conventional absorption or vapour-compression chiller, the evaporator is replaced by a desorber and the condenser by an absorber. The generation of cooling energy now no longer takes place by heating and evaporating the pure refrigerant, but by expelling refrigerant from a solution at a certain pressure.” [7]. Solid-material resorption systems mostly use chloride salts in which ammonia, used as a refrigerant, is adsorbed and desorbed. By adjusting the material pairing, broad temperature ranges can be covered for adsorption/desorption from -50 °C to 300 °C [6].

The main advantages of this technology over absorption cooling systems are [7]:

- Low amounts of gas (ammonia)
- Lower driving temperatures (suitable for coupling with CHP waste heat)

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[26] The heat ratio describes the thermal efficiency of ad/absorption chillers and, according to [3], is defined as the absorbed heat (gain) divided by the supplied driving heat (cost). The operating energy for auxiliary systems (esp. compressors/pumps) is not taken into account.

- Lower system pressure
- Avoidance of rectification

However, the two cycles required for this also need additional pumps and heat exchangers as well as an additional material flow (mixed flow). The mixed flow is necessary to ensure continuous operation, as otherwise the solution depletes on the cold side [8]. A demonstration system with a cooling output of 50 kW$_{th}$ has been installed at the Commercial Academy Freiburg [7] and a 25 kW$_{th}$ system is in operation as a test facility at TU Dresden [8].

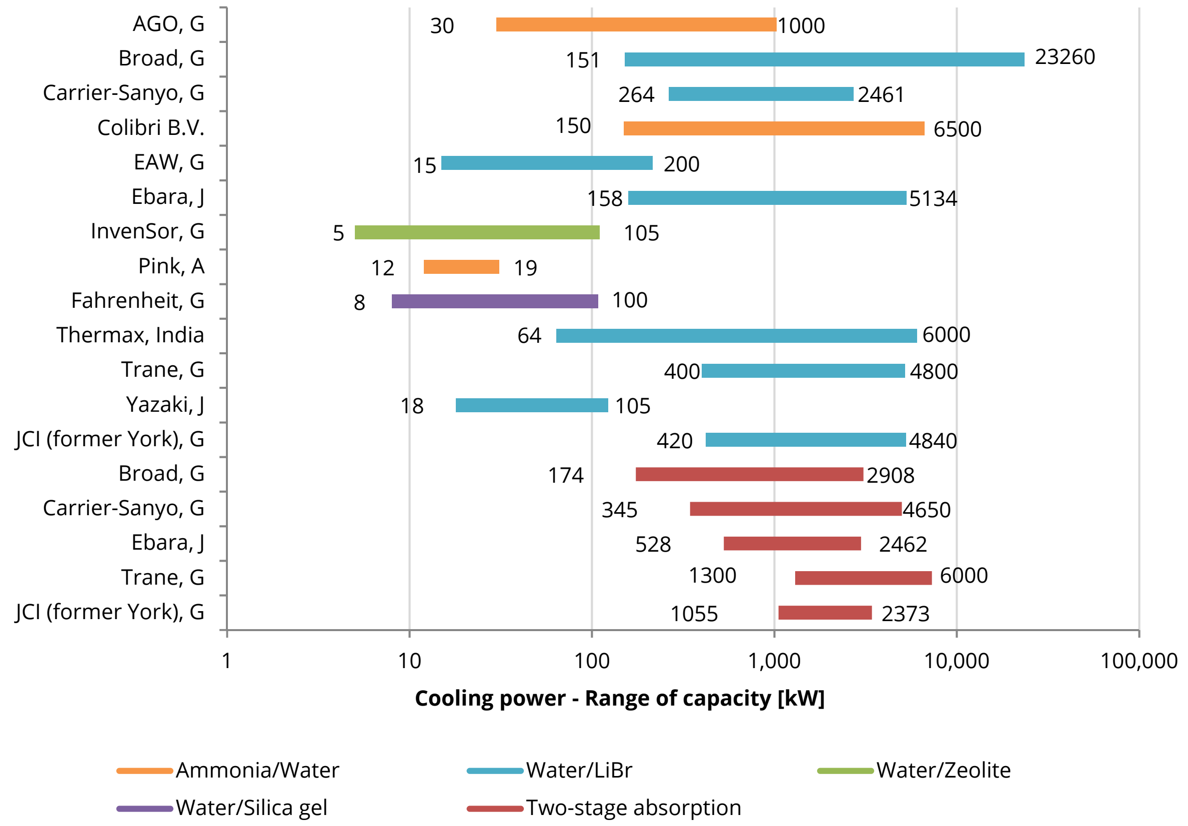

Figure 40: Output range of commercial ad/absorption chillers (above single-stage, below two-stage absorption systems), based on [4] and expanded

In steam jet cooling systems, a jet of steam is expanded through a steam jet vacuum pump. This reduces the pressure of the liquid to be cooled (usually water for cold water supply) in a connected evaporator. When the pressure of the steam falls below a certain value, the medium to be cooled (usually water) gives off heat due to the onset of evaporation. A boundary is formed by the freezing point temperature of the medium to be cooled [9]. Steam jet cooling systems are used in particular for industrial cold water supply when waste steam is available from other sources. The systems are state-of-the-art technology and are commercially available up to 20 MW$_{th}$ [10], for this reason they should be regarded as technically mature (TRL 9) and do not need to be considered in further detail.

12.2. Estimation of potential

a) Technical development potential

The majority of cooling energy needed is currently produced in situ using vapour-compression chillers. Cold supply can be optimized by enhancing the efficiency of the smaller local chillers and by using district cooling.

A very high technical degree of development can be established for *vapour-compression chillers*. Further developments are being made primarily in the optimization of system components:

- Optimization of the heat exchangers
- Development of additional refrigerants
- Further development of turbo compressors with smaller outputs
- Flexible application of the vapour-compression chillers when possible, e.g. load flexibility by means of cold storage [11]

As a thermodynamic cyclic process is involved, the following are also a part of optimization: internal recuperation, the use of multi-stage compressors, intermediate expansion and, where applicable, the separation into multiple cooling circuits to optimize the temperature spectrum [12], [13]. In addition to new refrigerants, natural refrigerants such as carbon dioxide and ammonia are increasingly being put to use, since they exhibit a low ozone depletion potential and greenhouse gas potential.

In the *district cooling* sector, cooling power should be provided centrally and generated primarily by means of free cooling (oceans, rivers, lakes). If this is not possible, ad/absorption chillers are normally used at first and then vapour-compression chillers to cover peak loads [14]. The available system outputs for *absorption chillers* are substantially higher than those for adsorption chillers. The electrical power requirement is approximately 5 % of the cooling output and the required waste heat temperature is 70 - 80 %, so a variety of heat sources can be utilized [15]. Very low cooling temperatures of -77 °C are possible to some extent. Aspects considered disadvantageous are the large plant dimensions compared with vapour-compression chillers as well as the low thermal efficiency [15]. The current development approaches in research are summarized in Figure 41. The approaches with blue borders in Figure 41 belong to the conventional optimization measures (internal recuperation, flash tank for intermediate expansion, design of the separating columns in NH_3/water systems). The multi-stage models in particular (red border), with modified heat exchangers and system dimensioning as well as reduced pump outputs, lead to substantially improved COP values of 1.2 to 1.4 compared to the base case with approximately 0.7. Double-effect plants are already commercially available up to 11 MW_{th} [16]. The output of an absorption chiller is heavily dependent on the physical-chemical properties of the working substance. These can be modified by additives (yellow border) to improve, for example, the separability of the refrigerant from the salt solution. Entirely different working mediums are also used, such as ionic liquids, which open up many combination possibilities due to their large number. Yet so far, they have not produced better results over water/lithium bromide (technical modification requirements for very different material properties) [4].

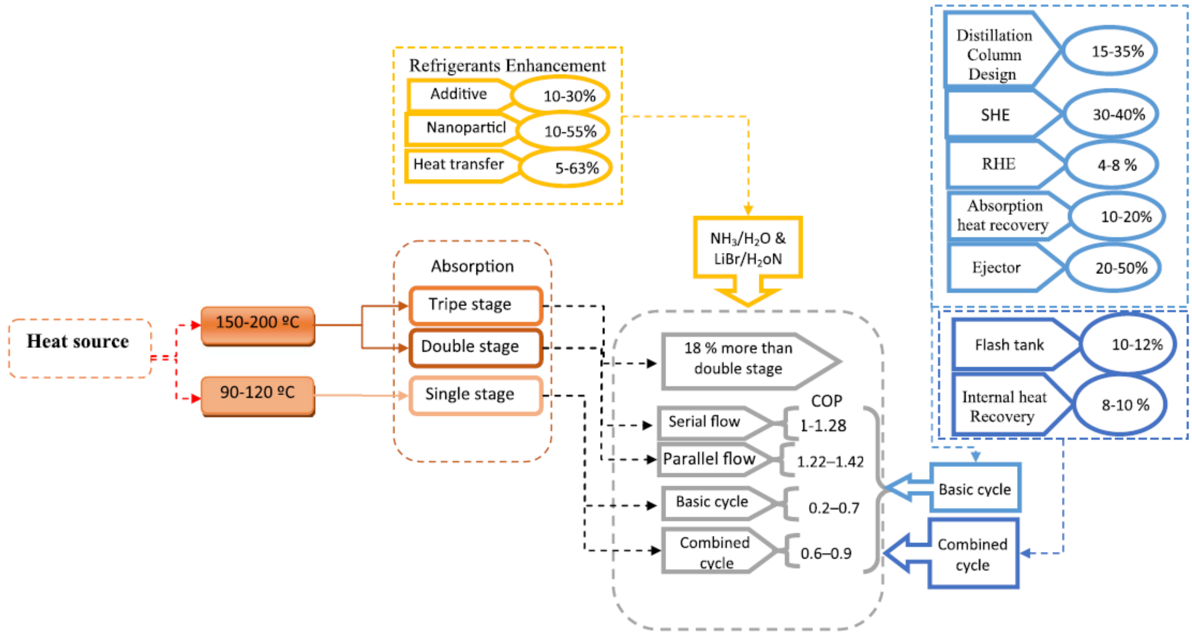

Figure 41: Research and development approaches for absorption chillers [15]

Compared to absorption chillers, *adsorption chillers* have various advantages [17]:

- Relatively simple design, few moving parts, low maintenance
- No crystallization or corrosion problems (materials used are unproblematic – water, zeolites, silica gel)
- Broad temperature range of heat sources possible (from 50 °C to 500 °C)

But also disadvantages such as:

- High requirements for the vacuum seal of the container
- Low COP compared to absorption technology
- Relatively large specific mass and volumes

The heat ratio for adsorption chillers depends primarily on the working pair used. An overview in [17] shows an array of possible combinations (e.g. activated carbon (powder) with methanol, ethanol, R134a, etc.), which were tested on a laboratory scale. The heat ratios were not improved, but higher specific cooling outputs ($kJ/kg_{Sorbent}$ and $W/kg_{Sorbent}$) were recorded, which may ultimately lead to more compact plants.

A core problem with *resorption chillers* is the low output figure[27], which should be improved by different process variants. This includes coupling the reactors to internal recuperation, modifying the material pairings and combining different sorbents as well as

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[27] The output figure, similar to the coefficient of power, indicates the ratio of the cooling output to the electrical energy used.

installing multi-stage sorption cooling systems with heat recovery [6]. According to information in [6], a variety of possible resorption systems are being developed and tested in experimental prototypes and in theoretical modelling experiments. The thermodynamic analyses still need to consider the variation of the thermodynamic properties during adsorption and desorption (pressure hysteresis) on a fundamental level. Overall, the field of resorption chillers is determined by research-based demonstration systems and no commercial provider has yet been able to establish itself [8], [7].

b) Expansion potential

To quantify the expansion potential for power-to-cold plants, the cooling requirement must first be determined. The present cooling requirement in Germany is presented in section 12.3. It is near impossible to estimate from today's perspective to what extent the cooling requirement will expand, and relevant research projects (e.g. Heat Roadmap Europe 4) are still in progress. However, the following tendencies are presented in [18] with particular reference to Hamburg:

- Increasing power consumption due to rising demand for cooling and air conditioning (increase in comfort standards, growth of building stock) – in particular due to the use of de-centralized room air conditioners
- District cooling remains limited to the existing district cooling network (no expansion/development of new networks)
- Increased energy efficiency in the cooling and air conditioning sector due to inspections and legal requirements

Therefore, if the total cooling requirement is assumed to be approximately constant, further assertions can be made about the expansion potentials of the technologies mentioned above. Vapour-compression chillers are not taken into account, as they represent state-of-the-art technology and could meet any additional requirement. This leaves the ad/absorption chillers to be examined for their expansion potential. The substitution potential for Germany was determined in [4] for this purpose. The results are shown in Figure 42 and Figure 43. Figure 42 reveals that in the industrial application sector (industry and food production), considerable quantities of waste heat could be used as energy for cooling. Yet according to Figure 43, this does not lead to equal savings in electrical energy when we take into account the electrical energy requirements of ad/absorption chillers for pumps, ventilators, etc. This is illustrated by the liquefaction of gases in the chemical industry, where electrical energy in the amount of approximately 7,500 GWh_{el}/a is being used to cover the cooling requirement of around 1100 GWh_{th}/a at very low process temperatures [4]. Figure 42 and Figure 43 also show that building air conditioning seems to offer little potential. This is only plausible on the premise of de-centralized cooling supply. When using district cooling networks, the cooling medium can be refrigerated centrally by using industrial compressors, large-scale absorption chillers or, where applicable, natural cold water sources (rivers, lakes, oceans), which are more efficient in comparison to local vapour-compression chillers [19].

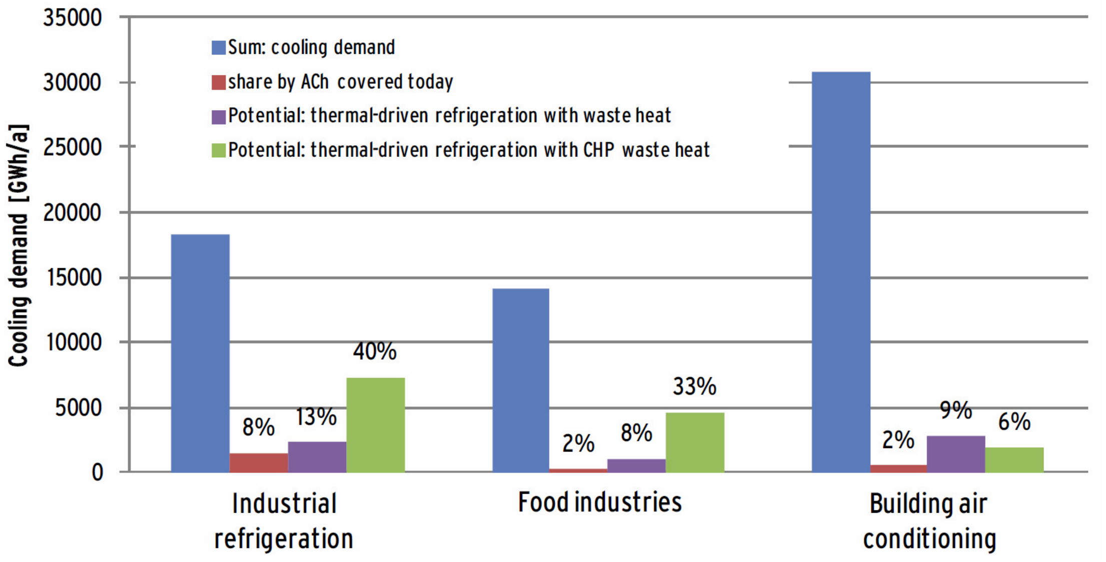

Figure 42: Substitution potential for vapour-compression chillers [4]

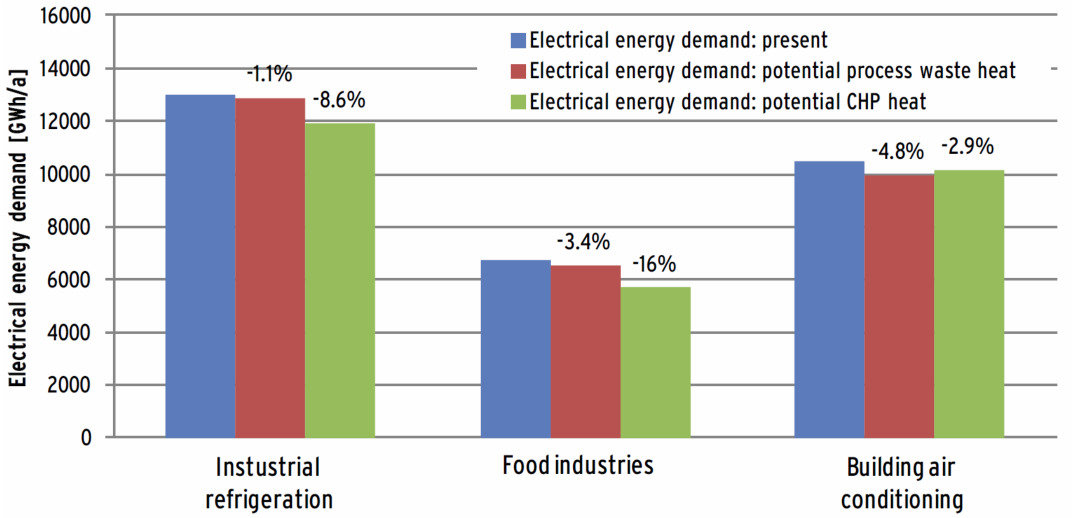

Figure 43: Saving electrical energy by substitution of vapour-compression chillers [4], including auxiliary energy

12.3. Representation of the achieved state of expansion

The current final energy requirement (2013-2017) for cooling purposes is 200 PJ/a and 55.6 TWh_{End} (corresponding to ~ 2.3 % of the entire final energy requirement) and fluctuates with the climatic boundary conditions. Figure 44 shows that this cooling requirement is covered almost exclusively by electrical vapour-compression chillers and is consequently responsible for approximately 11 % of the electricity requirement [20].

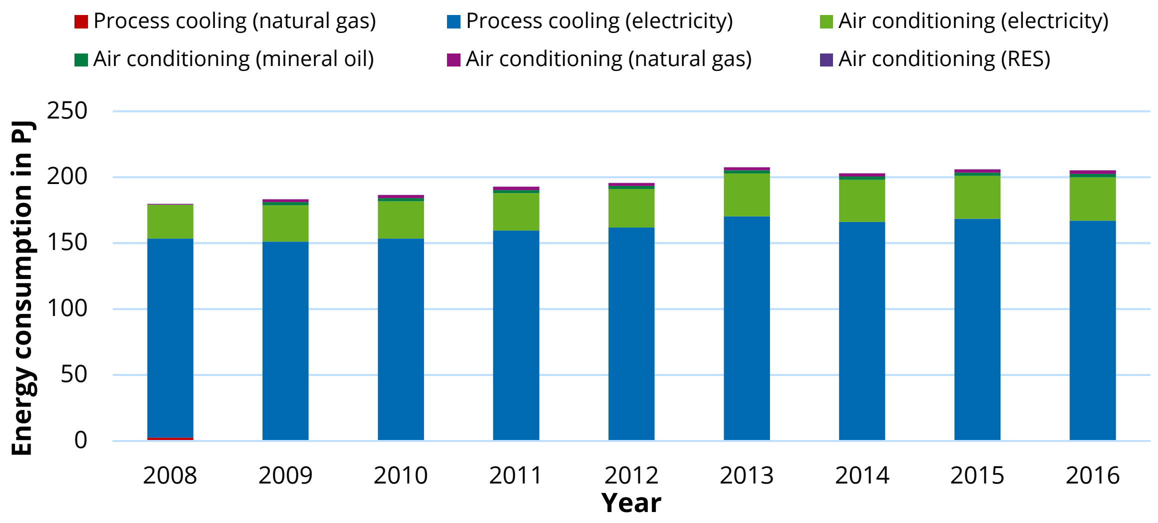

Figure 44: Energy consumption in Germany for the supply of cooling energy [20]

District cooling networks in Germany are only found in scattered locations around the country, for example in Hamburg, Munich and Berlin. In addition, some larger industrial sites have their own networks, such as Frankfurt Airport [19]. Meanwhile, in Finland and Sweden far larger district cooling networks are operating with chillers in the MW range. Table 20 shows a selection of large chillers in Europe and gives an indication concerning the plant sizes implemented to generate district cooling.

Table 20: Chillers in Europe for the generation of district cooling

Location	Cooling output (usually 6°C/12°C flow/return)
Uppsala	- 11 MW_{th} at the waste-to-energy plant (absorption chillers) - 3*8 MW_{th} vapour-compression chillers - 4 MW_{th} absorption chillers by means of district heating
Växjö	2x2 MW_{th} + 0.3 MW_{th} absorption chillers
Stockholm	280 MW_{th} (sea water, absorption chillers, vapour-compression chillers)
Helsinki	135 MW_{th} (sea water, 10x3.5 MW_{th} absorption chillers, 60 MW_{th} vapour-compression chillers)
Berlin	44 MW_{th} absorption chillers with district heating from CHP Mitte
Vienna	Several sites, e.g. 20 MW_{th} absorption chillers at main train station
Berlin	Total: approx. 50 MW_{th} - 4 * 2.5-3 MW_{th} (absorption chillers, water/lithium bromide) - 10 * 3.7-4.0 MW_{th} (vapour-compression chillers, R134a) - 1.6 MW_{th} (vapour-compression chillers)

12.4. TRL assessment

The power-to-cold technologies presented here are already commercially available up to a certain scale. The actual performance capacity is limited on an international level primarily in the adsorption sector. Additionally, the displacement of vapour-compression chillers by the comparatively mature absorption chillers has not led to substantial savings from an electrical standpoint in the industrial sector. There is a need to promote development of sorption chillers in the industrial sector for particularly low temperatures

(< 0 °C). Alongside the individual technical solutions, the systematic, optimized integration of chillers and heat pumps in existing processes represents a significant potential, according to [2]. The TRL classification in Table 21 below can be derived from the aspects presented in this chapter:

Table 21: Results of the TRL analysis

Technology	TRL	Supplementary sources
Vapour-compression chillers up to 20 MW_{th}	9	
Steam jet cooling systems up to 20 MWth	9	
Absorption chillers		
• **Single-effect, COP ~ 0.8 to 6.5 MW_{th}**	9	
• **Double-effect, COP ~ 1.2 to 4.5 MW_{th}**	9	
• **Additive/nanoparticle**	4	
Adsorption chillers COP 0.5-0.7		
• **Water/silica gel to 100 kW_{th}**	9	
• **Water/zeolite to 75 kW_{th}**	9	
• **Alternative material pairings**	4	
Resorption chillers	5	

12.5. References

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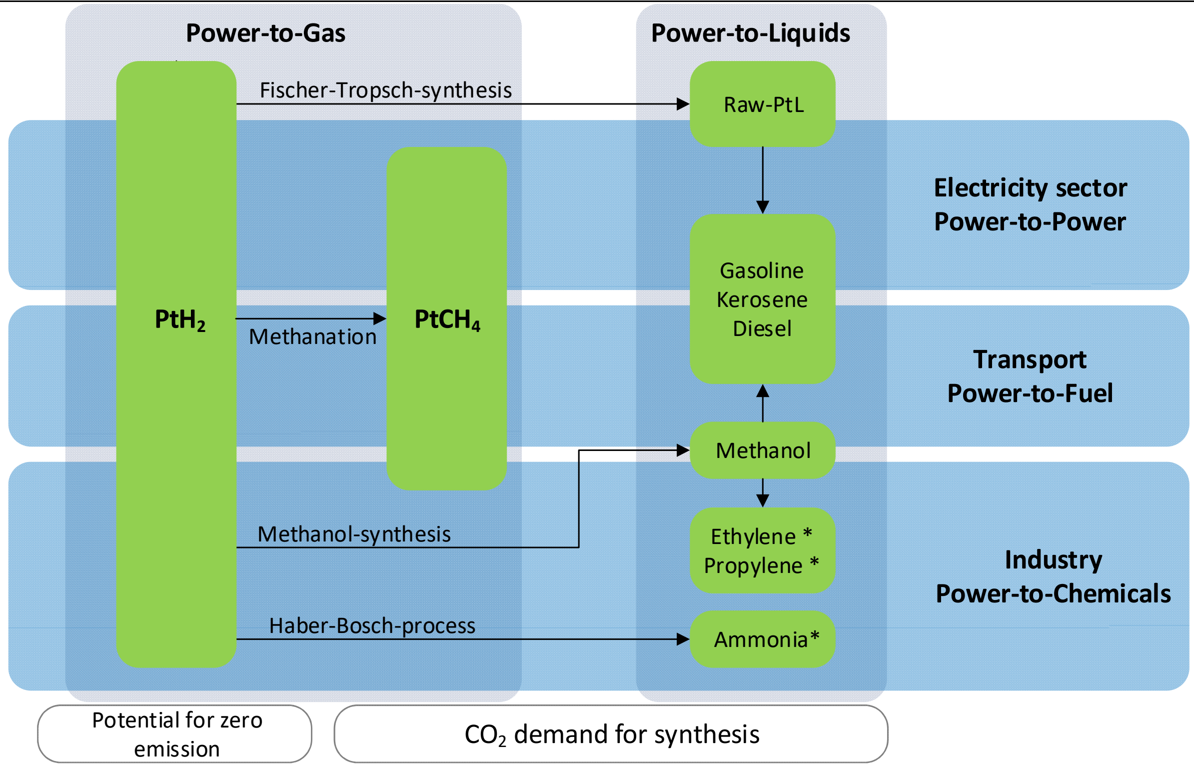
13. Power-to-chemicals

13.1. Technology description

This chapter addresses the power-to-chemicals (PtC, P2C) branch of technology, which represents a key pillar in the concept of sector coupling and encompasses several sub-fields (see Figure 45):

- Power-to-gas (PtG): the use of electricity to produce hydrogen or to further process this hydrogen to methane (methanation)
- Power-to-liquids (PtL): the use of electricity to produce liquid, mostly hydrocarbon-based energy sources, which can then be used for mobility (power-to-fuels) or chemical processes (power-to-chemicals in the sense of Figure 45)



* Liquid transport (under pressure)

Figure 45: Overview of power-to-chemicals, based on [1], translated

Since hydrogen and methane are also chemical raw materials, the term power-to-chemicals should here include the PtG and PtL processes. This chapter addresses the following technologies:

- Electrolysis processes (PtH_2)
- Methanation
- Methanol synthesis
- Fischer-Tropsch synthesis (FTS)

The Haber-Bosch process is not considered further, as technical maturity cannot be debated and ammonia is of little importance as a product for further use in energy production. Figure 45 also indicates that the basis for PtC is always the production of hydrogen. Various processes (including regenerative) can be used for the production of hydrogen itself (cf. Figure 46).

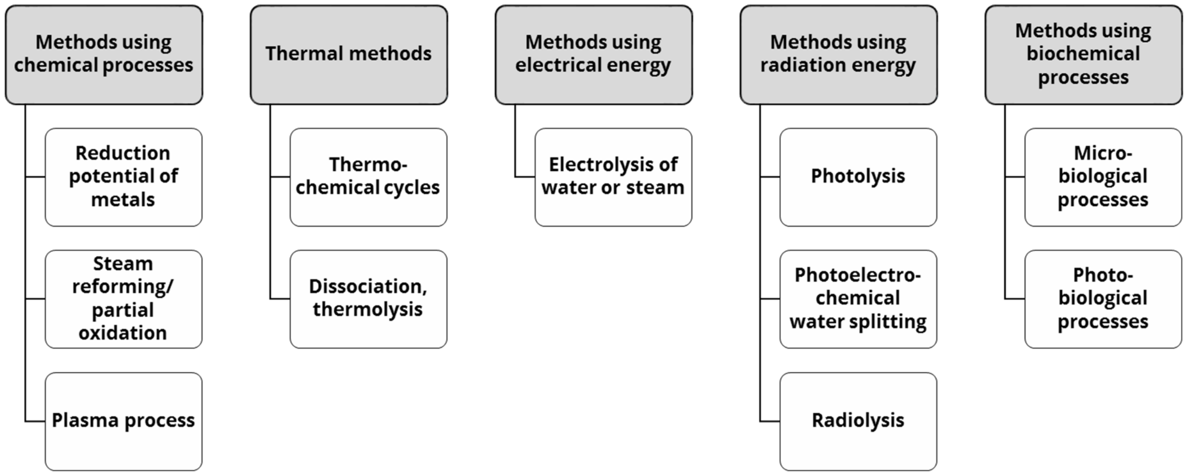


Figure 46: Process overview for hydrogen production

All of the processes mentioned here are generally subject to patents or at least laboratory regulations. So far, however, the only processes that have been successfully implemented on an industrial scale are electrolysis and the reforming of hydrocarbon raw materials (steam reforming of natural gas, gasification of coal, partial oxidation of oil). Reforming accounts for over 95 % of global hydrogen production [2].

Electrolysis therefore represents the central technology in transforming electrical energy into chemical energy sources for the German energy revolution. First the physical principles will be outlined before examining the technology of electrolysis cells. Water splitting as a chemical equation is represented as follows (equation (8)):

$$H_2O \rightarrow H_2 + 0{,}5\ O_2 \tag{8}$$

The reaction is endothermic, and the molar standard enthalpy of formation for liquid water is -285.83 kJ/mol. The required thermodynamic cell voltage (thermoneutral cell voltage) is calculated from the enthalpy of formation using Faraday's law (equation (9)) [3]:

$$V_{tn} = \frac{\Delta H_R}{zF} = 1{,}48\ V \tag{9}$$

When only the free enthalpy of reaction (Gibbs energy, -237.13 kJ/mol) is taken into account, the result is the minimum or reversible cell voltage needed to decompose water electrolytically (equation (10)) [3]:

$$V_{tn} = \frac{\Delta G_R}{zF} = 1{,}23\ V \tag{10}$$

This theoretical decomposition voltage is dependent on pressure and temperature. The gradients are shown in Figure 47 a) and b).

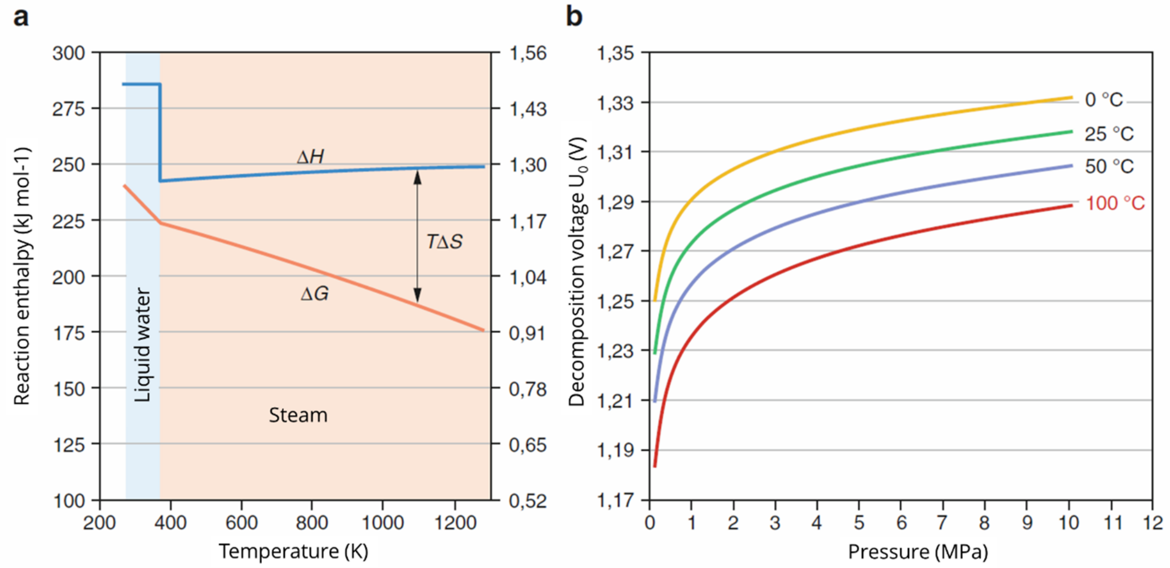


Figure 47: a) Temperature and b) pressure dependence of the theoretical decomposition voltage of water electrolysis [3], translated

Two central conclusions can be derived from Figure 47. Firstly, at high temperatures, the electrical energy needed to decompose water can be substituted with thermal energy. Secondly, the electrolysis produces two gas molecules from one water molecule. According to Le Chatelier's principle, electrolysis should occur at low pressures. High pressures require greater decomposition voltages.

Electrolysis systems have a similar basic structure, which is shown in Figure 48. The supplied water needs to be deionized so that no unwanted secondary reactions occur in the respective cell. Since electrolysis uses direct current, the alternating current from the German distribution grid must first be rectified. Furthermore, practical material conversion is never total, so the resulting product gases need to be separated from the water vapour.

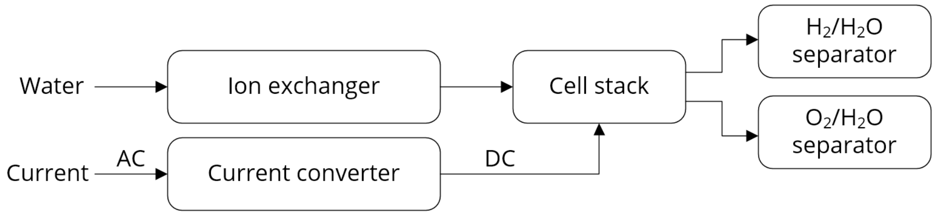


Figure 48: Basic structure of electrolysis systems according to [4], translated

Three different electrolysis cell types have been developed based on these principles; their basic composition is shown in Figure 49:

- Alkaline electrolysis cells
- Proton exchange membrane electrolysis (PEM electrolysis, partly SPE – solid polymer electrolyte)
- High-temperature electrolysis

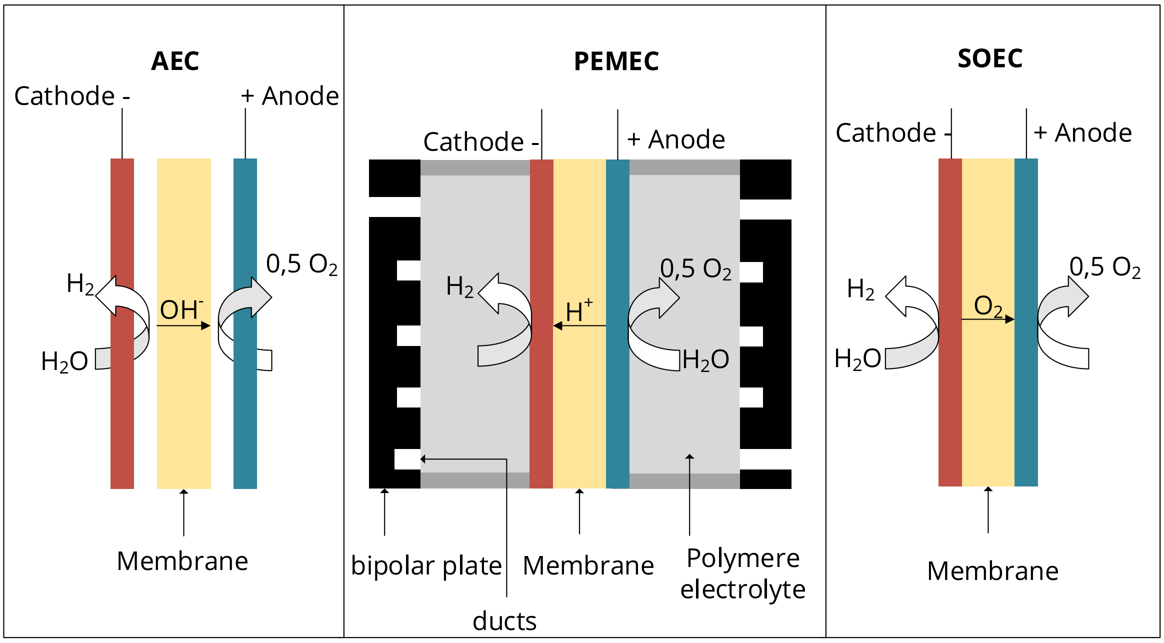


Figure 49: Cell structure and electrode reactions of electrolysis, based on [4], translated

The features of the cell types are briefly presented below. The performance data is summarized in Table 22. To ensure a sufficient overview, the manufacturers of commercial systems for alkaline electrolysis and PEM electrolysis are listed in section 13.5.

Alkaline electrolysis

The cell of an alkaline electrolyser consists of two half cells, which are separated by an ion-conducting membrane, the diaphragm. Two large electrodes containing suitable catalysts such as Raney nickel or noble metal oxides (ruthenium and iridium compounds) are located close to the membrane [5]. The electrolyte is water mixed with 30–40% potassium hydroxide[28] (KOH) by weight. This increases the conductivity and reduces the internal resistances within the cell, achieving an increase in efficiency. In operation, the water on the cathode side becomes atomic hydrogen and hydroxide ions. The hydrogen molecules are separated from the water and transported away. The hydroxide ions diffuse through the membrane to the anode side, where they react to form water and atomic oxygen. Constant circulation of the electrolyte is required for a homogeneous distribution of the charge carriers. At low loads, the currents caused by the rising gas bubbles are sufficient for this. However, at high loads active stirring is required [6]. A disadvantage of alkaline systems is the corrosive atmosphere that the electrodes and seals are exposed to. The flexibility is also limited. Once an electrolysis system is switched off, it needs about 30–60 minutes to restart [7]. Before restarting, the cells must be rinsed, as the dissolved gases in the electrolyte at partial loads and during intermittent operation lead to gas impurities (safety shutdown from 2 % H_2 in O_2) [8]. During operation, the alkaline electrolyser reacts very quickly to load changes. In [9], load variations between 25–100 % have been realized in under one second on a 40 kW_{el} electrolyser. The

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[28] Sodium hydroxide was also previously used, but steel and nickel electrodes corrode more heavily.

manufacturer ELB states that alkaline electrolysers can be operated in partial loads of 25–100% and that the range can be extended further by interconnecting several rectifiers with different outputs as well as by employing improved thermal management. The rectifier limits the load change rate [10]. Operation under pressure is possible and is more energy efficient than subsequent compression of the gas. The efficiency of alkaline electrolysis varies over the operational period and decreases with time (degradation). Initially, the electrodes are "activated" (application of noble metals or nickel sulphide activation) and the required cell voltage is greatly reduced, lowering the energy required by 0.3–0.8 kWh_{el}/Nm^3. The service life is 2–3 years [10].

The largest systems for water electrolysis have been realized in conjunction with hydroelectric power stations, with the hydrogen being used for the production of fertilizer (Aswan Dam, 200 MW_{el} for the Egyptian Chemical Industries, 1963 [11]; 135 MW_{el} Glomfjord, Norway for Norsk Hydro, 1953 [12]). A list of manufacturers of alkaline electrolysis systems is shown in Table 25 at the end of this chapter.

PEM electrolysis

"A PEM electrolysis cell [...] consists of a proton-conducting membrane (proton exchange membrane, PEM), which is sandwiched between the electrodes [29] to form what is known as the membrane electrode assembly (MEA). A solid polymer electrolyte (SPE), such as Nafion, is applied to the electrodes. It is highly porous and causes the current to flow from the bipolar plates to the electrode and transports water to the electrode as well as the product gases away from the electrode." [6] Water is conducted to the anode via channels in the bipolar plates and the product gases are transported away. In the anode, the water is split into atomic oxygen, two protons and two electrons. Oxygen molecules are then formed from the atomic oxygen. The protons diffuse through the membrane to the cathode and combine with electrons to form hydrogen [6].

According to [13], PEM electrolysis is characterized by the following features:

- A high operating pressure has practically no influence on the power requirement (cf. polarization curves[30] in Figure 50)
- In contrast to alkaline electrolysis, PEM electrolysis does not need to be kept at operating temperature
- Flushing with an inert gas or applying a protective voltage is not necessary
- PEM electrolysis starts immediately when switched on, without a preheating phase
- "The MEA determines the service life; the [bipolar plate] generates the costs"

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[29] The catalyst layers on the electrodes are composed of noble metals (platinum or iridium) due to the acidic proton-conducting electrolyte (ionomer) and the high anode potential from the noble metals (platinum or iridium) [4].

[30] Characteristic interrelation of the real cell voltage depending on the current density for a certain cell structure [14]

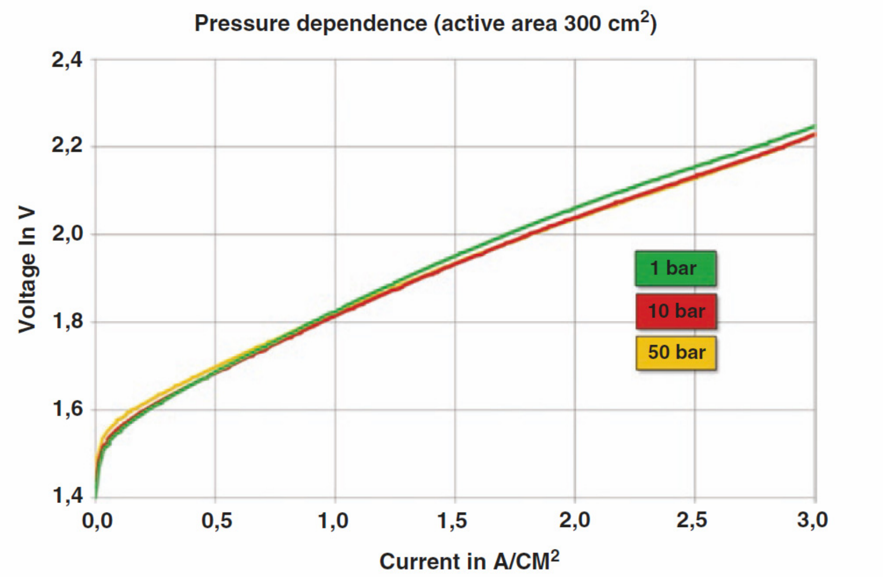

Figure 50: Pressure influence in PEM electrolysis [13]

[13] states that for scaling to large systems, efficient distribution of the water and the temperatures (thermal management) in the cells plays a crucial role, as otherwise the deprived areas reduce the efficiency and service life.

The load flexibility of PEM electrolysis, like that of alkaline electrolysis, was tested for a 40 kW_{el} PEM system in [9]. The reaction time, under one second, is shorter than with alkaline electrolysis. PEM electrolysis needs 387 seconds to start up (cold start 0–100 %) and 63 seconds to shut down. Furthermore, PEM electrolysis exhibits an overload capacity up to 200% (alkaline electrolysis likewise up to 150 % [15]). As a result, the required power build-up for electrolysers can be significantly reduced and efficiency losses can be accepted for a few overload hours per year [16]. The adjustment of the operating range can be summarized as follows:

“The operating range is limited by technical specifications, such as operation within a specified efficiency range, for a required service life or while maintaining a specified gas purity. At high current densities, the operating range is limited primarily by the level of efficiency that has to be maintained and by the expected service life. Increasing stack losses with rising current density reduce the efficiency of the electrolyser. Voltage also rises, resulting in an expected increased risk of corrosion and reduced service life. Cell voltages are therefore typically limited to 2–2.2 volts. [...] The gas purity of the anode side can be used in addition to efficiency to determine the lower limit of the operating range. The gas purity is taken into account based on safety-related considerations, since permeation of hydrogen to the oxygen side above four percent by volume leads to the formation of an explosive mixture.” [14].

The higher current density in a PEM electrolysis system (range 0–2 A/cm², see Figure 50) compared to an alkaline electrolysis system (0.1–0.4 A/cm², 1.6–1.8 V cell voltage) [17] causes the former to have a significantly higher output density and therefore a more compact design. A list of manufacturers for PEM electrolysers is shown in Table 26 at the end of this chapter.

High-temperature electrolysis

High temperature electrolysis is also known as steam electrolysis and is implemented in a solid oxide electrolysis cell (SOEC). An O^{2}-conducting solid electrolyte separates two half cells from one another. Superheated steam is conducted on the cathode side into the half cell, where it reacts with two electrons to form O^{2-} ions and hydrogen. The hydrogen is transported away with surplus steam and the O^{2-} ions travel by means of diffusion through the solid electrolyte to the anode, where the O^{2-} ions loose two electrons and react to form oxygen, which is then transported away [6]. Yttria-stabilized zirconia (YSZ ZrO_2 with 8 mol-% Y_2O_3) is most often used as the electrolyte due to its high conductivity as well as its thermal and chemical stability. The cathode catalyst is nickel, and lanthanum strontium manganite is used for the anode catalyst [4]. The key problems associated with solid electrolysis are the service life of the ceramic materials and the long-term operation. Solid electrolysers can be operated very flexibly as long as the cell is kept at operating temperatures.

The output parameters of current electrolysis systems are given in Table 22. The data provided illustrates the advantages and disadvantages of the aforementioned cell types. The corresponding efficiency of electrolysis systems has so far not been described in detail, as different benchmarks and scopes for the data exist in the literature. It is imperative that these factors are taken into account for a uniform representation. On the output side of an electrolyser, the hydrogen is the target product from an energetic standpoint (lower heating value (LHV): 3 kWh/Nm³ and higher heating value (HHV) 3.54 kWh/Nm³). The value changes depending on whether the HHV or LHV is used in the efficiency equation (= benefit/cost). Furthermore, to some extent only the energy requirement of the cell stack is calculated as cost. The approach is justified for the comparison of laboratory cells, yet it falls short of the mark for large systems with supporting equipment (pumps, compressors, control systems, conversion of AC/DC). Therefore, for an overall view, the system value should be used as the cost. Using the HHV in the numerator may be useful if the evaporation enthalpy of the water produced is actually used energetically during thermochemical utilization of the hydrogen (or subsequent products). With regard to Table 22, it is clear that the system efficiency for an efficient alkaline electrolysis system with 3 kWh/Nm^3_{H2} / 4.5 kWh_{el}/ Nm^3_{H2} is only approximately 66.7 %. For solid electrolysers, the thermal input must also be taken into account as cost.

Table 22: Overview of the important characteristics of current electrolysis systems based on [18]

Parameter	Unit	Alkaline electrolysis	PEM electrolysis	Solid electrolysis
Operational experience		For 80 years	For 20 years	No commercial products, R&D
H_2 production rate per module	Nm^3/h	< 760 modularly expandable	< 540 modularly expandable	42 Nm^3/h*
Electrical output per module	MW_{el}	< 3.4 modularly expandable	< 3.0 modularly expandable	Approx. 0.2 available from 2016
Operating temperature	°C	40 – 80	90 – 100	750 – 1000
Operating pressure	MPa	< 3.2	< 3.5	< 3.0
Spec. Energy consumption	kWh/Nm^3			
• **Stack**		4.1 – 5.0	3.9 – 5.1	3.3 (power) 0.4 (heat)
• **System**		4.5 – 7	4.5 – 7.5	3.44 (power) 0.40 (heat)
System efficiency (LHV_{H2}/W_{el})	%	66.7 - 42.9	66.7 - 40	87.2 (without heat)
Hydrogen purity	%	99.5 – 99.9 operation dependent**	99.5 – 99.9 operation dependent**	> 99.5% **
Minimum partial load	%	5 – 40	0 – 10	3
Load gradient	%/s	< 1	10	"Hot standby": 0.05 Cold start (0 – 100): Hours
Maintenance requirements	h/year	< 20	< 200	No data
Service life / Stack change	Years	10 (guarantee)	10 (guarantee)	Degradation: 0.7 – 1.6 per 1000 h
TRL	-	9	8	5

* Pilot system at a test rig of the U.S Navy in California: ** > 99.995% also possible with DeOxo drier

Methanation

Methane synthesis uses the hydrogen generated from electrolysis to produce methane together with CO_2. The advantages of methane are the higher energy density as well as the purity of the synthetic natural gas and, therefore, straightforward and diverse usability. However, the efficiency loss of the overall process, caused by the additional conversion step, should be mentioned as a disadvantage [6]. In principle, methanation can be divided into two types: chemical/catalytic methanation and biological methanation (see chapter 9 Biomass). Chemical/catalytic methanation is the focus here.

Two equilibrium reactions occur in chemical methanation. The first is the water-gas shift reaction in which the CO_2 is separated, and the second is the CO methanation:

1. Water-gas shift reaction: $H_2 + CO_2 \rightarrow CO + H_2O$ (11)
2. CO methanation: $3H_2 + CO \rightarrow CH_4 + H_2O$ (12)
3. Overall reaction: $4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$ (13)

Direct methanation is also possible. The dominant reaction path is debatable. Methanation is exothermic and the reactor must be uniformly cooled to avoid hotspots. Catalysts are used to further lower the operating temperature. Suitable examples are nickel, rhodium, ruthenium and cobalt. In most cases, nickel is chosen as the catalyst due to its high activity and selectivity as well as the low cost. Chemical methanation places high demands on the gas purity, as the catalysts are susceptible to gas impurities (sulphur in particular) and in the worst case can be deactivated [7].

Chemical methanation typically takes place at a temperature of 200–550°C and a pressure of 1–100 bar. There are various reactor concepts for chemical-catalyst methanation; their properties are summarized in Table 23.

Table 23: Advantages and disadvantages of the methanation reactor types [4]

Reactor	Advantages	Disadvantages
Fixed-bed		
• **Adiabatic**	Simple system, low capital costs	Hotspots, unsuitable for intermittent operation
• **Polytropic**	Low capital costs	Thermal management
Monolithic	Relatively high specific catalyst surface, small pressure drop, quick response time	Uneven gas distribution Up-scaling limited
• **Ceramic monolithic**		Brittle
• **Metallic monolithic**		Short service life
Micro-channel	Excellent thermal transfer	One-way system Up-scaling limited
Membrane		Membrane replacement Membrane costs
• **Partial input of a reactant**	Good temperature regulation	
• **H_2O permeation**	High CO_2 conversion	
Sorption	Almost 100% CO_2 conversion Relatively low operating pressure	Discontinuous operation management Regeneration cost

The adiabatic fixed-bed reactor is the most state-of-the-art, while the other reactors are still in development for PtG applications. The fixed-bed reactors stand out due to the uniform flow distribution of the catalyst components and long contact periods. The adiabatic version is serial connection of reactors whose temperatures are regulated by intermediate heat exchangers. The main disadvantages of the reactors are the hotspots and the very small range of flexibility regarding the load [4].

Fischer-Tropsch synthesis (FTS)

The Fischer-Tropsch synthesis, named after the two research scientists, F. Fischer and H. Tropsch, who discovered it in 1923, is a process in which various chain lengths can be extracted from synthesis gas, hydrocarbons and alcohols. This catalytic chain growth process was commercialized in Germany before and during the Second World War to manufacture fuel from coal. Discovery of large oil reserves made this process uneconomical after the war, but it has been used since the 1950s in coal-rich South Africa to reduce dependence on oil imports. The main reactions of FTS are [19]:

Alkanes: $$nCO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + nH_2O \quad (14)$$

Alkenes: $$nCO + 2nH_2 \rightarrow C_nH_{2n} + nH_2O \quad (15)$$

The optimal ratio of hydrogen (H_2) to carbon monoxide (CO) in the synthesis gas is 2:1 for olefin (equation (15)) or somewhat higher in the case of paraffins (equation (14)). A product mix of different lengths of hydrogen chains always forms, resulting in the need for a post-synthesis product treatment step in the form of distillation. The chain growth probability alpha (α) and the resulting product distribution can be influenced by selecting suitable catalysts and process conditions [19]. Figure 51 shows the typical product mass distribution as a function of the chain growth probability. The distribution is described by the Anderson-Schulz-Flory distribution statistical model.

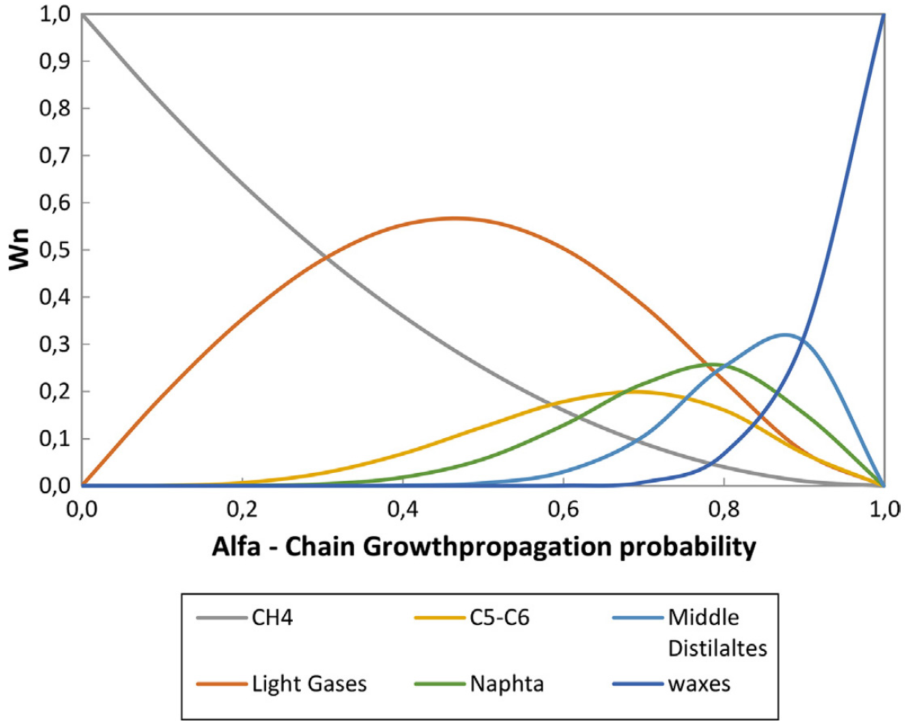

Figure 51: Product mass distribution as a function of alpha (α) [20]

Modern FT catalysts are made of cobalt or iron. Iron catalysts have a low chain growth probability and are used at high temperatures (300–350 °C) for the production of gasoline. The active cobalt catalysts result in greater alpha values, which are preferred for diesel and wax production at lower temperature levels (200–240 °C). Typical pressure levels range from 1 to 40 bar [22]. The use of a catalyst also depends on the synthesis gas used. Iron favours the water-gas shift reaction and increases the synthesis gas ratio (H_2/CO) in the reactor. Therefore, iron is suitable for low H_2/CO ratios, such as in coal gasification. Cobalt catalysts are employed for hydrogen-rich synthesis gas created from natural gas [19]. Values between $0.8 < \alpha < 0.94$ are given in the literature for cobalt catalysts [20], which is why middle distillates are the primary product of cobalt-based Fischer-Tropsch processes. Further development of FTS initially affected the yield increase of long molecule chains (e.g. Shell Middle Distillate Synthesis – SMDS), as the product composition is easier to control via subsequent hydrocracking under mild conditions [21].

Since FTS is exothermic at high temperatures, it is particularly suitable in conjunction with solid electrolysis, for heating and evaporating the water used. Gas conversion in a rector is never 100 %, so the unconverted synthesis gas and the hydrocarbons produced but not yet condensable are returned to the process. The liquid products are separated into groups in a treatment step and split into shorter hydrocarbon chains if necessary, in order to increase the yield of the desired raw diesel [23].

There is no doubt that FTS is state of the art and is being used on an industrial scale. There are multiple companies worldwide producing synthetic fuels from natural gas using optimized FTS. Examples mentioned are the Oryx gas-to-liquid plant of the South African company Sasol (synthesising 24,000 barrels of raw diesel, 9,000 barrels of petroleum and 1,000 barrels of LPG every day from natural gas) [24] and the Pearl gas-to-liquid plant in Ras Laffan with a daily total output of 140,000 barrels of GtL products [25]. The efficiency of power-to-liquid processes using renewable energy sources is heavily dependent on the electrolysis employed, reaching 65–70 % for solid electrolysis and 55–60 % for PEM electrolysis according to [6].

Methanol synthesis

Methanol synthesis represents an additional alternative in power-to-liquid concepts, and various methods are used to manufacture the gas commercially from synthesis gas. Methanol is one of the most important synthetic chemical raw materials in the chemical industry, where it is used as a solvent and an intermediate product for different product groups. Methanol is also gaining in importance as a fuel additive and substitute [26]. Figure 52 shows the possible applications of methanol.

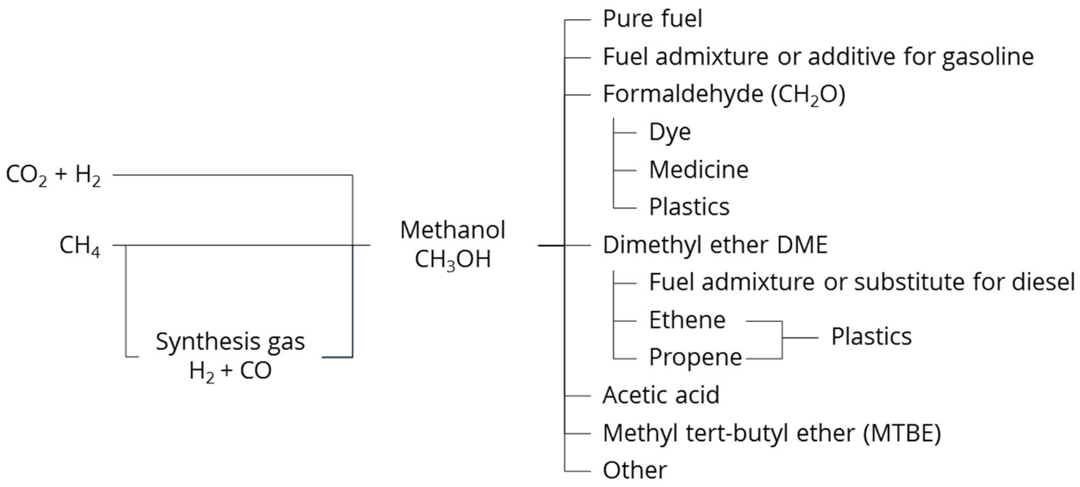

Figure 52: Universal areas of application of methanol according to [6]

The first commercial methanol synthesis operation was run in 1923 by BASF at high temperatures (320–450 °C) and at very high pressures (250–350 bar). Later, sulphur-free synthesis gas allowed more active and selective catalysts to be used (copper-based: $CuO/ZnO/Al_2O_3$), making low-pressure processes for methanol synthesis possible [19]. Figure 53 shows the simplified process of methanol synthesis starting from synthesis gas. The synthesis gas is compressed (approx. 50–100 bar), preheated (200–250 °C) and fed in to the methanol reactor. There it is transformed exothermically into methanol and water. Conversions of 15–25 % are achieved with a selectivity of over 99 % [19]. Then, the still-gaseous reactant is separated and the methanol-water mixture is distilled. The remaining reactants are recirculated, forming large circular flows.

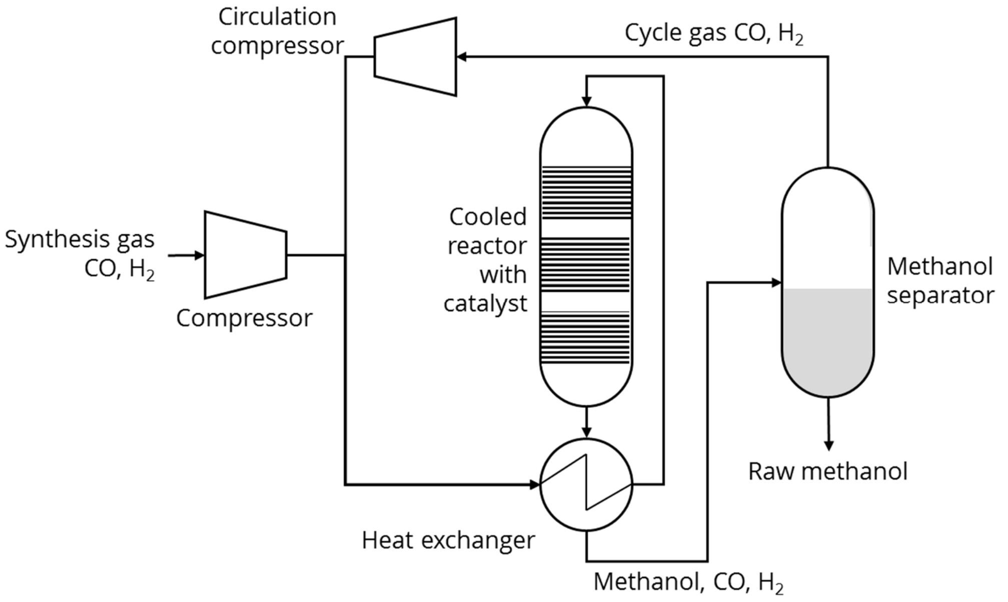

Figure 53: Methanol production based on [27]

Methanol is formed chemically by the hydrogenation of CO and CO_2. Both reactions take place in the reactor, connected via the water-gas shift reaction. The dominant process path has not yet been conclusively researched [28]. Methanol synthesis based on natural gas reforming is also implemented on an industrial scale (various manufacturers – Linde, Mitsubishi Heavy Industries (MHI), Air Liquide and others). An example is the two-step Lurgi MegaMethanol process. It consists of a serial connection of a water-cooled reactor and a gas-cooled reactor with a copper catalyst. Production rates are 2,500–10,000 tons of methanol per day [29]. Several low-pressure methanol process systems have also been realized for smaller production quantities (< 2,500 t/d) [29]. The total efficiency for the natural gas-based production of methanol is approximately 75 % [30]. An industrial electrolysis-based methanol synthesis system is being operated in Iceland by Carbon Recycling International. The plant, named after the chemist and Nobel laureate George Olah, has an overall power requirement of 9.5 MW_{el} covered by geothermal energy, and produces 5.58 $MW_{ch,MeOH}$ and approximately 4,000 t_{MeOH}/a [31]. Plant efficiency is 58.7 %.

13.2. Estimation of potential

a) Technical development potential

This section examines the possibilities for further development of the processes mentioned above.

Electrolysis

The requirements for the further development of electrolysers can be summarized as follows:

"Current research on electrolysers focuses on increasing the efficiency in the entire system of the electrolyser as well as the service life, output density and stack size, reducing the costs (particularly material costs), provisioning of pressurized systems to save on the subsequent compression of the H_2 produced and, last but not least, developing dynamic systems with rapid output changes." [2]

Nevertheless, the approaches for further development of the individual cell types vary.

Alkaline electrolysis

Frequent start-up and shutdown as well as the lower partial-load operation lead to a decrease in efficiency for alkaline electrolysers. Lateral diffusion results in an enrichment of the hydrogen on the oxygen side. Restarting the system currently requires costly leach purification. Exceeding a critical foreign gas concentration results in the system shutting down automatically. This problem could be alleviated, for example, with an adjusted leach flow or a separate leach cycle [8].

PEM electrolysis

Cost optimization is currently of primary importance for PEM electrolysis. The operating principle of the stacks has been proven in long-term operation, and connecting the stacks in parallel can be scale performance. In PEM, the cost drivers are the Nafion membrane and the platinum-plated anodes, and so research is focused on these areas [32].

Additionally, a further increase in pressure is in development to simplify the energy-demanding gas compression for storage. However, an increase in pressure above 200 bar leads to lateral diffusion and gas purity decreases [32]. Proof for long-term load-flexible operation in the MW range is still pending, according to [33].

High-temperature electrolysis

The greatest challenge facing high-temperature electrolysis is the materials used. The materials that are used degrade quickly due to the high operating temperatures, meaning that long-term stability is not guaranteed [7]. The goal is therefore to develop solid electrolytes with which the operating temperature can be lowered and the conductivity of the ions ensured. The operating temperature could also be reduced by means of a thinner membrane (20–50 µm). The high temperature differentials when starting up and shutting down present a further difficulty. The materials are subject to high stresses, the electrodes disintegrate and mechanical damage may occur due to the various expansion coefficients of the different materials [32].

Unitized Regenerative Fuel Cell

Another branch of research concerns the regenerative fuel cell, in particular the unitized regenerative fuel cell (URFC). These are systems that can function both as electrolysis cells and fuel cells. A relatively simple solution is the use of two separated cell stacks, which are housed in one system. The challenge is the harmonization into one cell stack, since the respective reaction conditions are different [34]. The fuel cell chapter 19 covers URFC in more depth.

Methanation

Methanation reactors for power-to-gas plants can operate as stationary or dynamic systems. Stationary operation requires a constant flow of H_2 and thus a large-capacity H_2 store, which increases costs [7]. When the reactor in a dynamic operation is in stand-by mode, it must be filled with H_2, as the catalysts oxidize in a CO_2-rich atmosphere. Also, to enable faster start-up, the temperature should not fall below 200 °C. The large temperature fluctuations in the reactor during heating and cooling present a further risk for the catalysts. This would require the development of catalysts that are better able to withstand these conditions. Therefore, a particular need for research on the stabilization of catalysts against mechanical, chemical and thermal damage or deactivation exists [7]. According to Sterner, proof of stability is yet to be furnished for CO_2 methanation catalysts used in intermittent operation over long periods [6]. The Audi e-gas demonstration project in Werlte, for example, operates with a hydrogen storage system that temporarily stores the H_2 production of the 6 MW_{el} electrolysers for up to an hour [35]. According to [4], the development potential is limited to catalyst research and reactor concepts (see also Table 23). The ideal efficiency of a methanation system is 78 % [36].

Fischer-Tropsch synthesis

FTS is implemented on an industrial scale as a chemical process and is used internationally in GtL systems. The high process maturity makes further development of the process rare. However, it can be further developed in terms of its flexibility and partial load capacity. The German company sunfire GmbH is a leader in utilising electrolytic hydrogen for FTS. There are plans for a project with an electrolyser output of 20 MW_{el} in Herøya, Norway, where continuous hydroelectric power is to be used as the energy source [37]. Research is also being conducted on modified reactor technology (micro-channel reactors) for use in smaller FTS systems. These reactors consist of parallel series of small channels (diameter 0.1–5 mm) that have catalytic surfaces and operate in offset with cooling channels. This allows high material conversion to be achieved with simultaneously improved temperature regulation and miniaturization [38]. The existing systems are on a demonstration scale and work continuously, as they are designed initially as GtL systems for gas flares.

Methanol synthesis

As a basic chemical process, methanol synthesis is a mature process with an efficiency of approximately 75 % (H_2 to CH_3OH). Despite this, the exact reaction mechanism of methanol synthesis has still not been clearly defined. So far, it is not known whether methanol is formed primarily by way of CO hydrogenation, or whether CO_2 hydrogenation plays a more important role. In the latter case, carbon monoxide would serve primarily as the carbon dioxide source for the subsequent hydrogenation, summarized below in the following reaction network (equation (16)) [28]:

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \underset{+2H_2}{\overset{-2H_2}{\rightleftharpoons}} CH_3OH + H_2O \qquad (16)$$

Current research has shown that novel catalysts make it possible to do without carbon monoxide entirely, i.e. a H_2/CO_2 ratio of 3:1 [39]. However, reactor pressures of 300 bar are needed for direct conversion. The George Olah Plant produces 4000 t of methanol per year according to this principle [38]. [30] reports that, in terms of further development, membrane reactors in which the water produced is transported away through a membrane can operate with cost-effective catalysts and high conversions. A next step is “One-step reactors”, in which not just methanol but also derived products, in particular dimethyl ether (DME), form directly in the reactor. Recent research projects focus primarily on load-flexible operation of methanol plants, which can be coupled directly to conventional power plants for CO_2 use [40].

b) Expansion potential

At present, the necessary expansion for PtC variations can only be calculated using scenarios. This involves first calculating the required feed-in and extraction capacities for

PtG concepts, as the additional process steps and products (PtL, FTS, methanol synthesis) would not be principally used to secure the electricity supply. There are a number of studies available that provide feed-in capacities for long-term storage for the electricity sector (see Figure 54).

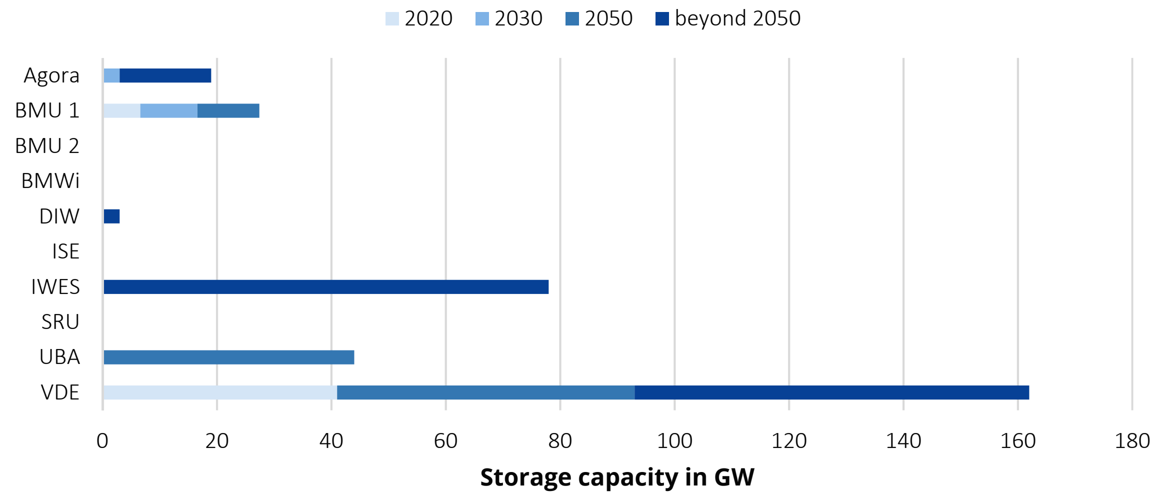

Figure 54: Upper limit of long-term storage requirement in Germany according to storage studies [41], translated

Agora - Agora Energiewende, initiative of the Mercator Foundation and the European Climate Foundation [42]
BMU 1 - German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety [43]
BMU 2 - German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety [44]
BMWi - German Federal Ministry for Economic Affairs and Energy [45]
DIW - German Institute for Economic Research [46]
ISE - Fraunhofer Institute for Solar Energy Systems [47]
IWES - Fraunhofer Institute for Wind Energy and Energy System Technology [48]
SRU - German Advisory Council on the Environment [49]
UBA – German Federal Environment Agency [50]
VDE - Association for Electrical, Electronic & Information Technologies [51]

They range from less than 20 GW_{el} to more than 100 GW_{el}. [52] calculates a maximum feed-in capacity of approximately 133 GW_{el} for PtG processes without considering short-term storage or other flexibility options. As in the chapter on electrochemical storage, the studies exhibit a wide range of power requirements. The flexibility options and storage variants considered (e.g. battery storage) for short-term surplus are the reason for the large deviations. [53] estimates that the power requirement in 2050 will be approximately 30 GW_{el} for PtG and approximately 5 GW_{el} for PtL (in a scenario with 85% CO_2 reduction). The power requirement for electrolytic water splitting to supply PtG, PtC and PtL processes will therefore vary within the mid double-digit GW_{el} range.

13.3. Representation of the achieved state of expansion

The current state of expansion for the various PtC projects in Germany is characterized primarily by demonstration systems. The largest systems already in operation are the Audi e-gas project (6 MW_{el} alkaline electrolysis with methanation [54]) and Energiepark Mainz (6 MW_{el} PEM), and their flexibility is being evaluated as part of the research projects.

Alongside these, there are currently 29 further projects listed on the powertogas.info information platform [35], which also includes PtL projects such as sunfire's. Compared to the projects mentioned above, however, the outputs are significantly lower at approximately 50–300 kW_{el}. An important milestone in scaling could be achieved with the realization of the announced 100 MW_{el} PtG plant by the grid operators Amprion and OGE [55]. The efficiency of the electrolysis in relation to the (lower) heating value is approximately 65 % for the large-scale projects. A detailed list of PtG projects up to 2013 is outlined in [56]. It contains electrolysis demonstration systems that are coupled directly to renewable energy sources as well as systems that are indirectly buffered via battery storage.

13.4. TRL assessment

The PtC processes presented here have each been technically realized to a certain degree and are in part very mature. In particular, the chemical processing of hydrogen from natural-gas-reforming processes to produce liquid hydrocarbons (PtL) occurs on a large scale. With regard to operational capability as part of the German energy revolution, a technical maturity has been achieved for the TRL assessment in the areas of fidelity and scale of testing. However, there is still no proof of a dynamic system that can be interrupted on at least an hourly and up to a daily basis due to a non-continuous energy supply. The operational environment for the technologies (hydrogen from electrolysis, flexible operation) is being tested in multiple German pilot projects but can at best be categorized as "relevant" (simulated + (limited) real input) for the TRL assessment. The TRL is categorized at no more than 7 for the particular application of alkaline electrolysis and the small pilot scales.

Methanation likewise only reaches a TRL of 5 with fixed-bed reactors, as here too the operational environment of the pilot systems only simulates long-lasting flexible operation to a very limited degree. Scaling with target values of several hundred MW_{H2} of hydrogen input also has a limited effect (less than 1/10).

For electrolysis systems, only alkaline electrolysis can be considered mature in terms of scale. Dynamic operation is possible to a limited extent (degradation behaviour), and shutdown and start-up require considerable effort. In contrast, PEM electrolysis exhibits very good dynamic behaviour (with limited service life, ~5 years) but is still restricted in its scalability. The existing pilot systems are too small to determine the prospects of a scenario with several hundred MW_{el} per plant. The TRL of solid electrolysis is limited by the small outputs and the laboratory-scale, simulated operational environment.

The following TRL classification in Table 24 can therefore be derived from the aspects presented in this chapter:

Table 24: Results of the TRL analysis

Technology	TRL	Supplementary sources
Electrolysis systems		
• **Alkaline electrolysis up to 200 MW_{el} (continuous operation)**	8	
• **Alkaline electrolysis up to 6 MW_{el}/module (flexible operation)**	7	
• **PEM electrolysis up to 6 MW_{el} (flexible operation)**	7	
• **Solid electrolysis**	4	
• **Power-to-gas plant up to 100 MW_{el}**	2	
Methanation		
• **Fixed-bed reactors (continuous)**	6	
• **Micro-channel reactors**	4	
• **Three-phase reactors**	4	
Fischer-Tropsch synthesis		
• **Based on natural gas (GtL)**	9	
• **Electrolysis and dynamic operation**	5	
Methanol synthesis		
• **Based on natural gas (GtL)**	9	
• **Electrolysis and dynamic operation**	6	

13.5. Manufacturer overview for electrolysis systems

Table 25: Overview of manufacturers of alkaline electrolysis systems [18]

Manufacturer	Series/operating pressure	H_2 rate Nm^3/h	Status/number of systems sold
Acta (IT)	EL (15 bar) (30 bar)	0.1 – 1.0 0.5 – 1.0	Commercial, in preparation Commercial, with alkaline membrane
ELB Elektrolysetechnik GmbH (DE)	Bamag (atm)	3 – 330	Commercial, (> 400)
	Lurgi (30 bar) NeptumH2 (60 bar)	120 – 760	Commercial, (> 100) in planning
Hydrogenics (B)	HySTAT-A (10/25 bar)	10 – 60	Commercial, (~ 1200)
PERIC (CHN)	CNDQ (15 bar)	5 – 10	Commercial
	ZDQ (15–32 bar)	5 – 300	Commercial, (~ ≥ 800)
McPhy (F)	Standard, MP, HP (3/8/18 bar)	1 – 16	All series commercial
Sagim (F)	BP-100, BP-MP, MP-8, (4/8/10 bar)	0.5 – 10	All series commercial (~ 300)
Teledyne Energy Systems (US)	Titan EL 1400 (7–10 bar) Titan EL 1000 (7–10 bar)	78 56	Commercial Commercial
Wasserelektrolyse Hydrotechnik (DE)	Demag (atm)	0.12 – 250	Commercial, (> 500)
MyPhy (F)	McLyzer (atm)	400	Commercial, (1200 Nm^3/h Audi etogas in Werlte)
NEL (NO)	A-150 (atm) A-300 (atm) A-485 (atm)	50 – 150 151 – 300 301 – 485	Commercial Commercial Commercial (> 850)
Tianjin Mainland (CHN)	FDQ 400 (30 bar)	2 - 600	Commercial (9 MW plant in Kokkola Industrial Park (Woikoski, Finland (3x3 MW), 16 bar)

Table 26: Overview of PEM system manufacturers [18]

Manufacturer	Series/operating pressure	H_2 rate Nm^3/h	Energy consumption kWh/Nm^3H_2	Partial load range %
Giner Electrochemical Systems (US)	High pressure (85 bar)	3.7	5.4 (system)	No data
	30 kW generator (25 bar)	5.6	5.4 (system)	
Hydrogenics (CA/B/DE)	HyLYZER (30 bar)		4.5 (stack)	0 – 100
			5.2 (system)	
	1.5 MW	0 – 290		
	2.5 MW	0 – 450		
Proton OnSite (US)	HOGEN S/14 bar	0.25 – 1.0	6.7	0 – 100
	HOGEN H/15 – 30 bar	2 – 6	6.8 – 7.3	0 – 100
	HOGEN C/30 bar	10 – 30	5.8 – 6.2	0 – 100
	M Series (15 – 30 bar)	100 – 400		
H-Tec Systems (DE)	ELS30 (30 bar)	0.3 – 4	5.0-5.5	0 – 100
ITM Power (UK)	HGas 60, (20–80 bar)	12	6.0	No data
	HGas 180 (20–80 bar)	37	5.1	
	HGas 360 (20–80 bar)	76	4.7	
	HGas 1000 (20–80 bar)	214	4.8	
Siemens (DE)	100 kW prototype (50 bar)	~20	No data	0 – 300
	SILYZER 200 (35 bar) Energiepark Mainz 6 MW_p	225	~5.5	0 – 300
ArevaH2Gen (F)	Hydrogen generators	10-120	4.4 (stack)	

13.6. References

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14. Mechanical storage

14.1. Technology description

This chapter discusses industrial mechanical energy storage. This includes compressed air energy storage (CAES) power plants and pumped hydro storage (PHS) power plants. Both processes can be divided into sub-classes, which will also be described below. In practice, both types of power storage plants combine the first conversion level of electrical to mechanical energy, storage as potential energy and the second conversion level of potential mechanical energy back into electrical energy, all in one plant. It would not be worthwhile to separate more finely into smaller categories using the matrix in Figure 2 because, in practice, pumps and turbines are used for the conversion levels for PHS, while compressors and gas turbines are used in CAES. However, these technologies are mature in their own right (TRL 9) and are available commercially from a wide range of vendors in all sizes. Only a combination of physical storage systems is suitable for TRL assessment.

Mechanical storage systems also include flywheel generators and their derivatives, but these are not examined further in this study because their storage densities are too low (they are only short-term storage systems). Of course, this is not intended to undermine their importance for the energy system, since every spinning turbine and every generator contains a storage system and has a stabilising effect on mains frequency.

Pumped storage power plants

The physical basis of hydropower has already been explained in its own chapter. The structure of pumped storage plants is widely understood, so this chapter will only detail examples of designs in [1] regarding their technology, structure and computation. In summary, pumped storage plants are a mature technology for which there is extensive experience all over the world in their use and operation. The flow-to-electricity efficiency is up to 83 % [1] with modern pumps, turbines and transformers.

Current experience with aboveground PHS plants with upper and lower reservoirs proves that the basic concept can be transferred to other variants of the process. These variants are:

- Ringwall storage systems
- Potential energy storage systems
- Spherical reservoir pumped storage systems
- Underground pumped storage systems

They are explained in more detail in section 14.2a).

Compressed air energy storage power plants

At the two listed compressed air energy storage power plants, Huntorf and McIntosh, ambient air is first compressed via compressors using electrical energy and then stored in underground salt caverns. In Huntorf, two caverns are operated for redundancy, while in McIntosh, just one large salt cavern is used for energy storage. The flushed-out salt caverns are air tight and pressure resistant because of their depth. Porous rock formations in a disused limestone mine are under consideration for projects in planning in the USA [1]. A simplified schematic for the CAES plant in McIntosh is shown in Figure 55 and shows the basic structure. The operating principles described below are based on the designs given in [1]. First, ambient air is compressed to 75 bar in several stages and cooled intermediately (left side in Figure 55). The compression heat is emitted into the atmosphere (a central feature of diabatic CAES). The cavern is operated in the pressure range 46-75 bar. To release the energy (right side in Figure 55), the compressed air is throttled to 42 bar and pre-heated using the recuperator with hot exhaust gases from the low-pressure turbine (previous cooling caused by the Joule-Thomson effect is balanced out). This is then heated again by burning natural gas in a combustion chamber before depressurising the hot gas in a high-pressure turbine. It is then heated once again using natural gas, and then depressurized from 15 bar to ambient pressure using the low-pressure turbine. The hot exhaust gases pre-heat the compressed air from the storage system in the recuperator.

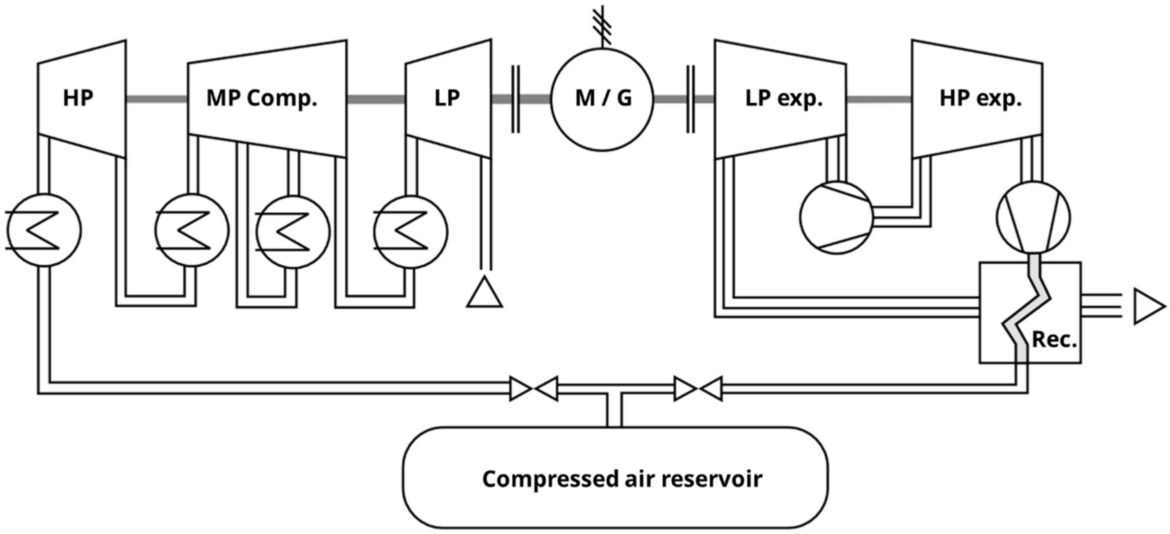

Figure 55: Schematic sketch of a CAES plant (McIntosh) [1], translated

An overview of key figures for a compressed air energy storage power plant is given in Table 27.

The cycle efficiency for diabatic CAES is defined by the following equation (17) and is calculated based on the McIntosh example:

$$\eta_{cycle} = \frac{E_{out,el}}{E_{in,el} + E_{in,th}} = \frac{1}{0{,}69 + 1{,}17} = 0{,}54 \qquad (17)$$

The combustion of natural gas makes this form of CAES essentially a combined form of compressed air energy storage and gas turbine power plant. The following variants of

CAES are currently in development to address the problem of energetic losses resulting from the output of the heat of compression:

- Adiabatic compressed air energy storage systems with variants using uncooled storage (U-CAES) and heat storage systems for intermediate storage
- Isothermal compressed air energy storage systems (I-CAES)
- Liquid air energy storage systems (LAES)

These variants are explained in more detail in section 14.2a).

Table 27: Key figures for the Huntorf and McIntosh compressed air energy storage power plants [1]

		Huntorf	**McIntosh**
Power Plant	Plant operator	E.ON Kraftwerke	Alabama electric coop
	Cycle efficiency	0.42	0.54
	Energy input for 1 kWh_{el} useful output	0.8 kWh_{el} /1.6 kWh_{gas}	0.69 kWh_{el} /1.17 kWh_{gas}
	Storage volume (useful output)	560 MWh	2,640 MWh
	Duration of planning – construction – commissioning	1969 – 1978	1988 – 1991
Compression	Compressor manufacturer	Sulzer (now MAN Turbo)	Dresser-Rand
	Max. el. power consumption	60 MW	50 MW
	Max. air mass flow	108 kg/s	approx. 90 kg/s
	Compressor units	2	3
	Charging time (at full load)	approx. 8 h	approx. 38 h
Storage	Cavern construction company	KBB	PB – KBB
	Pressure range in the cavern	46 – 72 bar	46 – 75 bar
	Cavern volume	310,000 m^3	538,000 m^3
Expansion	Turbine manufacturer	BBC (now Alstom)	Dresser-Rand
	Max. el. power output	321 MW	110 MW
	Control range	100 – 321 MW	10 – 110 MW
	Discharging time (at full load)	approx. 2 h	approx. 24 h
	Start-up time	14/8 min	12/7 min
	Max. air mass flow	455 kg/s	154 kg/s
	High-pressure turbine inlet parameters	41.3 bar/490 °C	42 bar/538 °C
	Low-pressure turbine inlet parameters	12.8 bar/945 °C	15 bar/871 °C
	Exhaust gas temperature	480 °C	370 °C (before recuperator)

14.2. Estimation of potential

a) Technical development potential

This section explains the technical possibilities for further development of pumped and compressed air energy storage. A clear distinction must be drawn between the “technically mature” classification (TRL 9) for mechanical storage systems and the classification as “impossible to improve/not worth improving”. Classical pumped storage plants, for example, are mature in themselves and have been extensively tested. Constant improvements are nonetheless still possible. These include, for example, the use of modern generators and converters, improvements in flow and operation and the use of pump turbines (Francis turbines, also available in an isogyre design) which means that fewer units need to be bought (e.g. pumps and turbines) but there are resultant efficiency losses [2].

Other variants of pumped hydro storage systems are listed in Figure 56 and briefly explained. Because the variants use the same technology as PHS, their round-trip-efficiency is approximately 81%.

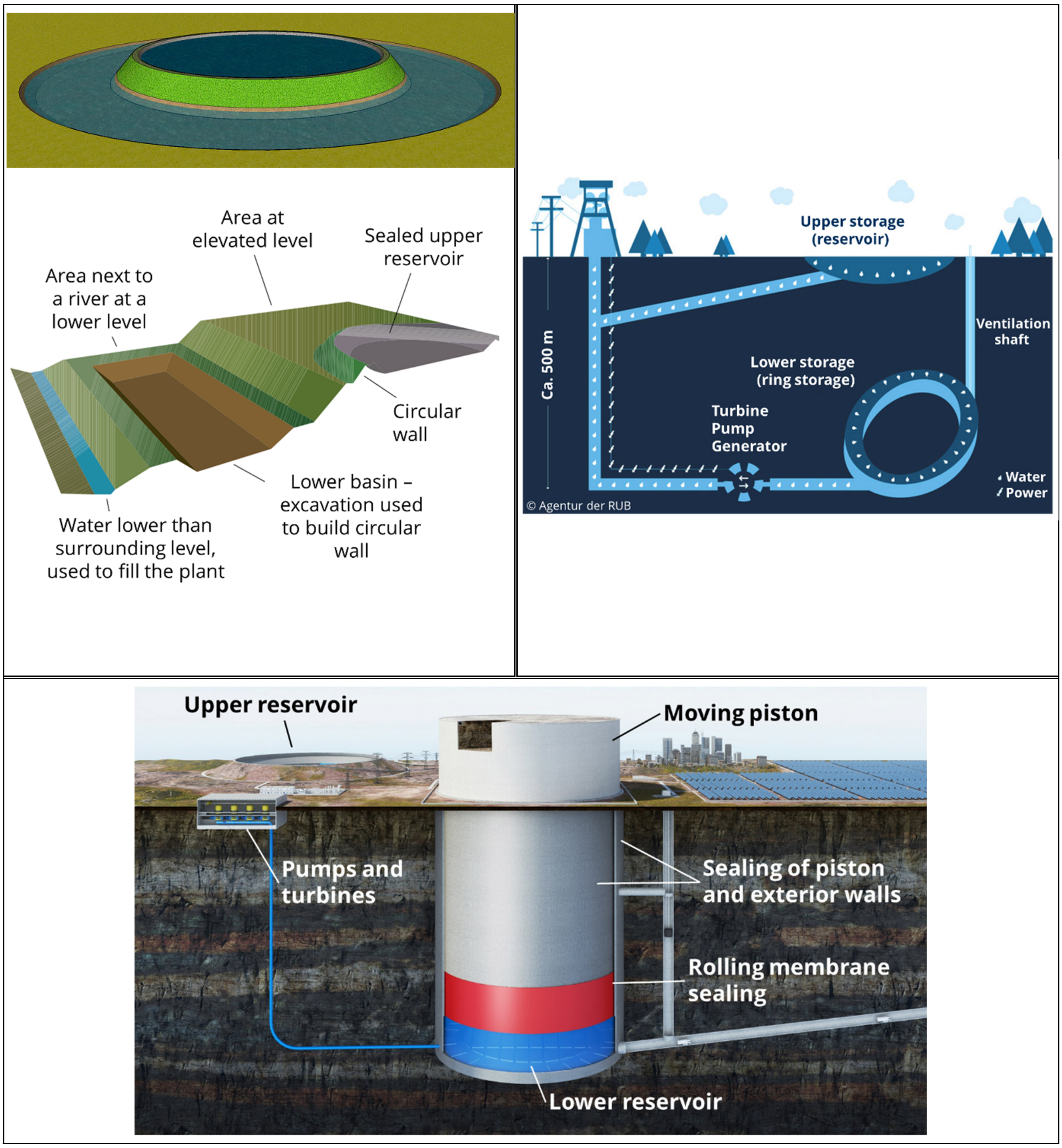

Figure 56: Hydropower storage system variants, top left: Ringwall storage system [1], top right: Underground pumped storage system as ring storage [5], bottom: Potential energy storage system [3], all translated

The idea of a ringwall storage system comes from Matthias Popp and is based on the excavation of a deep reservoir and the construction of a ringwall to form an upper reservoir. The storage capacity depends on the size of the upper reservoir and its height. So far, the concept has not been demonstrated in practice and the proof of function has only been shown analytically (TRL 2).

The potential energy storage system designed by Eduard Heindl uses the potential energy from the lifting and lowering of a stone cylinder. The higher storage density compared with water is a result of the high specific density of the solid rock. Water is pumped under the cylinder to lift it (thereby charging the system); the weight of the cylinder then forces this water through a turbine to discharge the system. The storage capacity is determined by the mass that is lifted and increases linearly with the volume. The cylinder volume increases quadratically with the radius, so an economy-of-scale effect is expected with increasing size. So far, the concept has not been demonstrated in practice and the proof of function has only been shown analytically (TRL 2).

Spherical reservoir pumped storage systems (e.g. [4]) use water pressure at great depths. In this concept, hollow concrete spheres with integrated pump turbines are lowered to the sea bed or lake bed and flooded. Electrical energy is stored by pumping water out of the sphere and discharged by allowing the surrounding water to enter the sphere through the turbine. The storage capacity depends on the sphere diameter and depth. According to [6], the storage capacity of a sphere with a diameter of 30 m at a depth of 700 metres is approximately 20 MWh_{el} (planned with a 5 MW_{el} pump turbine). A four-week demonstration trial was successfully carried out at the end of 2016 in Lake Constance using a sphere with a diameter of 3 m at a depth of 100 m. Compared with the target system, the storage system is still at laboratory scale and was tested only for a limited duration, so the maturity of the technology is currently assessed as no higher than level 4.

Instead of trying to use the limited surface capacities in Germany, efforts will focus on using underground pumped storage systems to move water underground in disused mining tunnels. Because the walls of these tunnels are too porous and would have to be sealed, designs are instead being considered that would use piping as a ring storage system. The plans are simplified if the upper reservoir can be placed above ground and any shafts that are required for water, electricity, ventilation, maintenance, etc. can be kept as short as possible [1]. There are similar concepts for redundant open-cast mines with spoil heaps. So far, the concepts have not been demonstrated in practice and the proof of function has only been shown analytically (TRL 2).

Some new approaches are being investigated to further develop the two known compressed air energy storage plants; these will be presented here. The obvious improvement to be made is the use or storage of the heat of compression. According to [1], research is being conducted into the direct storage of hot compressed air. Uncooled compressed air energy storage systems (UCAES) place high requirements on the compressors and storage containers because of the high temperatures and resultant temperature fluctuations. For this reason, UCAES has so far only been investigated at laboratory scale (TRL 4).

For energetic and technical reasons, air compression with intermediate cooling is significantly more advantageous for the implementation of adiabatic compressed air energy storage systems (ACAES). The heat of compression must then be made usable for discharging, by means of a thermal storage unit. Extensive research is being undertaken for this purpose in the ADELE research project (see also EnArgus Energy Research Information Platform [7]). The ADELE research series consisted of ADELE (feasibility study) and ADELE-ING (engineering a demonstration plant). Both research projects have been concluded. An intermediate set of results was given in [8] and a summary is presented in [9]. The construction of a demonstration plant in Staßfurt with an electrical output of approximately 90 MW_{el} and a storage capacity of approximately 360 MWh_{el} was not implemented by the industrial partners involved because of unfavourable conditions on the energy market [10]. The flow-to-electricity efficiency was expected to be raised to approximately 70 % [1]. Nonetheless, the process variants that were used (summarized in Figure 57) are noteworthy. The concept images represent only a very rough picture of the procedure, because the details of the technical implementation have not been released by the partners in the project [11]. Two different storage concepts were ultimately used to store the heat of compression. After the low-pressure compressor, a solid storage unit with optional electrical heating (power-to-heat system) would be used, and a liquid salt storage unit would be operated at high temperatures after the high-pressure compression [9]. The power-to-heat system reduces the system's overall efficiency but results in lower investment costs with improved plant flexibility. Project partner Ed. Zublin AG designed experimental pressure chambers made of prestressed concrete, for both high pressure (55-70 bar) and low pressure (13-16 bar), for the regenerator heat storage unit with solid ballast. Two concrete heat storage units heated indirectly by interior pipes have also been built as demonstration plants (see also section 15. Thermal storage) [8].

Variant	Variant 1 Base Case			Variant 2 ADELE Default	Variant 3 Regenerator-water column in secondary cycle		Variant 4 molten salt/ thermal oil	Variant 5 Multistage thermal oil	Variant 6 Multistage, LP-regenerator and thermal oil or concret-hp	
sub-variation	1.1.1 HT-HP 610 °C	1.1.2 HT-HP 610 °C	1.2.1 HT-HP 560 °C	2.1.1 HT-HP 650 °C	3.1.1 HT-LP	3.1.2 HT-LP	4.1.1 Salt/oil	5.1.1 LT 2-stages	6.1.1 LT 2-stages	6.2.1 LT 2-stages
- Process properties										
$T_{max\_comp\_out}$ [°C]	610	610	560	650	575	575	575	320	350	350
p_{max_cavern} [bar]	65	65	65	65	65	65	65	70	70	70
$p_{max\_heat\_storage}$ [bar]	65	65	65	65	15	15	1	1	1. Stage: 13 2. Stage: 1	1. Stage: 13 2. Stage: 70
$T_{max\_heat\_storage}$ [°C]	610	610	560	650	560	560	560	280	350/280	350/280
- Type of heat storage	Solid material regenerator	Solid material regenerator	Solid material regenerator	Solid material regenerator	Solid material regenerator	Solid material regenerator	molten salt/ thermal oil	Thermal oil	Solid material/ Thermal oil	Solid material/ Solid material
- Execution of the hot pipe	P92	internally insulated	P92	internally insulated	P92	internally insulated	P92	steel	steel	steel
- Intercooler (IC)/Air dryer	Air drying	Air drying	Air drying	Air drying	IC	Air drying	IC	-	-	-

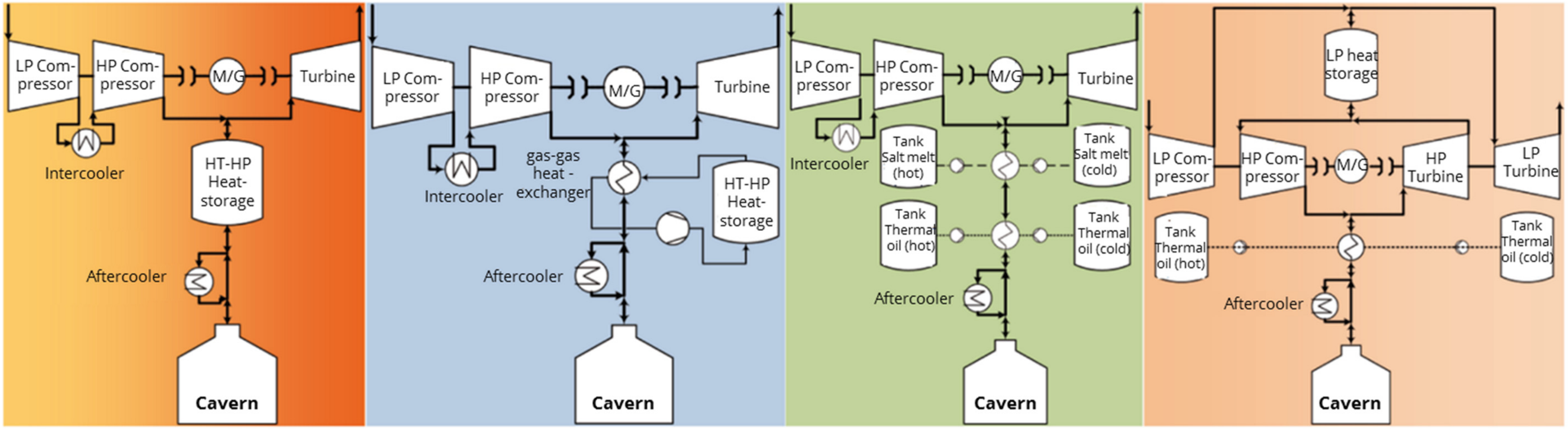

Figure 57: Process variants for ACAES in ADELE-ING [8], translated

In a more recent project, the ACAES concept was implemented as a pilot project in a supply tunnel for the Gotthard basic tunnel (cf. Figure 58). The tunnel was sealed at a length of 120 m with 2 concrete plugs and filled with up to 7 bar compressed air [12]. The heat of compression is stored using two thermal storage units. The air is then heated electrically to approximately 550 °C (to simulate higher compression) and passed first through 300 crosswise coated steel rods and then through a gravel storage unit [13] housed in a multi-layer insulated concrete container (12 $\mathrm{MWh_{th}}$). The air temperature in the tunnel is then approximately 20-30 °C [12]. This project raised the TRL from 2 (ADELE) to 3 (simulated media, laboratory scale, only partially implemented).

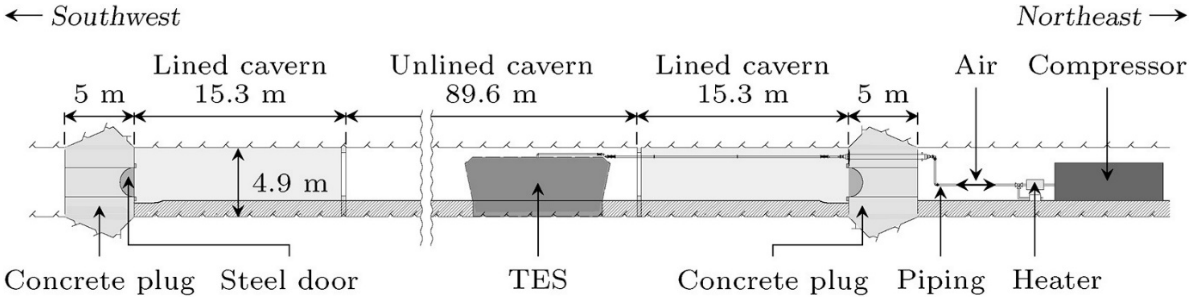

Figure 58: ACAES in Gotthard basic tunnel [12]

The principle of ACAES can be further improved by running the compression process isothermally and only applying the physical minimum of mechanical energy. For <u>isothermal compressed air energy storage</u>, the air must be cooled during compression. The achievable heat transfer in the compression chamber limits the entire concept. For this reason, the demonstration plants that were implemented only used large, slow-running piston compressors. A demonstration plant from 2013 by SustainX uses only a converted 6-cylinder diesel ship engine for this. An aqueous solution is also injected into the compression chamber for cooling [14]. The concept has found practical application in a pilot plant in Texas, where the 1.6 $\mathrm{MW_{el}}$ compressor is operated with a 2 $\mathrm{MW_{el}}$ wind turbine and the compressed air energy is stored in a salt cavern (charging ~ 250 h, discharging ~ 150 h). The heated water is separated and later used to pre-heat the air [15].

Another variation of air storage is <u>liquid air energy storage</u> (LAES). To increase storage density in this concept, the air is turned into a liquid for charging and then turned back into gas using gas turbines for discharging. The following designs for this are based on [16] and [17]. The basic structure is shown in Figure 59.

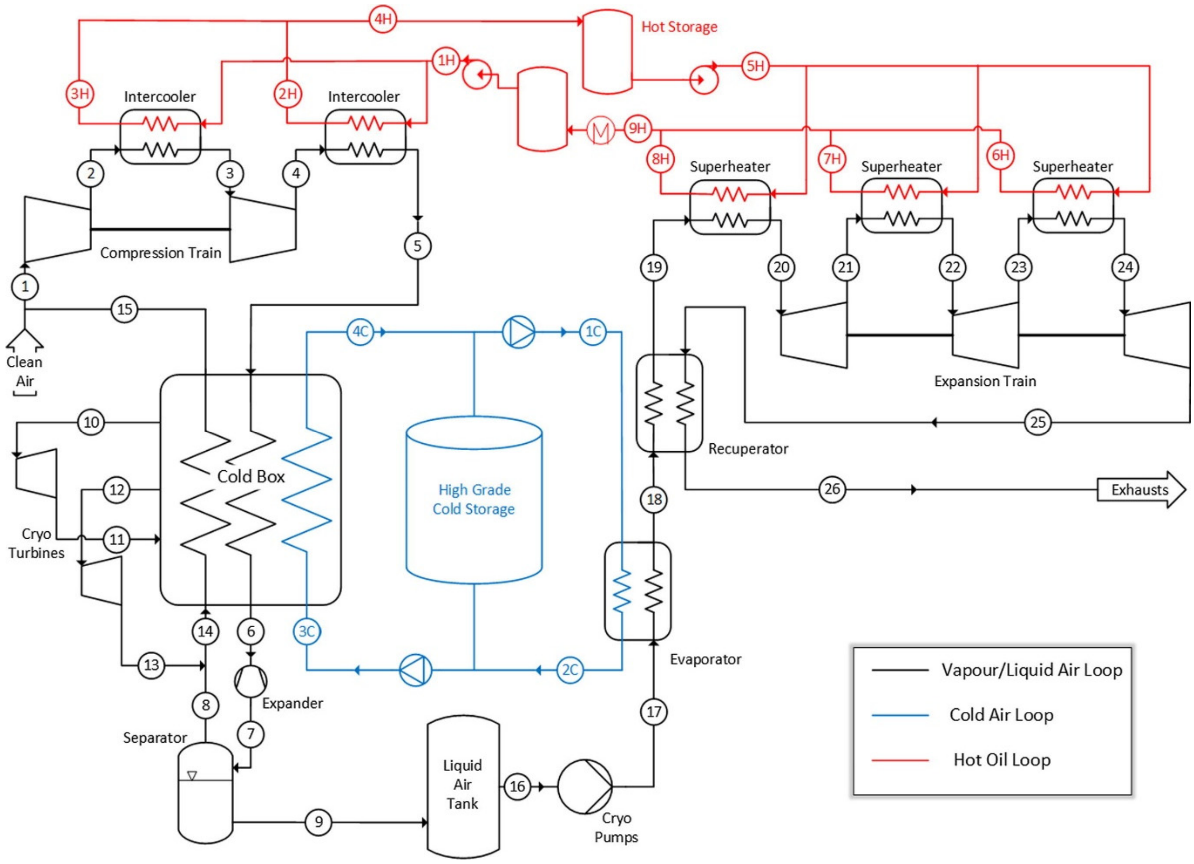

Figure 59: Structure of an LAES system [16]

First, clean fresh air is compressed with intermediate cooling to approximately 180 bar. The heat of compression is stored. Instead of then cooling the air directly via a throttle exploiting the Joule-Thomson effect, the compressed air is cooled further via the central cold reservoir. The air thus cooled can then be largely liquefied in a throttling step and stored at approximately 80 K. Unliquefied, separated air is then mixed back into the compression stream. To discharge the storage unit, the liquid air is first compressed using cryo-pumps and then evaporated via the cold reservoir (“charging” the cold reservoir), then pre-heated in the recuperator and, in several steps, superheated (discharging the high-temperature storage unit) and depressurized. Figure 59 makes clear that a large number of heat exchangers and thermal storage units are required for this process. The compression heat storage units work with thermal oil as a heat exchange and storage medium. The cold reservoir is a solid storage unit surrounded by quartzite stone, and the heat transfer medium used is air at ambient pressure. The flow-to-electricity efficiency is specified at 48 %. According to [18], a flow-to-electricity efficiency level of up to 60 % can be achieved from the standpoint of thermodynamics. There is a 350 kW_{el}/2.5 MWh_{el} demonstration plant at the University of Birmingham, UK. Another, larger pilot plant was commissioned in early 2018 (5 MW_{el}, 15 MWh_{el}) [19]. Higher overall efficiency levels of up to 80 % have been calculated in [20] if the LAES plant is combined with waste heat, ORC or gas turbine plants.

b) Expansion potential

From a technical standpoint, the expansion potential of pumped storage plants is limited less by demand than by the geographic and geological opportunities to build them. In [21], the potential for new conventional pumped storage power plants is assessed as 23.83 GW_{el} at 23 locations in Baden Württemberg and Thuringia. At the time of publication in 2014, 23 pumped storage plants were also in the planning and approval stages with a total output of at least 7800 MW_{el}. An overview of planned pumped storage plants and their current status are given in Table 29 at the end of this chapter. The Naturstromspeicher Gaildorf plant was built with its 'upper reservoir' integrated directly into the wind turbine tower. Unfavourable conditions on the energy market were blamed for most of the other storage systems being abandoned during planning or leading to negative investment decisions.

For compressed air energy storage power plants, the expansion potential is determined more by the availability of pressure-tight salt caverns. If we consider the results of the study [22], the use of the above-mentioned salt cavern potential for compressed air energy storage would result in the availability of 4.5 TWh_{el} of useful electrical energy. Thus, compressed air energy storage plants are in direct competition with the hydrogen storage potential. Liquid air energy storage plants are not affected by geological limitations, because sufficient storage space is already available with conventional liquid air tanks (for example, a 1600 m^3 liquid air tank can store ~ 220 MWh_{el} [23]).

14.3. Representation of the achieved state of expansion

There are currently 30 PHS plants in operation in Germany with a total pump output of ~ 6.5 GW_{el}, turbine output of ~ 6.1 GW_{el} and a storage capacity of ~ 40 GWh_{el}. The Huntorf plant is the only compressed air energy storage plant in operation in Germany.

Despite the maturity of PHS technology, as described in section 14.2a), no extra storage capacity is currently in development and even the existing capacity is being successively reduced for economic reasons.

14.4. TRL assessment

The mechanical storage technologies presented here are very heterogeneous in their degrees of maturity. The principle of the pumped storage plant is very mature and derivatives of this, such as underground storage units or ringwall storage plants, exist only as an industrial concept, as demonstrations on a small scale would not be expedient. Therefore, existing feasibility studies always refer to large-scale projects. These large-scale projects currently have a TRL of 2 (only on paper with analytical proof), but could jump to TRL 8 very quickly if implemented because of the mature complementary technologies for pumps and turbines. The situation is similar for compressed air energy storage plants. In the special case of liquid air energy storage, pilot projects are being advanced at least in England. In Germany, a consortium consisting of Linde and Mitsubishi Hitachi Power Systems Europe is also focusing on LAES and, according to information it has published, currently has a 80 MW_{el} plants in development [23], although it has not yet implemented any demonstration power plants.

The following TRL classification in Table 28 can therefore be derived from the aspects presented in this chapter:

Table 28: Results of the TRL analysis

Technology	TRL	Supplementary sources
(Conventional) pumped storage power plants	9	
• Ringwall storage systems	2	
• Potential energy storage systems	2	
• Spherical reservoir pumped storage systems	4	
• Underground pumped storage systems	2	
Compressed air energy storage power plants (CAES)	8	
• Uncooled compressed air energy storage systems (U-CAES)	4	
• Adiabatic compressed air energy storage systems (ACAES)	3	
• Isothermal compressed air energy storage systems (I-CAES)	6	
• Liquid air energy storage systems (LAES)	6	

Table 29: Updated overview of PHS projects in Germany and their status, based on [21]

Power plant name	Output	Status	Company	Built?	Status as of 05/2018
Atdorf	1400	Planning approval procedure	Schluchseewerk AG	No	Withdrawal (11/10/2017)
Blautal	60	Regional planning procedure	Stadtwerke Ulm/Neu-Ulm GmbH, Eduard Merkle GmbH & Co KG	No	Cancelled (06/07/2016)
Forbach	200	Regional planning approval obtained	EnBW AG	Partially	4 separate power plants since 1926, proposals for 220 MW (07/11/2016), plans for a new sub-level, upper level postponed (currently)
Sorpeberg-Ermecketal	420	Planning	Mark-E Aktiengesellschaft, Grünwerke GmbH	No	Cancelled
RIO	300	Regional planning approval obtained	Stadtwerke Trier	No	Cancelled (26/10/2017)
Halde Sundern	10 – 15	Feasibility study	RWE Innogy GmbH, RAG Montan Immobilien GmbH	No	No investors
Energiespeicher Riedl	300	Planning approval procedure	Donaukraftwerk Jochenstein AG	Planning	Approval process for the Energiespeicher Reidl project is about to enter oral discussion phase.
Waldeck 2 +	300	Investment decision outstanding	E.ON SE	Partially	Planning for construction of a new turbine suspended, storage volume and therefore energy storable in upper reservoir II increased by 11%
Einöden	150	Planning	Pumpspeicherwerk Einöden GmbH	Planning	Project suspended
Lippe	320	Feasibility study	HOCHTIEF AG	No	Cancelled (07/2015)
Jochberg	700	Planning	Energieallianz Bayern GmbH & Co. KG	No	Cancelled (06/09/2014)
Nethe	390	Regional planning and regional plan alteration approval obtained	Trianel GmbH	Planning	Construction until 2025
Leinetal	200	Regional planning approval obtained	HOCHTIEF AG	No	Cancelled (07/2015)
Rottachsee	40 – 60	Planning	Allgäuer Überlandwerk GmbH	?	Not specified
Breitenstein	60	Planning	Allgäuer Überlandwerk GmbH	?	Not specified
Leutenberg	380	Planning	STRABAG AG	Planning	Planning suspended (12/17)
Ellrich	640	Planning	STRABAG AG	No	Cancelled (01/2015)
Schmalwasser	Over 1000	Regional planning procedure	Trianel GmbH	Planning	Planning – application for planning approval procedure not yet submitted (02/18)
Heimbach	280 – 320	Regional planning procedure	Stadtwerke Mainz AG	Planning	Planning delayed (04/17)
Naturstrom-speicher Gaildorf	16	Planning approval procedure	MBS Naturstromspeicher GmbH	Yes	Wind turbine-integrated PHS plant; commissioning planned for end of 2018 (01/18)
Osser	Not specified	Planning	Visprion Engineering GmbH	No	Cancelled (08/2015)
Hainleite	240 – 500	Regional planning procedure	HOCHTIEF AG	No	Cancelled (07/2015)
Poschberg	450	Feasibility study	Max Aicher Poschberg Projekt GmbH	Planning	Planning

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15. Thermal storage

15.1. Technology description

This chapter discusses thermal energy storage. There are a variety of possibilities for the storage of heat depending on the area of application. The aim of this study is to highlight the technological state of the art as well as the development potentials and then to assess these with the TRL. The discussion of thermal storage has to be restricted, because this is an extensive area that can only be sketched out in basic terms here. First the essential properties of thermal storage systems are put forward. Next, the most common technologies are presented and classified. Section 14.2a) then addresses potential further developments.

Essential properties

In [1], thermal storage systems are grouped and described as follows:

- According to material type:
    - Sensible heat storage is based on the temperature change of the storage medium when charging and discharging. Water is the most widespread medium. The storage systems also include geothermal probe storage (storage in rock formations) and further variants with solids (foundation storage, concrete storage, etc.). “Direct heat storage is not possible when solids are the storage medium; they require an additional heat transfer medium which is liquid or gaseous. Therefore, the limiting factor is often not the operating temperature of the storage medium, but the limit of the heat transfer medium or system components that come into contact with the storage medium. [2]“. In high temperature ranges, molten salts are used.
    - Latent heat storage: Latent heat describes the enthalpy change that the material undergoes when changing physical state. The temperature remains the same for pure substances and changes within a temperature range for mixtures of substances. Phase change materials (PCM) offer the advantage of largely constant temperatures and high storage density. The thermal conductivity is the limiting factor in most phase change materials [3].
    - Thermo-chemical storage is based on reversible chemical reactions. The charging process is endothermic, while discharging is exothermic. Such systems operate at approximately 200–400 °C [1]. Typical agents are mentioned in [1], for example, iron carbonate or the hydrogenation of magnesium oxide. Thermo-chemical energy storage systems exhibit very high storage densities compared to sensible and PCM storage (cf. Figure 62). This type of storage is the object of research that focuses on reversibility and cycle stability [4].
    - Thermo-physical storage systems, according to [5], should include storage that is based on ad- and absorption processes; in [6], such systems are categorized as thermo-chemical storage.

- According to storage period and turnover rate:
    - Daily/short-term storage. The duration of the storage cycle is short and the storage period is low, e.g. a day. Typical examples are storage systems for thermal solar power stations or domestic hot water tanks. For example, researchers are investigating PCMs for the cooling of PV plants.
    - Seasonal storage accumulates surplus heat in summer and releases it again in winter. The storage temperatures are 27°C–80°C. Low-cost, available storage materials are required for the large heat quantities. For this reason, sand, gravel and water mixtures are used.
- According to locality:
    - Centralized storage is constructed at the site of the large-scale heat supply.
    - Decentralized storage is used on a small scale for end consumers.
    - Mobile storage is used if connection by pipes is not economically or technically feasible. Due to storage density, only PCMs and thermochemical stores come into consideration for transportation by lorry. Passive storage systems are also used for transporting foods requiring refrigeration.
- According to storage mechanism:
    - Active storage systems need to be charged by an auxiliary system (e.g. pumps) in which a heat transfer medium is transported through the storage system. Charging and discharging can take place directly and indirectly (via heat exchangers).
    - Passive storage systems make use of thermal inertia or natural convection to charge and discharge (e.g. in buildings for air conditioning).
- According to storage temperature:
    - Cold storage for temperatures under 20°C. This includes cold water and ice storage, for example. Other PCMs are also used (e.g. paraffin).
    - Low-temperature storage systems operate in the temperature range of 20°C–100°C, often for heating purposes or (seasonal) solar heat storage.
    - Medium-temperature storage is intended for temperatures of 100°C–250°C in industrial waste heat (sterilization, drying, boiling etc.), sugar alcohols as storage medium.
    - High-temperature storage is over 250°C mostly in (solar) power plants or in industrial high-temperature processes. Solids or molten salts are used.

Most of the storage types presented, regardless of their size, cannot be dismissed as irrelevant in the technological state of the art for the energy revolution. Decentralized cold and low-temperature storage systems, in the form of daily storage systems (hot water tanks) as well as underground seasonal storage systems, help shift the timing and amount of heat requirements. They are a central tool in reducing the domestic and commercial heat requirements for cooling purposes. This reduction in the heat requirement is a central assumption in current studies on the feasibility of decarbonization and full supply with renewable energy sources.

The level of development of thermal storage is very heterogeneous and heavily determined by the storage medium used. Figure 60 provides a first indication. The high level of development of sensible and latent storage systems given in the diagram is based on experience with water as an energy store. It is widely known as a sensible storage material and is used as a latent heat storage for ice (solid-liquid) and Ruths accumulators (liquid-gaseous).

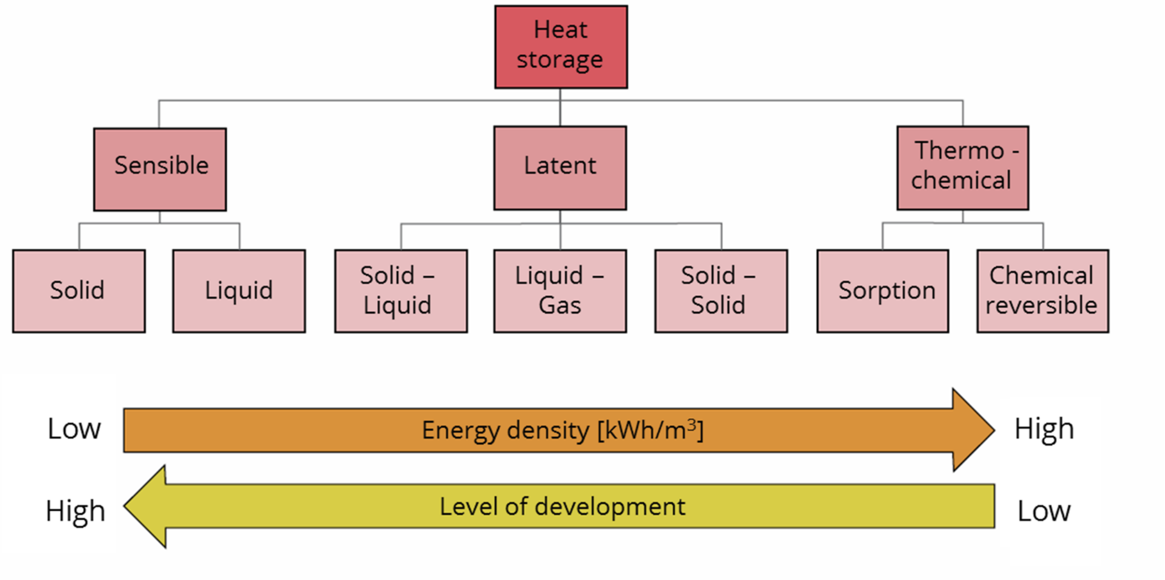

Figure 60: Overview of the different storage materials for storing thermal energy, translated [1]

This overview can only examine a fraction of the storage technologies; therefore, an appropriate selection of centralized storage systems is presented below.

Water storage for district heating networks and power plants

Water storage represents the most widespread form of thermal storage. It has been used in thermal power plants as well as in constant-pressure and variable-pressure accumulators. Constant-pressure accumulators contain water at boiling temperature under boiler pressure and are an extension of the boiler water space [8]. “In the event of an increased steam requirement, water from the accumulator is supplied to the steam generator at near-boiling temperature, which can increase the steam output of the boiler.” [8]. In gravity accumulators (also Ruths accumulators), the pressure in the accumulator is variable. It is charged with steam from the boiler or via a turbine connection. The steam condenses in the water space of the accumulator, increasing the water level, pressure and temperature. When the steam is drawn off, the pressure in the accumulator drops and part of the water evaporates – the pressure and temperature fall in the accumulator [8]. Both storage variants were previously used as an alternative for steam stores in coal-fired power plants to cover peak loads [9]. They were displaced by improved controllability and alternative peak-load power plants (gas turbines).

Atmospheric (to 95 °C) and pressurized (to 130 °C, often higher [5]) storage tanks are used in district heating networks. The tanks are made of concrete or steel, with larger accumulators using tanks made of waterproof steel-reinforced concrete. They have a cylindrical design to ensure that the contact surfaces of hot and cold water are reduced for stratification of the water (to avoid thermal conduction). Insulation is provided either by filling the space between the tank wall and the outer casing with foam or by using insulating panels [1]. In Germany, a series of large hot water stores are integrated into the district heating network. An overview is presented in section 14.3.

Cold storage

Cold storage systems operate as cold-water stores below 20 °C. The supply and return temperatures are typically 6–12 °C and are also suitable for dehumidification. For air conditioning, a temperature difference of 10–16°C (local cooling) is currently used and temperatures of 16–20 °C are being targeted in research (LowEx cooling) [5]. The low temperature differentials lead to very high system efficiencies, yet require large heat transfer surfaces at the same time. The storage systems resemble hot water stores in design, but differ in numerous details (materials, insulation (dew point problems), very large volume flows) [5]. They are installed above and below ground or integrated into buildings; the method of charging/discharging is usually direct. They are designed for short-term storage and serve to shift the load for air conditioning using compression chillers [10]. Since it is not within the scope of the present work to discuss further forms of storage or their structural and operational properties, reference is made here to the basic literature [11]. The same applies to ice storage systems. These are generally already available commercially for the purposes of air conditioning up to 10 kW_{th} [12], and are designed as ice-on-coil systems (iced tubular coil, heat exchanger in the tank) [11]. A water tank is fitted with copper coils, which are chilled by the refrigerant of a compression chiller, freezing the water during low-load phases or in the night, when the compression chiller unit operates more efficiently (temperature difference is lower). This reduces the electrical energy requirement for the compression chiller during the day. Their greatest disadvantage, however, is the poor heat transfer and the low evaporator temperature necessary for compression chillers (-6 °C), which result in higher operating costs [5]. German manufacturers, for example [13], use ice storage systems in underground cisterns for heating purposes, as they tap into the solidification heat of water using a heat pump.

Seasonal storage

Hot water heat accumulators installed below the ground are used for long-term storage of thermal energy. They are designed as earth basins and are sealed off from the environment. For reasons of cost, the materials used are water, sand and gravel. The accumulators are up to 100,000 m³ in size [14]. An overview of the seasonal storage systems in Germany is presented in section 14.3. “Due to the heat insulation materials used, the storage temperature is limited to approximately 85 °C.” [1]

High-temperature storage

Water is no longer used as a storage medium for temperatures > 250 °C due to the associated high pressures. Molten salt stores are at the most advanced stage of development in this area as they are used in solar thermal plants to offset the day-night cycle. The storage temperatures are between approximately 250 °C and 565 °C, as the salt crystallizes when the temperature falls below ~240 °C and disintegrates under extreme temperatures releasing oxygen. "Andasol I uses 25,000 tons of a liquid salt mixture made of $NaNO_3$-KNO_3, for which two tanks, each with a diameter of 36 m and a height of 14 m, were needed (each 14,250 m^3). The plant can supply an output of 50 MW_{el} for a further 7.5 hours with full tanks. A critical aspect of this direct heat accumulator is that the salt used has a melting point of about 220 °C, meaning the temperature must not drop below this value while in the pipes or fittings." [2] in regard to [15]. Based on the data, a storage capacity of 375 MWh_{th} can be calculated. The salt at Andasol is heated from 290 °C (cold storage) to 390 °C [16]. The average specific heat capacity for the 240 °C to 566 °C range is 1.5 kJ/kgK [17].

Indirect heat stores are another alternative, these can be filled with salts, PCMs or concrete and heated/cooled by finned tubes. The disadvantage of higher investment costs is counterbalanced by a low energy expenditure during operation as well as a high level of plant safety [18]. A concrete accumulator was designed as a demonstration system for temperatures up to 400 °C (100 kW_{th}, 400 kWh_{th}) by Ed. Züblin AG in cooperation with the German Aerospace Center (DLR). The reduction in strength (30–40 %) after long-term cycles between 330 °C and 390 °C poses a problem [19].

15.2. Estimation of potential

a) Technical development potential

This section examines the technical possibilities for further development of some of the storage types mentioned above. A clear distinction must be drawn between the "technically mature" classification (TRL 9) for thermal storage systems and the classification as "impossible to improve/not worth improving". Optimization approaches are constantly being presented for large water stores in district heating networks and implemented in laboratory, demonstration and pilot projects. Some examples of the approaches for large water stores are:

- Optimization of the design and insulation (e.g. using a segmental design and fillings with new insulating materials) [20]
- Optimization of the heat exchangers for indirect use
- Optimization of thermal stratification, reduction of convection (e.g. minimization of inflow velocity by means of annular gap nozzles)
- Optimization of charging strategies and storage monitoring (e.g. distributed temperature sensing – DTS) for temperature field recording in large stores [21])

- Unpressurized elevation of the storage temperature (to 115 °C) by two-zone storage (a tall water column above the warm layer increases the pressure so that temperatures higher than 100 °C are possible in layers, although the tank is operated at atmospheric pressure; implemented in Nuremberg-Sandreuth [22]
- Further approaches are presented in [23].

In terms of a technology readiness assessment, water storage already fulfils all the requirements for a mature system (TRL 9) in scalability, system dependability and operational environment.

In addition to water as a sensible storage medium, PCMs and solid-based high-temperature storage systems are still in the development phase for large-scale application purposes. A wide range of materials suitable for heat storage purposes is known for PCMs (cf. Figure 61). In fact, PCMs exhibit large storage densities, but the thermal conductivity is often the limiting factor. Therefore, the accumulators are fitted with internal structures where possible, which improve the heat transfer by conduction or convection (e.g. finned pipe heat exchangers or agitators). The focus of development is to improve the transportation of heat in order to maximize thermal capacity when charging and discharging [1]. In addition to the problems mentioned above, the thermal cycle causes strength degradation in solid storage, such as concrete storage. Similar problems also arise for metal hydride storage systems when charging and discharging with hydrogen.

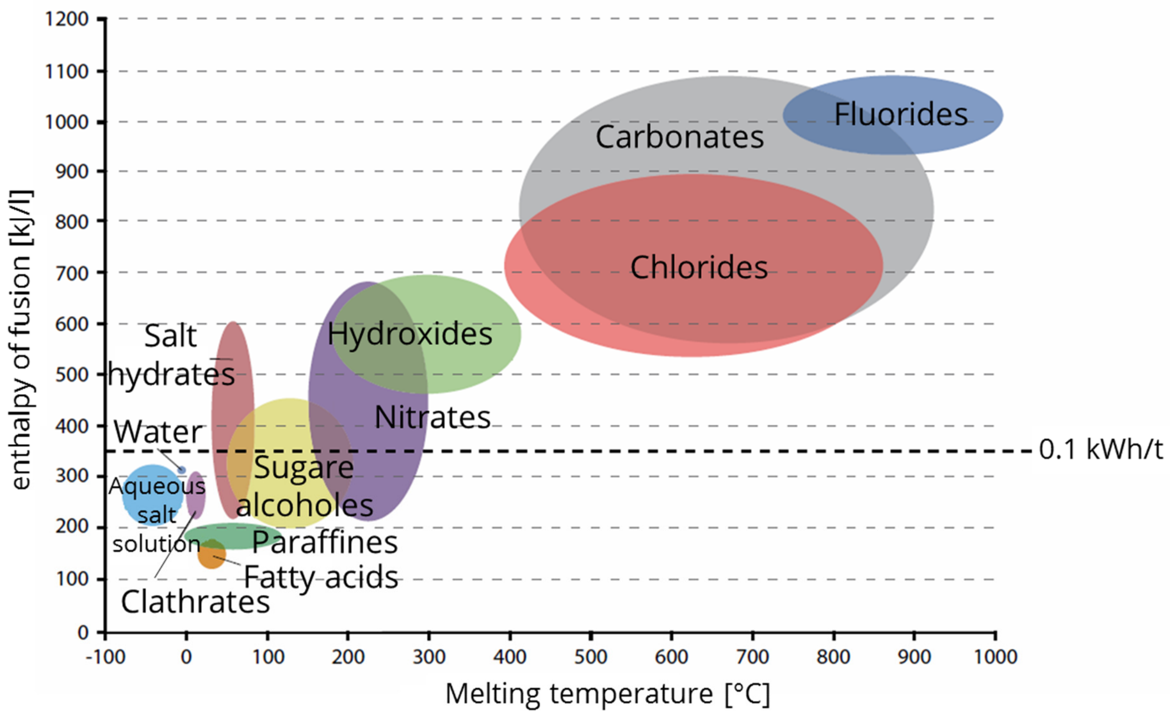

Figure 61: Overview of PCMs [1]

In summary, the development of latent, high-temperature, (molten salts, solids) and thermochemical storage focuses on the materials used. An overview of the most well-known storage mediums is presented in Figure 62. Key figures, for example the specific energy density, are characterized and determined on a laboratory scale. This means that the technological degree of maturity of most storage mediums is limited to TRL 4 at most.

As described earlier, seasonal storage systems use the most inexpensive media that are available in abundance, i.e. water, sand and rocks. According to [1], the need for further development primarily lies in the use of cost-efficient insulation concepts as well as optimized stratification charge units, since the correct storage stratification reduces exergetic efficiency losses due to mixing. Thermo-chemical storage offers an alternative whose energy loss is negligible over time. Practical experience with zeolite-based seasonal storage (adsorption heat) also exists on a demonstration scale [24] for single-family houses. The central problems mentioned in [24] with respect to large seasonal storage systems continue to be the high investment costs caused by a shortage of space, unsuitable building ground and the costly retrofitting of old buildings.

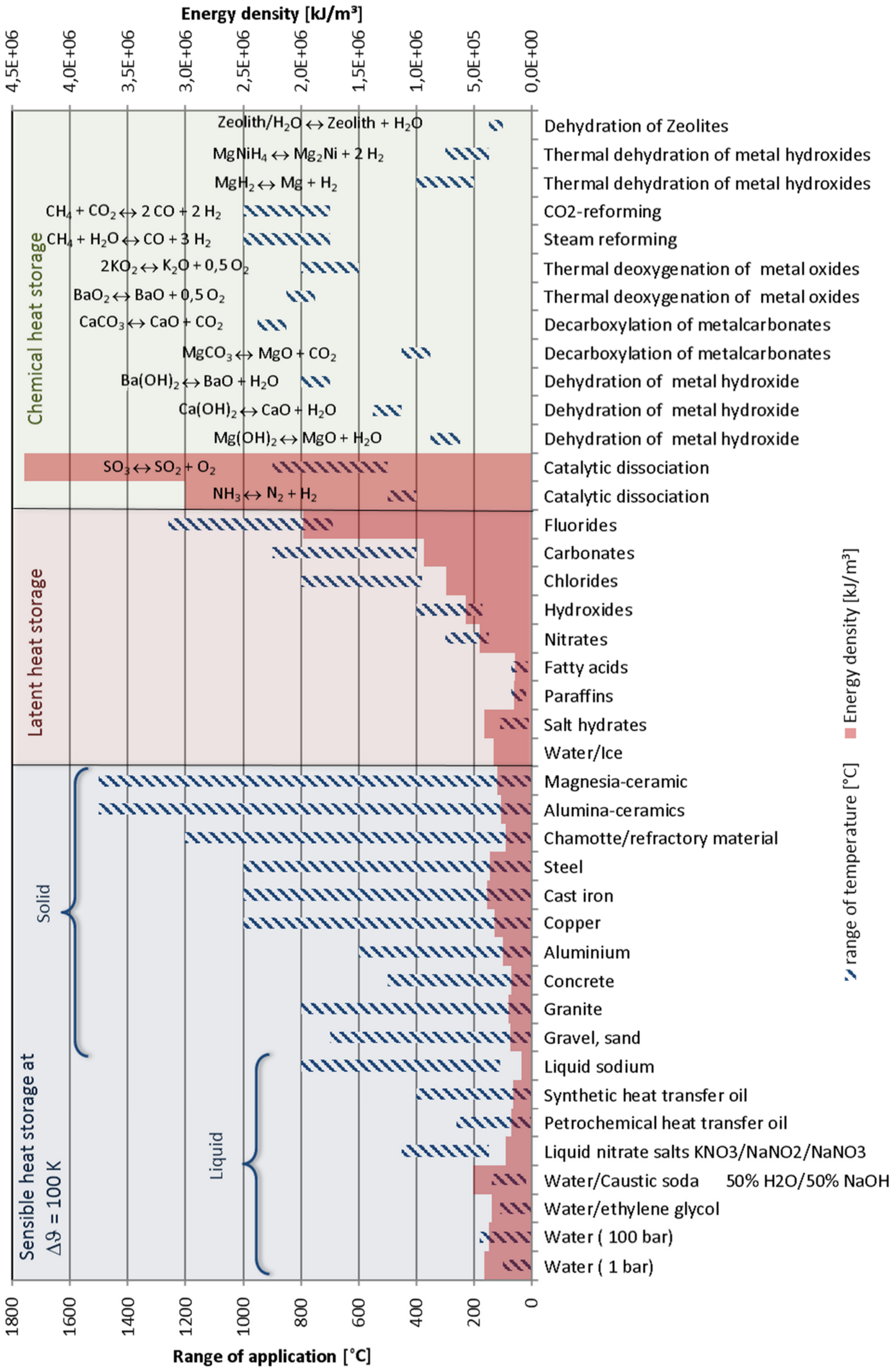

Figure 62: Area of application and energy density of heat storage media with data for chemical heat accumulators, [2] based on [25] and [3], translated

In addition to the storage systems mentioned earlier, power-heat-power storage is also in development. Research is being conducted on this in two large projects in Germany. One of these involves the DLR's Carnot battery [26]. The aim is to store thermal energy in suitable tanks at 50 °C–500 °C (as water or molten salt stores) using high-temperature heat pumps. The stored heat can be converted back into energy using thermal engines. The challenges raised in [26] are the efficiency, the bivalent operational capability of a thermal engine (e.g. a Stirling engine for charging and discharging) and the limitation of the storage losses. Heat pumps are predestined for such projects from a technical standpoint, but the maximum supply temperatures (on a MW scale to 120 °C, see chapter 11. Power-to-heat) are still very low. Storage at higher temperatures can be realized at MW scale via molten salt storage up to 566 °C using nitrate-salt mixtures (typically 60 % $NaNO_3$; 40 % KNO_3) [27], in which the storage temperature must not fall below the solidification temperature of 220°C (TRL 8, commercial demonstration power plant for CSP). The annual efficiency of molten salt storage is 95 % [28]. So far, this project approach has only produced concepts for the Carnot battery as a system (TRL 2).

The second project, I-TESS (integrated thermal energy storage system for the energy revolution), by the Jülich Solar Institute at the Aachen University of Applied Sciences, intends to integrate the concepts mentioned above into existing power plants in order to increase flexibility. Extensive experience with molten salt storage in conjunction with conventional power plant technology forms the basis of this approach. The storage systems can be heated by power-to-heat technologies or by the boiler of a steam power plant [28]. Here, too, only concepts for implementation exist (TRL 2).

b) Expansion potential

In the German energy revolution, thermal storage has less to do with the potential for expansion and more to do with the need for expansion. At present, this can only be assessed using scenario analyses. Key parameters for the assessment are the heat requirement as well as the time and location of the requirement. Therefore, it is necessary to make several assumptions concerning the future need for heat supply. Decentralized storage systems could be implemented for private residential buildings, or even centralized storage when expanding district heating supply. Decentralized heat pumps could also ensure the heat supply in densely populated areas if the district heating supply temperatures were lowered. Consequently, any assessment of storage requirements for space heating and hot water are subject to great uncertainties. In order to nevertheless determine an order of magnitude, the study "Energy System Germany 2050" by the Fraunhofer Institute for Solar Energy Systems (ISE), summarized in [1], can be consulted. In the study, the current heat requirement (in 2015, approximately 783 TW_{th} final energy for space heating and hot water; no process heat ~532 TWh_{th} [29]) is initially reduced by 60 % using efficiency measures. The scenario does not consider full supply with renewable energy sources, but attempts to reduce greenhouse gas emissions at optimal costs by 85 % compared to 1990. Fossil energy technologies remain in the system. The centralized storage required is estimated at 25 million m³ (charge at 54 TWh_{th}/a, discharge at 40 TWh_{th}/a). Decentralized storage draws in 70 TWh_{th}/a and feeds out 56 TWh_{th}/a. A part of the heat supply is also fed from methane gas stores.

15.3. Representation of the achieved state of expansion

The current level of expansion for large-scale heat storage can best be described by means of the storage types. Hot water stores for district heating networks are widespread in Germany. The rapid expansion seen in recent years has led to incomplete statistics, so Figure 63 was prepared based on data from the German Federal Office for Economic Affairs and Export Control (BAFA) [30]. This only considers the expansion for heat storage, and the statistics only permit vague conclusions on the storage sizes realized. It is clear from the data in [30] that stores > 50 m³ account for over 98 % of the expanded storage volumes since 2014. An overview in [6] (as of July 2017) shows 29 large heat stores in Germany with volumes of 3,000–50,000 m³ (approximately 510,000 m³ in total). One of the largest district heat stores in Germany entered operation in 2015 at the "Potsdam-Süd" CHP plant in Potsdam. It contains 41,224 m³ of water and can store 1,200 MWh_{th} [31].

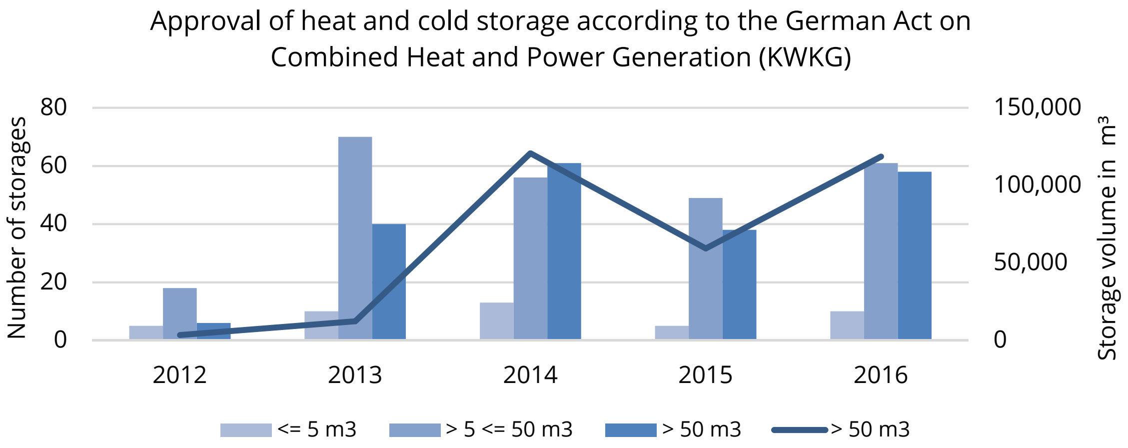

Figure 63: Expansion of heat and cold storage according to the German Act on Combined Heat and Power Generation (KWKG) [30]

Several demonstration projects also exist for seasonal storage systems (cf. Table 30). Considerably larger stores with volumes up to 100,000 m³ (Lyckebo, SE) have been realized and are in operation worldwide, especially in Denmark and Sweden [14]. According to [14], PCM and thermo-chemical-based seasonal storage is still in the laboratory stage.

Table 30: Seasonal storage [14], [32]

Location	Storage volume in m³	Capacity MWh_{th}
Tank stores		
Hamburg, Germany (I/II)	4,500/4,150	260/240
Friedrichshafen, Germany	12,000	675
Hannover, Germany	2,750	160
Munich, Germany	5,700	330
Aquifer		
Rostock, Germany	20,000	600–800
Rastatt, Germany	23,000	690–920
Neubrandenburg, Germany		approx. 14,300
Gravel-water heat accumulators		
Chemnitz, Germany	8,000	240–400
Steinfurt, Germany	1,500	45–75
Stuttgart, Germany	1,050	31.5–52.5
Augsburg, Germany	6,500	195–325
Eggenstein, Germany (Pit)	4,500	175
Geothermal probes		
Neckarsulm, Germany	63,360	950–1,900
Attenkirchen, Germany (tanks/geothermal probes)	500/9,350	165
Crailsheim, Germany	37,500	580

Germany is also home to numerous cold storage systems. The plants in Chemnitz (3,500 m³, ~ 32 MWh_{th} cold water [33]) and Biberach (6,500 m³ cold water [34]) are cited as large application examples. Another overview is given in [35].

Furthermore, [36] lists numerous large-scale molten salt storage facilities (29 plants with an output of more than 20 MW_{th} and storage periods up to 15 hours). One example worth mentioning is the Solana generating station; its salt storage tanks have an output of 280 MW_{th} with a capacity for 6 hours [36]. The plants generally operate in conjunction with solar thermal power stations and are therefore not found in Germany.

15.4. TRL assessment

The thermal storage technologies presented here are very heterogeneous in their degree of maturity. The practical experience with water as the storage medium results in very high TRL evaluations in almost all forms of application (cold, hot water, steam, seasonal gravel-water stores, etc.). Despite the fundamental maturity, optimization measures are being explored to make water storage more efficient and economical. Sensible solid storage (ice, firebrick, foundation, geothermal probe storage) also have high levels of maturity. Niche applications have matured in the PCM sector (e.g. pocket warmers) but large-scale use for the energy revolution remains out of reach. Together with the approaches to thermo-chemical storage, there is a lack of knowledge and experience on a material level, meaning many experiments are implemented on a laboratory scale. Demonstrations or pilot projects become public only occasionally, yet the new storage mediums do not reach the cost efficiency of established processes.

The following TRL classification in Table 31 can therefore be derived from the aspects presented in this chapter:

Table 31: Results of the TRL analysis

Technology	TRL	Supplementary sources
Sensible storage medium		
• **Liquid**		
○ **Hot water storage**	9	
▪ **2 zones**	8	
▪ **DTS**	6	
○ **Cold water storage**	8	
○ **Molten salt**	8	
• **Seasonal storage**		
○ **Water/gravel mixture**	7	
○ **Aquifers**	7	
○ **Geothermal probes**	7	
• **Solid storage (concrete storage)**	4	
• **Power-heat-power storage**	2	
Latent heat storage		
• **Ice storage**		
○ **For heat pumps (household)**	9	
○ **For air conditioning systems**	9	
• **Paraffin for domestic storage**	9	
Thermo-chemical storage systems (general)	4	
• **Zeolite (seasonal household storage)**	5	

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16. Chemical storage systems

16.1. Technology description

This chapter discusses energy storage on a chemical basis. In general, hydrocarbon compounds (crude oil and its refinery products, natural gas, etc.) have very high volumetric and gravimetric storage densities and are therefore in widespread use today for energy storage. For this reason, there is extensive experience in the physical storage of conventional fossil hydrocarbons for mobile and stationary applications in barrels, tanks, gas canisters, gasometers, spherical gas tanks, underground caverns, pore and aquifer storage facilities, etc.

Since the energy landscape of the future will be shaped by electrolysis and hydrogen, the focus will therefore be on technologies facilitating hydrogen storage. The challenges of storing hydrogen lie in its physical characteristics. The melting point of hydrogen is -259.20 °C, the boiling point is -252.77 °C and the explosive limit in air is 4–75 % by volume. Hydrogen has a very high diffusivity because of its low molecular weight and size. This means that the gravimetric lower heating value (LHV) is 33.3 kWh_{th}/kg_{H2} (higher heating value (HHV) 39.4 kWh_{th}/kg_{H2}) but the volumetric LHV is only ~ 3 kWh_{th}/m^3_{H2} (HHV 3.54 kWh_{th}/m^3_{H2}) [1]. The (by definition) low volumetric energy density is the central motivation for the development of storage systems for hydrogen.

Before purpose-built storage units are erected for industrial hydrogen production in the energy industry, hydrogen can also be mixed with conventional natural gas. A key investigation on this was carried out by the German Technical and Scientific Association for Gas and Water (DVGW) in 2013, and the results on hydrogen compatibility are presented in Figure 60. It is clear that most applications with up to 10 % hydrogen by volume can continue to be operated without concern. There is a need to adapt systems when operating gas turbines (especially adjusting burner configurations, although this has been successfully realized by Siemens at up to 45 % by volume [2]) and in the use of natural gas vehicles [31]. According to [3], the working gas capacity in caverns at the end of 2016 was 11.8 billion Nm^3. It is assumed, as an example, that 10 % of this by volume could be substituted with H_2; so the possible hydrogen portion in terms of energy (in relation to LHV) is already 3.54 TWh_{H2} (the storage capacity of German pumped-storage power plants is approximately 0.04 TWh_{el}).

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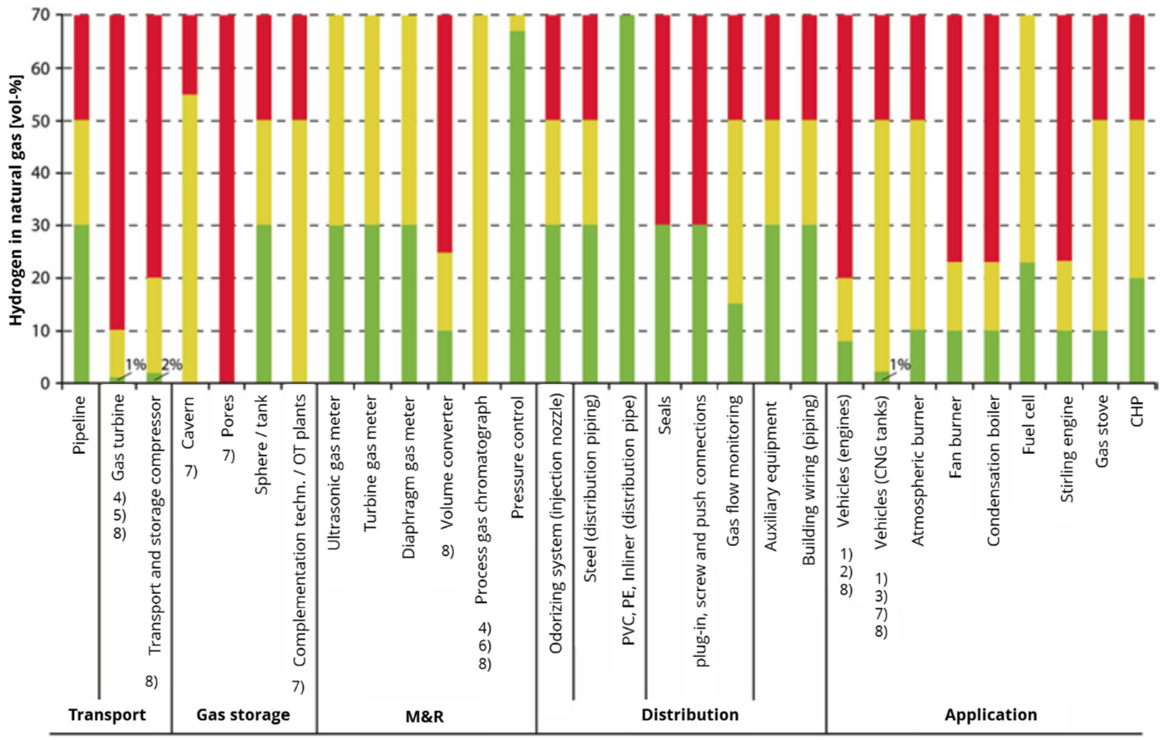
[31] In natural gas vehicles, max. 2% H_2 by volume because of limited compatibility in steel tanks (hydrogen embrittlement). For gas motors, up to 20% H_2 by volume is not expected to cause any problems as long as the motor-specific methane figures are maintained [1].



1) Limits regarding regulations, standards and manufacturing guidelines
2) Consideration of methan number
3) Max. 2 vol-% H_2 (DIN 51624)
4) Limits regarding sensitive components
5) Seal elements, flashback, guarantees
6) H_2-fraction > 0.2 vol-%; PGSs (gaugable H_2 measurement required)
7) DVGW follow-up project / R&D project for further research
8) Solution for higher H_2 content available

🟩 Admixture of H_2 non-hazardous 🟨 Need for adaption and control 🟥 Need for research and screening

Figure 64: Hydrogen tolerance in the natural gas network, [5] based on [6], translated

The most important variants for pure hydrogen storage are shown in Table 32.

Table 32: Variants of hydrogen storage, based on [7]

Physical	**Material**
Pressure storage (Compressed gaseous hydrogen, CGH_2)	Metal-hydride storage
Cold- and cryo-compressed hydrogen (CcH_2)	Liquid organic hydrogen carriers (LOHC)
Liquid hydrogen (LH_2)	Sorbent surface storage (MOFs, zeolites, nanotubes)
Slush hydrogen (SH2)	

The specific storage densities for the above-mentioned physical storage variants are summarized in Figure 65. To better contextualize the values specified, reference is made here to the comparison value for diesel mobility, approximately 9.82 kWh_{th}/l_{diesel}.

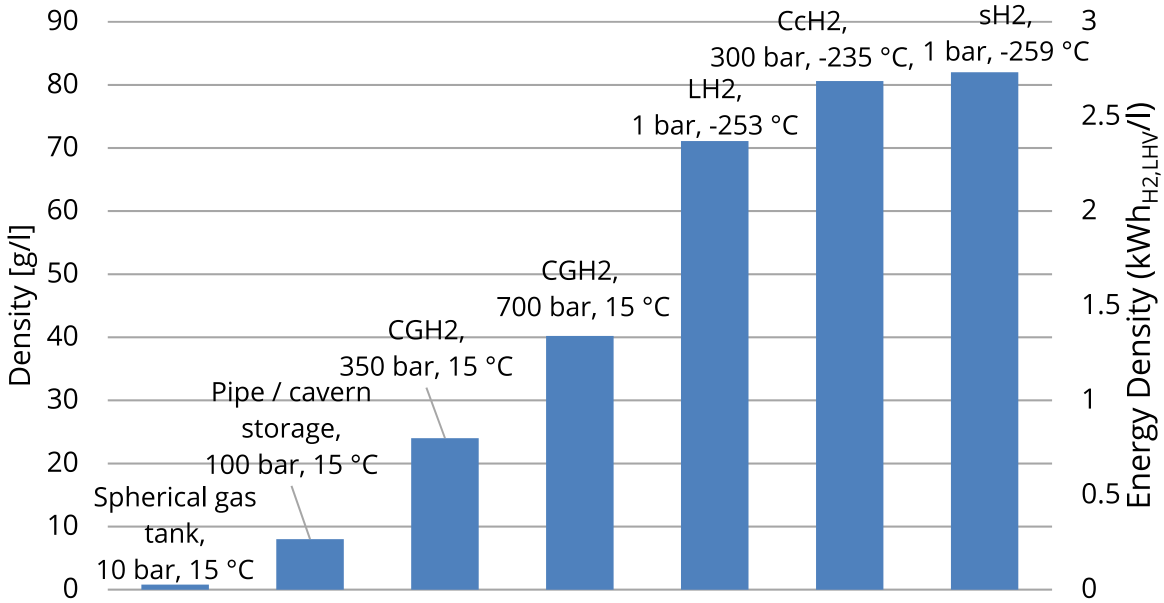


Figure 65: Comparison of specific densities and energy densities for different storage variants, [7] expanded, material data [8]

The storage variants which, thus far, have only been mentioned, are examined in greater technical detail below.

Technical gas container for compressed hydrogen (compressed gas – CGH_2)

Commercially available gas tanks for H_2 storage are made of austenitic stainless steel, because H_2 is adsorbed on material surfaces due to its small molecular size and is dissociated and diffused by the material in an atomic state. This in turn leads to the embrittlement of the material. In addition to the container, valves are needed to reduce pressure. Pipes and sensors can also be used to control pressure, temperature and density. The associated storage pressures can range from virtually atmospheric (gasometer, 2 still used today) to 100 bar for pipe storage units and up to 700 bar in industrial gas containers or gas tanks for mobility applications [5], [7], [9]. The compressor density required for compressed hydrogen is problematic. “About 9 to 12 % of the final energy made available in the form of H_2 is consumed for the compression of hydrogen from 1 to 350 or 700 bar.” [7] (See also Figure 69 in section 14.20). For compression up to approximately 100 bar, hydrogen behaves almost like an ideal gas. This reduces the effort required to compress it to this pressure [10].

Liquid storage in tanks (LH_2)

Hydrogen can be cooled and compressed into a liquid state at temperatures below -252.77 °C and can then be stored in well-insulated storage containers (cryo-storage). Ingress of warmth into the container from wiring, convection and radiation must be minimized to prevent the liquid H_2 evaporating as far as possible. The storage units are double-walled and vacuum-insulated. To avoid any pressure increase from evaporated hydrogen, small amounts of gas are constantly released (boil-off) [7]. These evaporation losses are around 0.3 % to 3 % per day, depending on the size of the container [9]. LH_2 is mostly used in aerospace applications; the largest tank is at the Cape Canaveral rocket launch base (~ 3,800m^3 LH_2). The energy input required to keep the hydrogen liquid is min. 30-40 % of the input current (LHV) [11].

Cold- and cryo-compressed hydrogen (CcH_2)

The compression and cooling processes can be combined to further increase the storage density (cf. Figure 66). To do this, the hydrogen is first cooled and then compressed, but remains gaseous. "How far the hydrogen is cooled determines whether it is cold-compressed hydrogen (above 150 K) or cryo-compressed hydrogen (CcH_2)." [7] CcH2 is usually intended for use in mobility applications. According to [12], the associated storage tank is at the prototype level. The associated compressor and cooling unit were developed with Linde AG (100 kg H2/h; < 1 % LHV energy requirement).

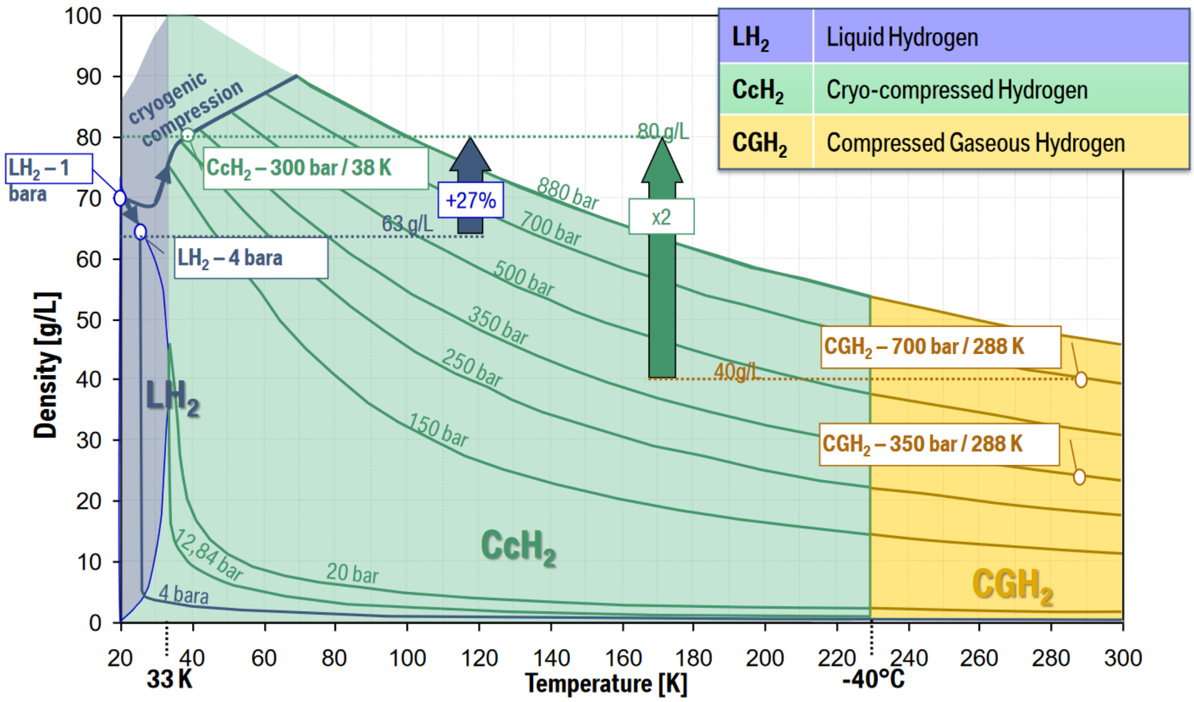


Figure 66: Density of CcH2 [12]

Underground storage

Pore, aquifer and salt cavern storage systems have proven themselves in the gas industry to store larger amounts of natural gas (>100 million m^3). The deeper the deposits are underground (depth), the larger the possible storage densities. Pore storage systems are usually displaced gas or oil deposits, while aquifers are porous water-bearing formations. Both underground storage systems are only conditionally suitable for hydrogen storage. In the spent deposits to be used for storage, up to 50 % of the fossil hydrocarbons remain in the storage system. This would always result in undesired contamination in the case of pure hydrogen use. There are also various minerals and some microorganisms in the stone matrix that could react with the hydrogen [5]. In aquifer storage systems, there is also the problem that the suitability of the geological formation (i.e. that it is porous, that water-bearing layers are under gas-tight, domed stone layers) must be proven through exploration [5]. An example of this is the aquifer storage system that has been operated for more than 20 years by Gaz de France at Beynes, which as a storage volume of 330 million Nm^3. The hydrogen content is 50-60 % [13]. The salt cavern storage systems mentioned above are another variant in which the reactivity and contamination of the H_2 is not such an important consideration. There are artificially created hollow areas in huge underground salt deposits. They are created in the solution mining process when salt is leached out with fresh water. Water-free media (liquid/gaseous hydrocarbons) can then be stored. The storage pressure depends on the depth (minimum pressure: 6 bar/100 m, maximum pressure: 18 bar/100 m). If several caverns are created in parallel, high input and output feed capacities can be achieved in one system. There are several cavern storage systems worldwide for pure hydrogen (cf. Table 33) [14].

Table 33: Storage caverns for hydrogen , expanded with information from [14]

	Great Britain	**USA**		
	Teesside	Clemens Dome	Moss Bluff	Spindletop
Operator	Sabic Petrochemicals	ConocoPhillips	Praxair	Air Liquide
Caverns	3	1	1	1
Commissioned	Early 1970s	1986	2007	Under construction
Geom. volume	3 x 70,000 m^3	580,000 m^3	566,000 m^3	580,000 m^3
Pressure range	Approx. 50 bar (constant)	70 – 135 bar	77 – 134 bar	70 – 135 bar
Energy (working gas $GWh_{chem,LHV}$) (calculation with ideal expansion, 15°C)	~ 25.4 [15]	~ 93.7 (83.3 according to [15])	~ 79.2	~ 93.7

The caverns listed in Table 33 provide practical experience of hydrogen storage. According to [14], there are not yet any hydrogen caverns in Germany because “more safety elements would be required before hydrogen caverns could be approved, such as underground safety valves, additional casings and packer elements. The specific characteristics of hydrogen, such as the high reactivity and volatility, require adjustments to materials that have long been used for natural gas storage. Both aboveground and underground components of the salt cavern storage systems, such as pipelines, fittings, pipework, cementation, etc., must be investigated to ascertain whether adjustment is needed.” The ability of German salt caverns to hold hydrogen without leaking must also be proven [14]. However, [5] assumes that salt caverns are technically leak-proof, provided that operating pressures are maintained. [14] specifies the storage efficiency (not including electrolysis and transport) at 97 %.

Material storage variants are an object of research and are presented in section 16.2a).

16.2. Estimation of potential

a) Technical development potential

In this section, the development opportunities for the technologies mentioned above will be examined in more detail. The material storage variants given in Table 32 are also briefly presented; the later conversion of hydrogen into methane or other chemical compounds (methanol, ammonia, DME, etc.) could be included in this category. These variants are examined in the chapter 13. Power-to-chemicals.

In general, the storage methods with very high storage densities (compression to 700 bar, condensation, material storage, etc.) are conceived for mobility applications (rocket launches, electric vehicles with high range, submarines, etc.). The mobility sector is without doubt a significant challenge for the German energy revolution, but industrial hydrogen storage in the TWh range is being realized in underground storage systems. The pressures required for this are significantly lower and range between 50 and 200 bar; this means efficient compressor technology has the greatest utility for operating the storage systems.

Compressed gas – CGH$_2$

The compression of hydrogen can be performed using various types of compressor. Generally, turbo compressors are suitable for large volume flows and lower pressures. Multi-stage piston compressors reach very high pressures, but process smaller volume flows. For smaller volume flows and high pressures, membrane pumps are also available to industry (cf. Figure 67). System cascading is recommended depending on the field of application.

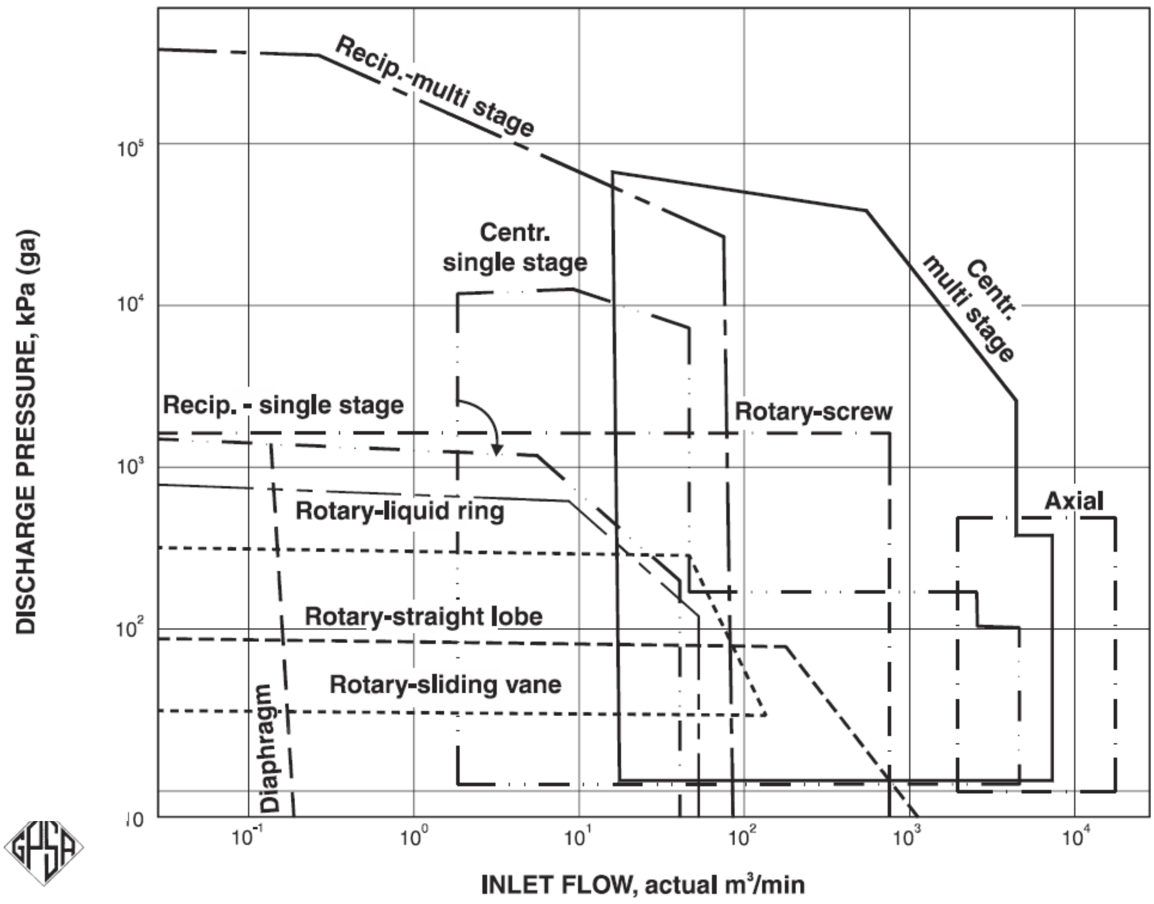


Figure 67: Compressors and fields of application [16]

Ionic compressors are a relatively recent development, finding application in BMW's CcH2 concept for example. The ionic compressor used there is Linde’s IC90 [17], a series circuit of piston compressors filled with an ionic fluid. This has three main advantages. Firstly, the existing compression heat can dissipate very well and the compression takes place almost isothermally (ionic fluid must be recooled). Secondly, the hydrogen does not dissolve in the fluid (no losses/separation of H_2 required). Finally, the piston compressors run constantly with lubrication, which improves lifespan and efficiency [18].

Research has also yielded electro-chemical compressors, whose structure is shown in Figure 68. “Here there is an electro-chemical cell, with a similar structure to a PEM electrolysis cell, in which hydrogen is oxidized on the anode side by applying DC voltage. The protons move over the membrane to the cathode, where they are reduced again with the electrons from the external circuit. The principle of a proton pump offers potential for improvement over mechanical compression, mostly with regard to efficiency and maintenance intensity.” [19]. HyET has already built demonstration plants that compress a few kg H_2 per day [20].

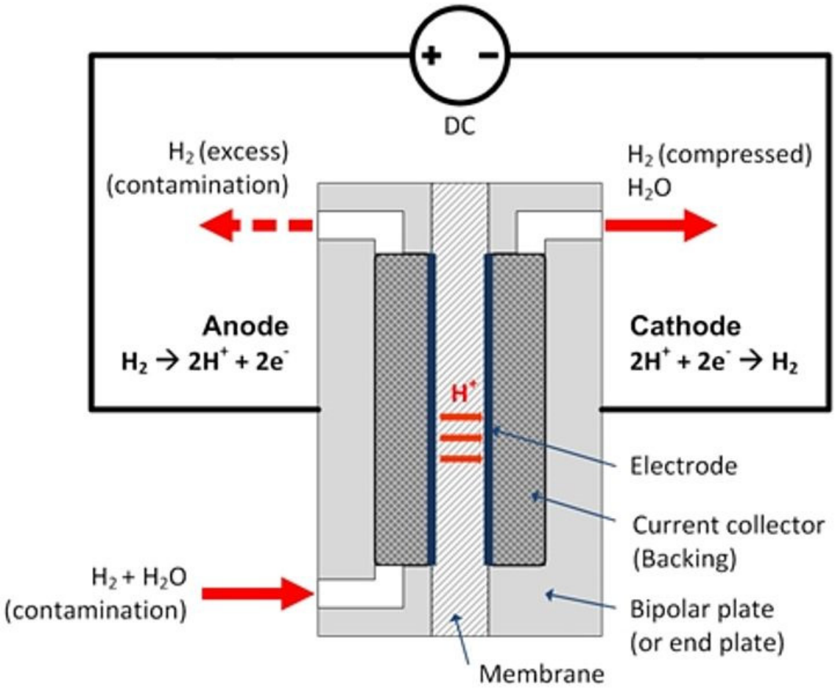


Figure 68: Structure and functional principle of electro-chemical compressors, graphic: Fraunhofer Institute for Solar Energy Systems ISE [19]

Overall, compressor technology is already at a high level of maturity. This is also clear from the theoretical minimum work for compression shown in Figure 69. For moderate compression and storage at approximately 200 bar, less than 5 % of the energy stored (LHV_{H2}) is spent.

Pressurized storage

The basic ability of hydrogen to be stored in salt caverns has already been demonstrated by the plants mentioned above. The project consortium HYPOS has been formed in Germany to improve individual technologies in several sub-projects in order to further develop the existing infrastructure (e.g. the electricity grid, gas network, gas storage systems, hydrogen pipelines) [21]. The projects cover the fields of chemical conversion, transport and storage, assessment, utilization and distribution, efficiency, safety and strategy. Because the projects are chiefly aimed at optimising existing technologies, reassessment using the TRA is not expedient. According to [22], besides technical issues of detail, the main issues that remain relate to efficiency and gas purity. Firstly, it must be possible to compensate for any fluctuations in gas composition in a balanced way, and long-term business models must be developed. Secondly, the gas purity of the hydrogen feed-in is always lower than the purity of the output, which must be taken into account in subsequent fields of application. The salt caverns can be flushed, but residual gas and sump always remain in the cavern. According to [22], however, the membrane process for gas purification is technically mature and does not present any obstacles.

Another approach is followed in the Underground Sun Conversion project by the crude oil exploration company RAG Rohöol-Aufsuchungs Aktiengesellschaft, in which existing pore natural gas storage systems are to be used as biological methanation reactors. In this process, naturally-occurring subterranean micro-organisms turn the supplied hydrogen and carbon dioxide into methane, which is later withdrawn as needed. The Underground Sun Storage research project demonstrated the feasibility of the process at laboratory scale (TRL 3) and is now planned to be implemented in the technical centre by 2020 [23]. This means TRL 5-6 could be achieved once the project has been completed.

Liquid hydrogen (LH_2)

A new approach to liquefying hydrogen is the use of magnetic cooling. In this process, paramagnetic salts are magnetized and demagnetized. During demagnetization outside of an electro-magnetic field, the particles take on a disordered state, which takes energy from the environment. The use of this concept to condense hydrogen is being investigated (Active Magnetic Regenerative Liquefier). The system is currently at laboratory scale and has only been tested in parts [24].

Cooling the liquid to melting point again results in the hydrogen transitioning into a “kind of slush or jelly” [7] (hydrogen slush, SH2) and the storage density can be increased by another 16 %. This approach is being investigated for aerospace purposes [7].

Metal hydride storage (MHS)

A metal hydride can be defined as a concentrated, single-phase bond between a metal and hydrogen. Simple binary metal hydrides can be separated into two basic types by the type of metal-hydrogen bond [9]:

- Saline hydrides:
  - Hydrogen is present as a negatively-charged ion (H^-)
  - Are formed in reactions with metals in the first and second main groups (e.g. sodium hydride, calcium hydride); however, up to magnesium hydride (forming partly ionic and partly covalent bonds with hydrogen), these are too stable to be used as metal hydride storage
- Metallic hydrides:
  - Are formed from transition metals; hydrogen enters a metallic bond
  - High electric and thermal conductivity, but very brittle
  - Typical examples are titanium hydride (TiH_2) and thorium hydride (ThH_2).

A simple MHS tank consists of a pressure hull, metal hydride powder, which forms the storage bed, as well as a valve and a fine particulate filter that stops the powder escaping. High gas flow rates require disproportionately more complex structures. Because heat is removed during loading and added during unloading, an MHS must be able to function both as a pressurized container and as a heat exchanger [25]. There is no evaporation loss from an MHS. Furthermore, it is possible to achieve low pressure losses between 8 and 30 bar, making it easy to couple electrolysers with output pressure ranges on this order. Metal hydride storage has so far only been used in experimental vehicles because a number of problems with MHS have not yet been solved [26], [27]:

- High container weight because it is filled with metal powder
- Hydrides with high storage densities require high temperatures (> 100 °C) in order to be extracted
- Hydrides are not stable in the long term; the metal powder becomes finer and finer (presenting an explosion hazard with oxygen)

Metal hydrides have not yet gained acceptance because "[despite] decades of research [...], no metal hydride has yet been found that has sufficient hydrogen storage capacity in the temperature operating window of a vehicle or a PEM fuel cell." [27]

Liquid organic hydrogen carriers (LOHC)

Another alternative to hydrogen bonding is liquid organic hydrogen carriers. These include N-ethylcarbazole, toluene (turns into methylcyclohexane through hydrogenation), dibenzyltoluene, ammonia borane and formic acid [28]. Hydrogenation (feed-in) takes place exothermically with catalysts at 30-50 bar and 150-200 °C [7]. However, for endothermic dehydrogenation, i.e. extraction at 1-3 bar, temperatures from approximately 250-300 °C are required and the hydrogen must be purified of LOHC vapour [7]. These temperatures are also too high for PEM cells, and so LOHC has not been widely adopted [27]. [29] reports a practical application in a bus with a hydrogen engine, as well as a stationary application combined with a 25 kW_{el} fuel cell. According to information from the German company Hydrogenious Technologies, a plant has already been marketed for a commercial field test with a feed-in capacity of 100 Nm^3_{H2}/h and extraction capacity of 2.5 Nm^3_{H2}/h [30].

Surface storage (sorbents)

Hydrogen can be readily adsorbed on porous surfaces. This is the functional basis of nanotubes and metal organic frameworks (MOFs). Nanotubes are nano-structured carbon compounds that only have appreciable storage capacities at temperatures around 77 K. The capacity falls by at least one order of magnitude at room temperature [27]. According to [31], the hydrogen content in single-walled nanotubes (SWNTs) at room temperature and 45 bar is approximately 0.63 % by weight.

Hydrogen can also be stored in pores in metal organic frameworks (e.g. $C_{36}H_{36}O_{13}Zn_4$). In practice, approximately 5 % by weight is stored as hydrogen at low temperatures (77 K). The storage capacity falls by one order of magnitude at room temperature [27].

Adsorption storage systems therefore remain an object of research.

b) Expansion potential

The expansion potential for chemical storage systems, with a special focus on hydrogen, must be considered from two perspectives. Firstly, the efficiency of storage by compression or condensation is physically limited. These limits and the current technological state of the art are shown in Figure 69. For this reason, the process that has the smallest thermodynamic losses should be chosen for industrial storage. In this case, this means choosing the lowest possible compression.

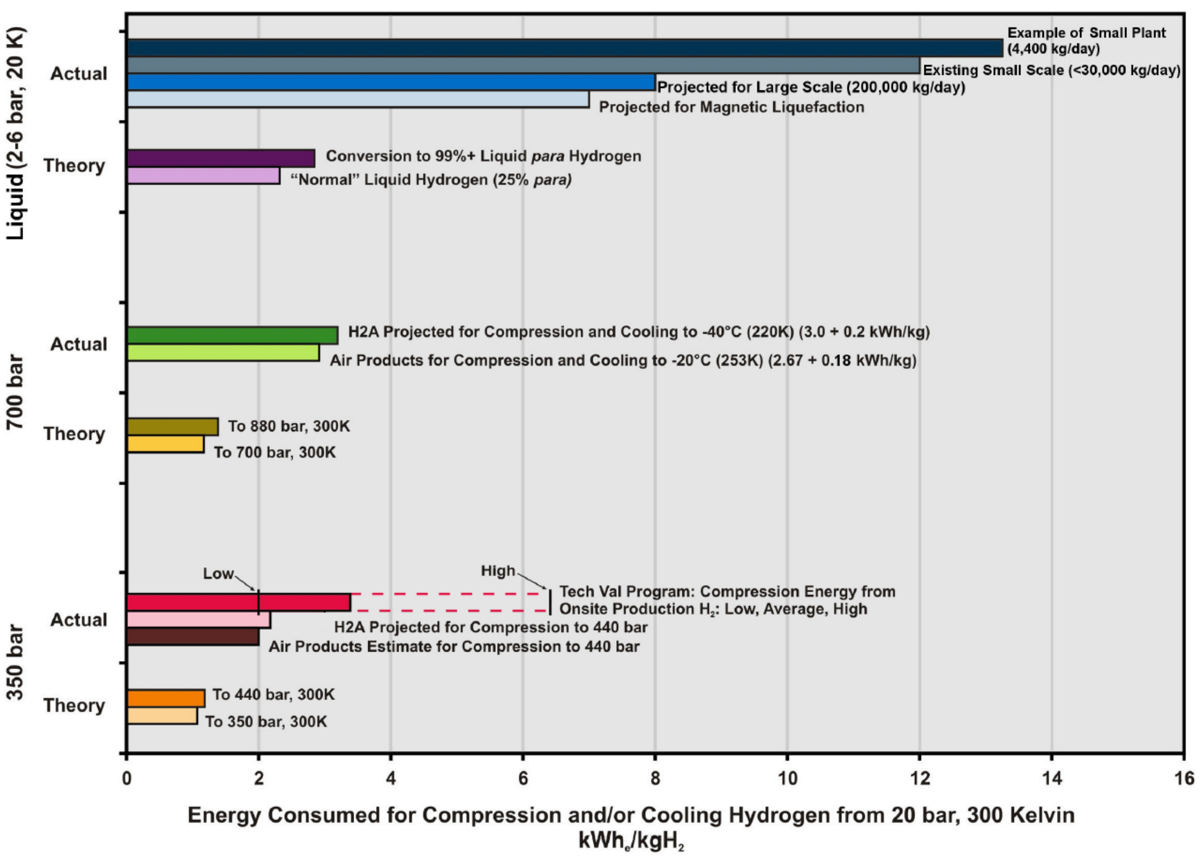


Figure 69: Amount of energy required for hydrogen storage [11]

Secondly, the expansion potential for storage capacity must be considered. Underground storage has the largest storage capacities. There are already some cavern storage systems in Germany (11.8 billion m^3 in caverns, see section 16.3), but the capacity in Germany could be significantly expanded. In a joint project funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), the potential storage capacity (for working gas) in salt formations in the north German basins is estimated and assessed at 1600 $TWh_{th,H2}$ [32].

16.3. Representation of the achieved state of expansion

The current level of expansion for gas storage is published by the German Federal Network Agency in annual monitoring reports. The results are given in Figure 70.

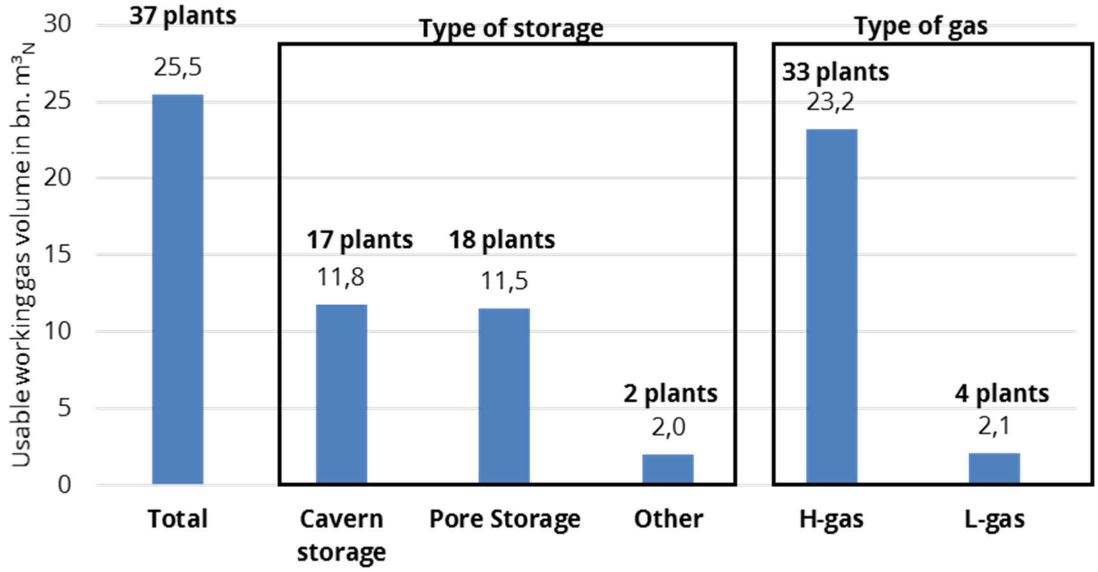


Figure 70: Working gas volume in German underground storage systems, as of 31.12.2016, data based on [3]

If the cavern storage systems were filled with 11.8 billion m³, there would be a theoretical storage capacity of approximately 35.4 $TWh_{th,H2}$. The study [33] determines the following storage capacities for selected existing cavern storage systems:

- Xanten and Epe (North-Rhine Westphalia): approx. 7.2 TWh_{th}
- Jemgum, Krummhörn, Nüttermoor, Etzel, Huntorf, Bremen-Lesum and Harsefeld (northern Germany): 13.8 TWh_{th}
- Bernburg, Staßfurt, Bad Lauchstädt (Saxony-Anhalt:) 5.4 TWh_{th}

16.4. TRL assessment

The storage technologies presented here are strongly focused on hydrogen. This is in view of the fact that the storage of solid, liquid or gaseous fossil energy sources cannot form any technical challenge or bottleneck for the energy revolution. Hydrogen has particular properties as a gaseous energy source that have also been preliminarily presented here. Its low volumetric energy density represents a challenge for economical storage and transport. For this reason, both the storage media and the technologies required for compression have been considered in this chapter. Because the established compression technologies are already state of the art and commercially available in large output spectra (turbo, membrane, piston compressors, each in multi-stage versions and some with intermediate cooling), they have not been discussed in detail. Hydrogen storage in caverns is already generally achievable on a large scale (up to TWh_{th}), as example plants have shown worldwide (cf. Table 33). However, significant challenges still exist in mobile storage and the use of hydrogen for fuel cell vehicles. The TRL classification in Table 34 below can be derived from the aspects presented in this chapter:

Table 34: Results of the TRL analysis

Technology	TRL	Supplementary sources
Hydrogen compression		
• **Turbo compressors**	9	
• **Piston compressors**	9	
• **Membrane compressors**	9	
• **Ionic compressors (H_2 filling stations)**	7	
• **Electro-chemical compressors**	3	
Hydrogen storage		
• **Gasometers up to 1 bar**	9	
• **Pipe storage up to 100 bar**	9	
• **High-pressure containers up to 700 bar**	9	
• **Cavern storage for H_2**	8	
• **Pore/aquifer storage for H_2**	3	
• **Fuel tanks for cryo-compressed H_2 for mobility**	6	
Liquid hydrogen		
• **Tanks for liquid hydrogen**	9	
• **Magnetic cooling**	3	
• **Slush hydrogen**	3	
Material storage		
• **Metal hydride storage**	6	
• **Liquid organic hydrogen carriers (LOHC)**		
○ **For hydrogen logistics**	7	
○ **For storage**	5	
• **Adsorption storage (MOFs, nanotubes)**	4	

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17. Electro-chemical storage systems[32]

17.1. Technology description

Electro-chemical storage systems generally refer to batteries. “A battery consists of a cell or several cells electrically connected with each other.” [1]. No distinction is therefore made here between accumulator batteries and ordinary batteries because their function is primarily based on the type of underlying galvanic cell. A basic component of a galvanic cell is one positive and one negative electrode made from different materials that are connected via an electron-and-ion conductor (electrolyte). The basic structure is shown in Figure 71 based on the example of a lithium-ion cell. If the electrical circuit to the conductor is closed and the cell is discharged, there is oxidation in the negative electrode (the anode) and reduction in the positive electrode (cathode), i.e. an overall redox reaction. If this process is irreversible, this is known as a primary cell. If the process can be reversed by an electrical current (charging), then the cell is a secondary cell and the electrodes reverse their roles. The material combinations that can be used are very diverse, so only the most important secondary cells are considered in this chapter. Fuel cells are also considered galvanic cells and are sometimes called tertiary cells. They are discussed in a separate chapter.

Before discussing the individual cell types, it is necessary to present the key figures for a battery storage system. These are:

Table 35: Key figures of battery storage systems [2]

Parameter	Meaning
Output	Charging/discharging output
Output density	Output per unit of mass/volume
Output gradient	Output-related charging/discharging speed
Reaction time	Response/access time
Storage capacity	Energy content of the storage unit
Energy density	Amount of energy per unit of mass/volume
Efficiency	Efficiency of energy conversion or energy storage process
Rate of self-discharge	Percentage of stored energy lost by self-discharge during a period of time
Depth of discharge (DOD)	Percentage of energy withdrawal from a battery in relation to the total capacity (0% DOD = full)
State of charge (SOC)	Describes the amount of energy that can still be withdrawn from the storage unit
Cycle stability	Maximum number of cycles until the storage capacity of a storage unit falls below a specified value
Rate of charge and discharge (C rate)	Refers to the current as a multiple of capacity; e.g. a C rate of 0.5 with a 5 Ah battery indicates a (charging) current of 2.5 A.

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[32] The following explanations and correlations are based in part on the research project carried out by Lisa Troeger and supervised by myself: “Methods of assessing the potential of electro-chemical storage systems”, diploma thesis, TU Dresden, 2018.

In practice, operating conditions have a significant influence on the number of cycles and the service life of a battery. In general, the specified service life of a battery is shortened and the number of possible cycles reduced by [3]:

- High depth of discharge
- High C rates
- High temperatures during use (i.e. high ambient temperature)

The most common battery types and their levels of development are presented below. A generalized comparison of the relevant key figures is given in Table 40 at the end of this chapter. This makes clear that the energy and output figures are spread throughout wide ranges even within one battery type. Depending on cell configuration, the batteries are then used in battery storage systems designed for either output (e.g. start-up procedures) or energy (e.g. stationary, long-term supply for shipping networks, signalling systems, etc.) [6].

Lead-acid (PbA) batteries

A lead-acid accumulator battery has a positive electrode made of lead oxide (PbO_2), a negative electrode made of lead (Pb) and the electrolyte is 37 % sulphuric acid (H_2SO_4) when fully charged [5]. The cell reaction (20) shows that the acid concentration decreases during discharge [6]:

$$\text{Positive electrode:} \quad PbO_2 + 3H^+ + HSO_4^- + 2e^- \leftrightarrow PbSO_4 + 2\,H_2O \qquad (18)$$

$$\text{Negative electrode:} \quad \overset{\pm 0}{Pb} + HSO_4^- \leftrightarrow \overset{+2}{Pb}SO_4 + H^+ + 2e^- \qquad (19)$$

$$\text{Cell reaction:} \quad \overset{+4}{Pb}O_2 + \overset{\pm 0}{Pb} + 2HSO_4^- + 2H^+ \leftrightarrow 2\overset{+2}{Pb}SO_4 + 2\,H_2O \qquad (20)$$

Lead-acid accumulator batteries are technically mature and have proven themselves in use for many applications (e.g. automotive, uninterruptible power supply (UPS) units, stand-alone PV systems). Further developments have taken place in electrode configuration (tubular plate, grid plate designs) and electrolyte bindings. The liquid electrolyte can be thickened and bound by a mat (absorbed glass mat – AGM – battery) or by adding SiO_2 (gel battery). The systems only have relief valves to vent unrecombined gases. This reduces the cost of maintenance (i.e. re-filling it with water) and increases the number of cycles that can be performed. Both variants are state-of-the-art technology and are commercially available [3]. Example systems worth mentioning here are the battery storage systems in Berlin-Steglitz (1986-1994; 17 MW_{el}, 5.6 MWh_{el} [6]) and in Goldsmith, Texas (36 MW_{el}, replaced in 2016 by a Li-Ion battery [7], [8]).

Nickel-cadmium (NiCd) and nickel-metal hydride (NiMH)

NiCd batteries are also a mature technology and the cells consist of a positive nickel hydroxide electrode and a negative cadmium electrode. The electrolyte is a 20 %

potassium hydroxide solution. Compared with lead-acid batteries, they have a higher number of cycles and gravimetric energy density (cf. Table 40) [3]. They are also technically mature, but the toxicity of cadmium means that they are rarely used. This disadvantage is circumvented with the use of NiMH batteries, in which the cadmium is replaced with a lanthanum-based metal alloy. This reduces cycle stability and increases gravimetric energy density. NiMH batteries self-discharge relatively quickly (20-50 % per month) [9]. The self-discharge is caused by the hydrogen binding to the positive Ni electrodes and has been limited to approximately 15 % p.a. with the development of low self-discharge NiMH (LSD-NiMH) batteries. The improvement is thanks to an improved separator and an additional alloy that has a hydrogen-binding layer on the anode side. This reduces the natural decay of the anode side and cathode degradation caused by hydrogen. It also improves cycle stability and reduces the internal resistance of the cell. As the manufacturer Sanyo is already marketing the 4th generation of LSD-NiMH batteries (lasting approximately 2,100 charging cycles [10]), the technology can be considered mature. Large plants based on NiCd have also been implemented, such as the plant in Fairbanks Alaska, which has been in operation since 2003 with 27 MW_{el} (13,760 cells, 6.75 MWh_{el}) [11].

Lithium-ion batteries (LiBs)

A lithium-ion battery consists of several galvanic cells whose structure is shown in Figure 71 as an example. The cell consists of two electrodes with an ion-conductive electrolyte and a porous separator membrane in between them that insulates the electrodes from each other. The electrodes consist of the active materials, e.g. graphite or amorphous carbon on the anode side and metal oxides on the cathode side (e.g. lithium cobalt oxide (LCO)) and a collector material typical for this specific purpose. Copper is usually used for the negative electrode and aluminium for the positive. When the battery is charged and discharged, lithium ions move back and forth between the electrodes or are stored in the crystal lattice of the active materials [12].

The large amount of attention currently being paid to LiBs is a result of their good output data in comparison with other galvanic cells (cf. Table 40). The characteristics of the battery can vary widely depending on the electrode material used. High-energy combinations with high storage capacities or output-oriented batteries can both be manufactured, for example. Figure 72 provides an overview of the possible electrode materials.

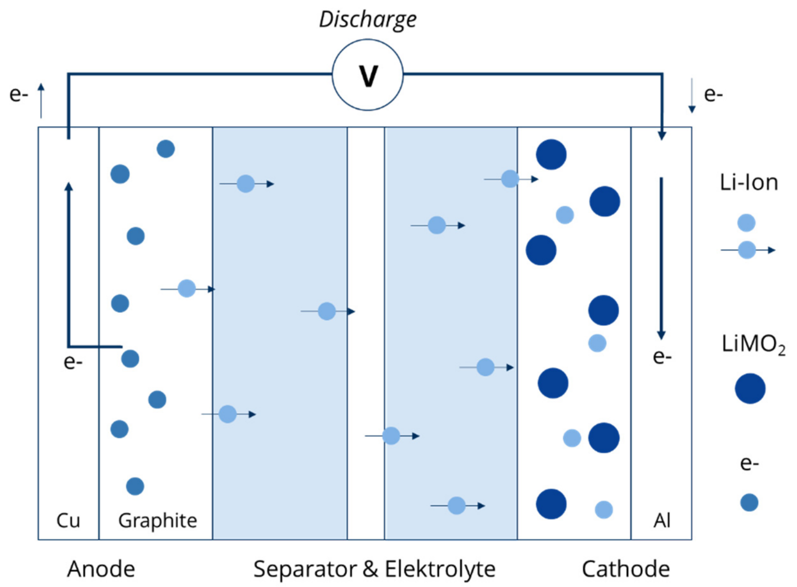

Figure 71: Structure of a lithium-ion battery cell, [13], translated, based on [12]

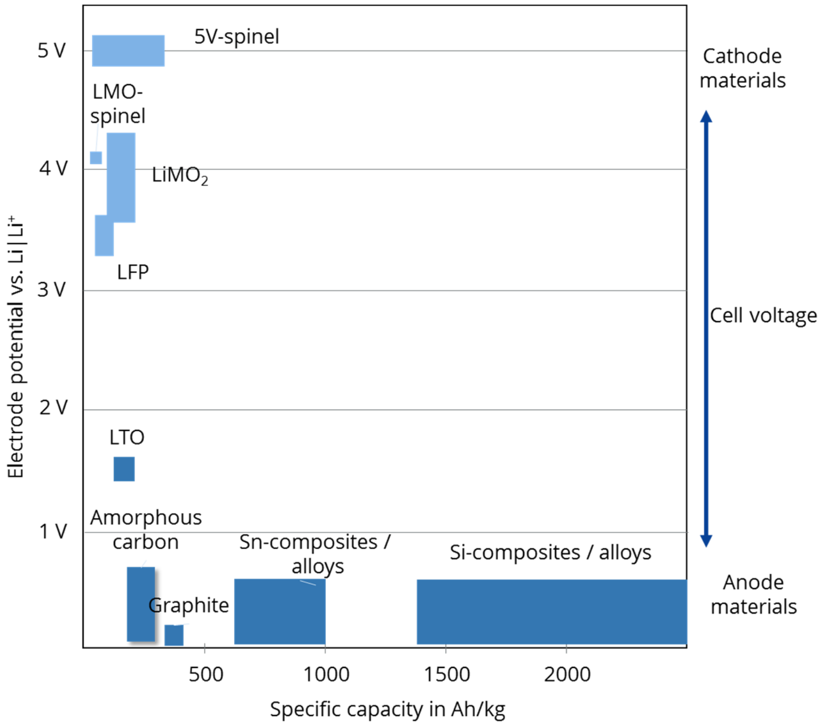

Figure 72: Potential and specific capacities of different electrode materials, [13], translated, based on [14]

However, because of safety-relevant interactions, not all materials can be combined freely [14]. The materials used in commercial LiBs are [15]:

- Anode: Graphite, amorphous carbon, lithium titanate (LTO)
- Cathode: Classified, based on crystal structures, as layered metal oxides (lithium cobalt oxide $LiCoO_2$; lithium manganese oxide $LiMnO_2$; mixed crystals such as lithium nickel cobalt manganese oxide), spinels (lithium manganese oxide spinel;

with manganese nano particles = 5 V spinels for high outputs) and olivines (lithium iron phosphate, LFP)

- Electrolyte: liquid solvents (ethylene carbonate, propylene carbonate, dimethyl carbonate, diethyl carbonate) combined with lithium hexafluorophosphate ($LiPF_6$) as a conductive salt, and additives (usually vinylene carbonate) or polymer electrolyte (polyethylene oxide; electro-chemically and mechanically more stable, more compact cell design) [16]
- Separator: polyethylene and polypropylene are widely used; however, these materials are sensitive to temperature and shrink at higher temperatures (melting from 160 °C), which can bring the electrodes into direct contact

LiBs are already widely used in mobile devices and decentralized PV storage units. Currently, the largest operational LiB system is the Hornsdale Power Reserve in Australia (100 MW_{el}/129 MWh_{el}) [17].

High-temperature batteries (HTBs), sodium-sulphur (NaS) and sodium-nickel chloride ($NaNiCl_2$)

HTBs are another type of cell. They work at a temperature around 300 °C, at which the electrodes are present as liquids and are separated by a solid electrolyte. The NaS battery is a commercial example of this type of cell; its structure is shown in Figure 73.

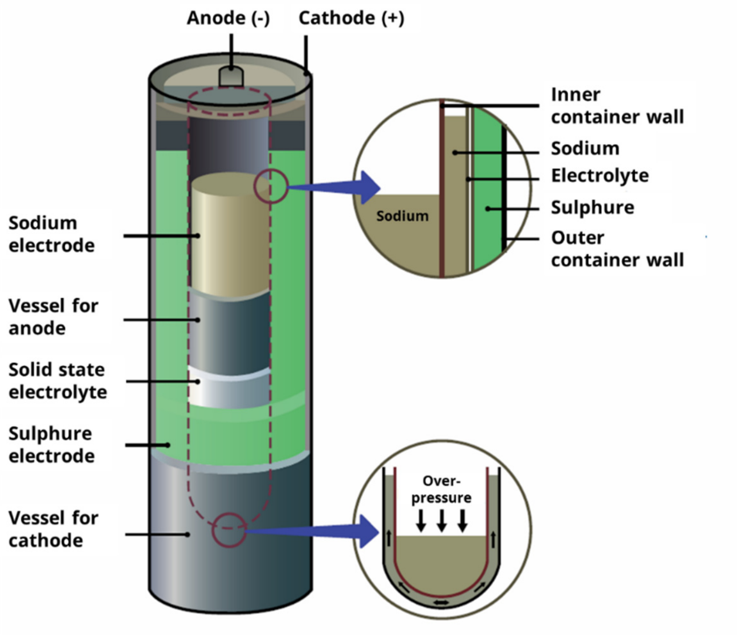

Figure 73: Structure of an HT-NaS battery [6], translated

During discharge, the sodium functions as a cathode and is reduced. The liquid sulphur is in a graphite felt (because it is not conductive itself) and acts as the anode. The electrolyte is a ceramic, doped β-aluminate (Al_2O_3) that begins to conduct ions at 300 °C and lets sodium ions through to the sulphur during discharge (formula (21) according to [6]):

$$2\,Na + 5\,S \rightarrow Na_2S_5 \qquad \text{2.08 V open-circuit voltage} \qquad (21)$$

After approximately 65 % discharge, the available sulphur decreases and sodium tetrasulphide Na_2S_4 is formed. During this process, the cell voltage falls to 1.9 V [6]. The battery has the lowest internal resistance at approximately 300-350 °C. The NaS-HTB has low self-discharge (0.05 % per day) and does not need to be heated in continuous operation because discharging is exothermic and the temperature only drops slightly during charging because of the ohmic resistance. Battery downtime is problematic; the cells must be heated during this time. This can increase self-discharge to up to 20 % per day [3]. NaS batteries can be significantly overloaded for short periods (5x rated output for approximately 30 s) [3]. The biggest problem with HTBs is the high reactivity of the liquid sodium with water and the exothermic reaction with sulphur, which can cause entire modules to catch fire and be destroyed if the cell is damaged and further protective measures are not in place [6]. Na-$NiCl_2$ batteries are another variation (also ZEBRA – Zero Emission Battery Research Activities – batteries). Here, the sodium functions as the anode and the cathode is $NiCl_2$, NaCl sometimes with $FeCl_2$. The main advantage over NaS, according to [3], is improved safety thanks to the solid electrolyte based on $NaAlCl_4$. The liquid sodium reacts with the electrolytes first and solidifies.

The output figures for NaS are given in Table 40. More than 450 MW_{el} of battery output is installed worldwide [3], and the largest systems are operated in Japan to offset wind power facilities (Rokkasho – 30 MW_{el}, 245 MWh_{el} [18]; Buzen – 50 MW_{el}, 300 MWh_{el} [19]). According to [20], Na-$NiCl_2$ batteries have been implemented up to 5 MW_{el} and 10 MWh_{el}.

Redox flow batteries (RFBs)

The RFB, also called a flow battery, is a galvanic cell in which the redox pairs are dissolved in the electrolyte as ions. The electrolyte functions as an energy source that flows through two half-cells. This means that in an RFB, output and capacity are decoupled and are scalable independently of each other. The amount of electrolyte and the concentration of the redox-active species in the solution determine the capacity. The output depends on the cell surface and the number of cells in a stack.

The vanadium RFB (VRFB) was the first to penetrate the market; its structure in a cell reaction is shown in Figure 74.

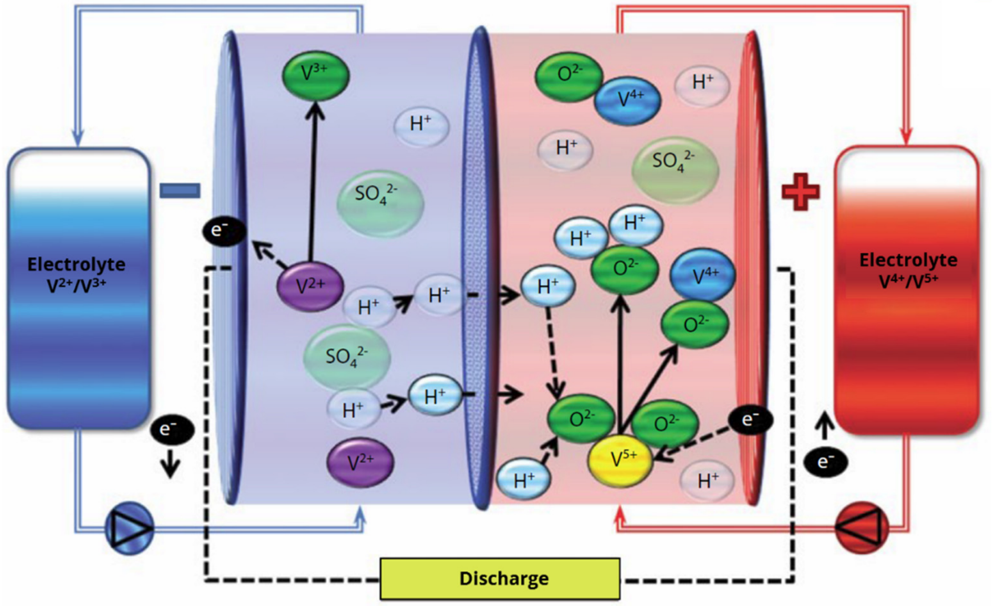

Figure 74: Reactions inside the half cells of a vanadium RFB [6], translated

A solution of vanadium pentoxide (V_2O_5) in aqueous sulphuric acid (H_2SO_4) is used as an energy-storing electrolyte. The solubility of V_2O_5 in H_2SO_4 is limited and limits the energy density to 15-25 Wh/l at approximately 1.4 V cell voltage [6]. The electrolyte is pumped through the cell and hydraulically separated by a membrane. The membrane allows ion exchange, and perfluorinated, sulphonated, ion-selective Nafion® membranes of type 115 and 117 are usually used (for good ion conductivity and chemical stability). Reduction and oxidation take place at the electrodes. The electrodes must have a large surface and must be electrically conductive and chemically and electro-chemically stable. Carbon felt electrodes consisting of polyacrylonitrile fibres (PAN) or cellulose/viscous fibres and graphite are therefore frequently used [20]. Several cells are separated in an RFB stack by bipolar plates that are mostly made of graphite (> 80 %; conductive and corrosion-resistant) and polymers (thermosetting plastics; fluoropolymers or phenolic resin) as a binder. Pumps, wires, valves, heat exchangers and electrolyte tanks are also required for an RFB; these must be resistant to sulphuric acid or must have a protective coating [6]. Because the hydraulic peripherals are subject to a certain inertia during operation, RFBs are limited in the speed at which they can react. The start-up and shut-down phases (flushing and emptying electrode half cells) can therefore take up to 7 minutes in larger systems [3]. The VRFB is so far the most widely used. Other electrolytes, especially those with larger volumetric energy densities, are shown in 13.2a). The largest system in Germany, at 2 MW_{el} and 20 MWh_{el}, is the demonstrator in Pfinztal [22]. In Japan, the Minami Hayakita Station, a VRFB with an output of 15 MW_{el} and a capacity of 60 MWh_{el}, was commissioned in 2015 [20]. Another large project with a target output of 200 MW_{el} and 800 MWh_{el} storage capacity is currently under construction in Dalian, Lioaning, China [20].

17.2. Estimation of potential

a) Technical development potential

This section examines the possibilities for further development of the storage systems mentioned above. Some of these battery storage systems are already very mature and widely used, so development is primarily in the form of optimization and improvements to existing technologies, rather than fundamental changes to them.

This is the case for lead-acid batteries in particular. The cell chemistry remains unchanged here, but thermal and electrical management becomes important in wiring large battery systems because excessive temperature increases – including local ones – reduce the service life of the battery. This is a result of sulphation (formation of sulphate crystals), corrosion on the anode (increased internal resistance), dendrite formation with deep discharge, acid layering (countered with electrolyte circulation) and electrolyte loss from gassing (unavoidable electrolysis; can be controlled by automatically topping up electrolyte with distilled water). For this reason, the thermal behaviour of cells, stacks and entire containers is being simulated to optimize cooling.

The ecological disadvantages of NiCd batteries have been mitigated by the introduction of nickel-metal hydride batteries. In NiMH batteries, the central problem of rapid self-discharge has already been tackled by introducing LSD-NiMH.

Thermal management is even more important for high-temperature batteries (HTBs) than for lead-acid batteries. Battery stacks are therefore fitted with a large number of vacuum-insulated thermal elements to maintain a full picture of the battery's condition. Deep discharge > 70 % is also avoided because the internal resistance and therefore thermal losses significantly increase and the cell voltage decreases (through formation of Na_2S_3 instead of Na_2S_5). Other development work addresses the safety of the cells. Because individual cells can always be faulty, the cells are insulated thermally and electrically between each other and the cell blocks against each other. Fireproof shielding is installed between module levels [6].

Where redox flow batteries are used, the energy density of vanadium-based electrolytes is still low at first. The limited solubility of the V_2O_5 can be improved through the use of ionic fluids [6], but these only allow low electric current densities [23]. The sulphuric acid solution can also be modified with inorganic additives (H_3PO_4 and $(NH_4)_2SO_4$) and other acids (HCl) and the solubility of vanadium improved [23]. Other developments focus on the choice of material for the bipolar plates and membranes and the ideal connection across the pressed-in graphite felt [24]. There are many other metallic RFBs reported in [23] (polysulphide-bromide, zinc-bromine, lithium) that work with organic solvents and have higher energy densities than VRBs. However, these are mostly limited to laboratory tests. The use of organic electrolytes (polymers) in organic or inorganic solvents is expected to produce sinificant improvements in the performance and environmental compatibility of RFBs [23]. The energy supplier EWE is planning an RFB with 700 MWh_{el} storage capacity based on polymers bound in a saline solution. The storage capacity is achieved using existing salt caverns [25].

There are many different approaches for the further development of lithium-ion batteries. The main disadvantages compared with lead-acid technology are the high dependence on temperature, significant safety risks and the restrictions and precautions associated with these, as well as higher costs [15]. These disadvantages can be partly resolved, and cycle stability improved, using solid electrolytes. However, these also increase internal resistance, so more material combinations must be investigated [26]. In electric mobility, there are high quality requirements placed on separators for LiBs. Large-format and long-lasting cells and separators should be used and the safety and reliability of the cells are central considerations. The separator must be protected mechanically against puncture and thermally against shrinking and fusing. Alternative separator concepts work with layered membranes and separators made of nano fibre mat materials, for example [27]. The overall focus of development, however, is primarily on the development of new electrode materials and combinations. These include coatings, particle size variations and new additives. Because of the large number of publications, an overview of commercial cells and further developments is given in Table 36.

Table 36: TRL overview of commercial cells [28] and research cells (based on structured literature analysis in [13])

Cathode	Anode	Commercialized	Applications (examples)	TRL
NCA	Graphite	1999	Electric cars such as Tesla Model S	9
LCO	Graphite	1991	Consumer applications	9
NMC	Graphite	2008	E-bikes; electric cars like the Nissan Leaf	9
LMO spinel or LMO spinel/NMC	Graphite	1996	Power tools; electric cars like the Chevy Volt, BMW i3	9
LFP	Graphite	1996	Consumer applications; stationary storage units	9
LMO spinel or NMC	LTO	2008	Electric cars like the Mitsubishi i-MiEV, Honda Fit electric car	9

Table continued on next page.

	Active materials	TRL
Anode materials	Graphite/graphene	4 - 5
	Carbon	4 - 5
	LTO	4
	Silicon composite and alloys	4 - 5
	Tin composite and alloys	4
Cathode materials	LCO	2 - 6
	LNO	2 - 4
	LMO	3 - 4
	NMC	4 - 6
	NCA	4
	LMO spinel	3 - 5
	High-voltage spinel	4
	LFP	4

The possibility of metal-air batteries is still a very recent direction of technological research. In the long term, these future technologies could enter the market some time after 2030 and could exceed the output parameters of LiBs, RFBs and other battery types with regard to service life, energy density and output density (theoretically several thousand Wh/kg) by a significant margin [29]. Oxygen from the atmosphere would have to serve as a cathode element in a porous base material. The chargeability of sodium-, zinc- and lithium-air batteries has already been demonstrated experimentally [3]. The zinc-air cell has an energy density of 700 Wh_{el}/kg and an efficiency of 60-65 %. The cycle stability is still very low at < 100 charging cycles [3]. As yet, there has been no breakthrough in these novel battery technologies. The lithium-air battery is still at the basic research stage.

b) Expansion potential

At present, the necessary expansion of energy storage systems can only be calculated using theoretical scenarios. In doing so, it is possible to differentiate between short-term and long-term storage systems. Electro-chemical storage systems are classified as short-term storage systems because of their limited capacity and high output capability. The storage requirement for short-term storage systems results from market-based and grid-based electricity surpluses [2]. In this context, market-based means that more electrical energy is being provided than is currently required to meet demand. Grid-based surpluses result from limited transport capacity that is in turn a result of a lack of grid expansion. Because the calculation and simulation of grid utilization is a complex field, capacitively ideal transferability is assumed in most studies and only the surpluses determined by the market remain. However, this approach ignores some of the storage technology behaviour that actually benefits the grid and can even lead to overloading if only the market is taken into account (e.g. a storage system could be charged in an overloaded area because of low electricity prices caused by oversupply). "The study results predicting when long-term storage systems will be needed fluctuate between 60 and 95 % renewable energy sources for gross electricity consumption. Because of the lower costs of electricity storage for shorter storage durations, short-term storage systems are needed earlier. Factors that have a significant influence on the requirement for stored electricity include imports and exports, the flexibilization of conventional power plant parks and the flexible integration of new electricity consumers, such as electric vehicles, air conditioning systems and electric heat pumps." [2].

These factors must at least be considered in the following when taking into account the upper limit of output for short-term storage systems from several studies Figure 75:

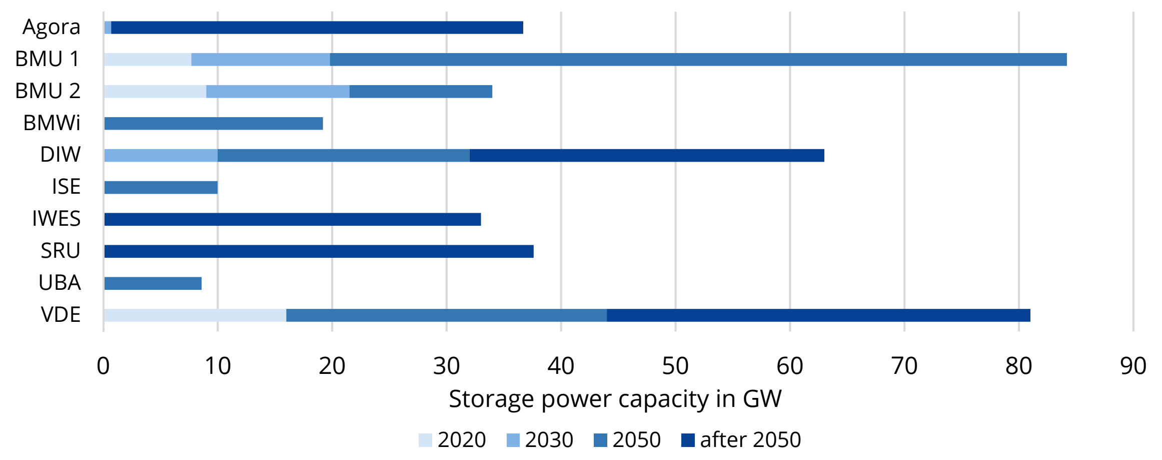

Figure 75: Upper limit of short-term storage requirement in Germany according to storage studies, [13], translated

Table 37: Requirement for battery storage systems for the energy revolution

Source	2020	2033	2050	After 2050
BMWi	-	-	0-19.2 GW [Lead-acid]	-
DIW	-	-	6.5 GW [Lithium-ion]	7 GW [Lithium-ion]
IWES	-	-	10 GW	-
VDE	8 GW [Sodium-sulphur; lead-acid]	-	16.8 GW [Sodium-sulphur; lead-acid; lithium-ion]	-
Agora	-	0.7 GW	0 - 36 GW [Including pumped-storage unit]	-
ISE	-	-	Yes	-

Agora - Agora Energiewende, initiative of the Mercator Foundation and the European Climate Foundation [30]
BMU 1 - German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety [31]
BMU 2 - German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety [32]
BMWi - German Federal Ministry for Economic Affairs and Energy [33]
DIW - German Institute for Economic Research [34]
ISE - Fraunhofer Institute for Solar Energy Systems [35]
IWES - Fraunhofer Institute for Wind Energy and Energy System Technology [36]
SRU - German Advisory Council on the Environment [37]
UBA – German Federal Environment Agency [38]
VDE - Association for Electrical, Electronic & Information Technologies [39]

Some studies also specify concrete, scenario-dependent output ranges for battery storage systems (cf. Table 37). The scenarios for the required storage output until 2050 fluctuate between 0 and 36 GW_{el}.

17.3. Representation of the achieved state of expansion

The current level of expansion for the various electro-chemical storage systems in Germany is shown in Table 38 but is by no means exhaustive; it considers only systems that are currently in operation and is based on the data from [20]. The table includes primarily large storage systems. This means the applications of mobility, military technology, household applications, etc. are neglected, even though they do contribute to further development and to the technological state of the art.

Table 38: Level of expansion of electro-chemical storage systems in Germany [20]

Battery type	Output min/max [kW_{el}]	Capacity min/max [kWh_{el}]	Number	Total output [MW_{el}]/ Total capacity [MWh_{el}]
Vanadium RFB	10/325	100/1,600	6	1.025/4.515
Lead-acid battery[33]	15/1,500	30/1,005	4	1.665/1.335
Lithium-ion	3/15,000	4/22,500	31	143.3[34]/207.2
HT batteries (NaS)	30/1,000	76/6,000	3	1.83/10.87

17.4. TRL assessment

The electro-chemical storage technologies presented here are technically mature and available up to a certain order of magnitude. In the field of large storage units, i.e. outputs and storage capacities in the MW_{el} and MWh_{el} range, several demonstrators are commercially available. The following TRL classification in Table 39 can therefore be derived from the aspects presented in this chapter:

Table 39: Results of the TRL analysis

Technology	TRL	Supplementary sources
Lead-acid batteries up to 20 MW_{el}	9	
NiCd and NiMH batteries up to 20 MW_{el}	9	
• LSD-NiMH batteries	9	
Lithium-ion batteries (LiBs) up to 100 MW_{el}	8	
Lithium-ion batteries (LiBs) up to 15 MW_{el}	9	
• Cell level: NCA, LCO, NMC, LMO, LFP, LTO	9	
• Cell level: Silicon, tin composite	5	
High-temperature batteries (HTBs)		
• NaS up to 50 MW_{el}	8	
• ZEBRA (Na-NiCl2) up to 5 MW_{el}	8	
Redox flow batteries (RFBs) up to 1 MW_{el}	9	
• VRFBs up to 15 MW_{el}	8	
• Zinc-bromide up to 1 MW_{el}	8	
• Polymer-based organic RFBs (cells)	4	
Metal-air batteries	4	
• Zinc-air accumulator batteries	5	

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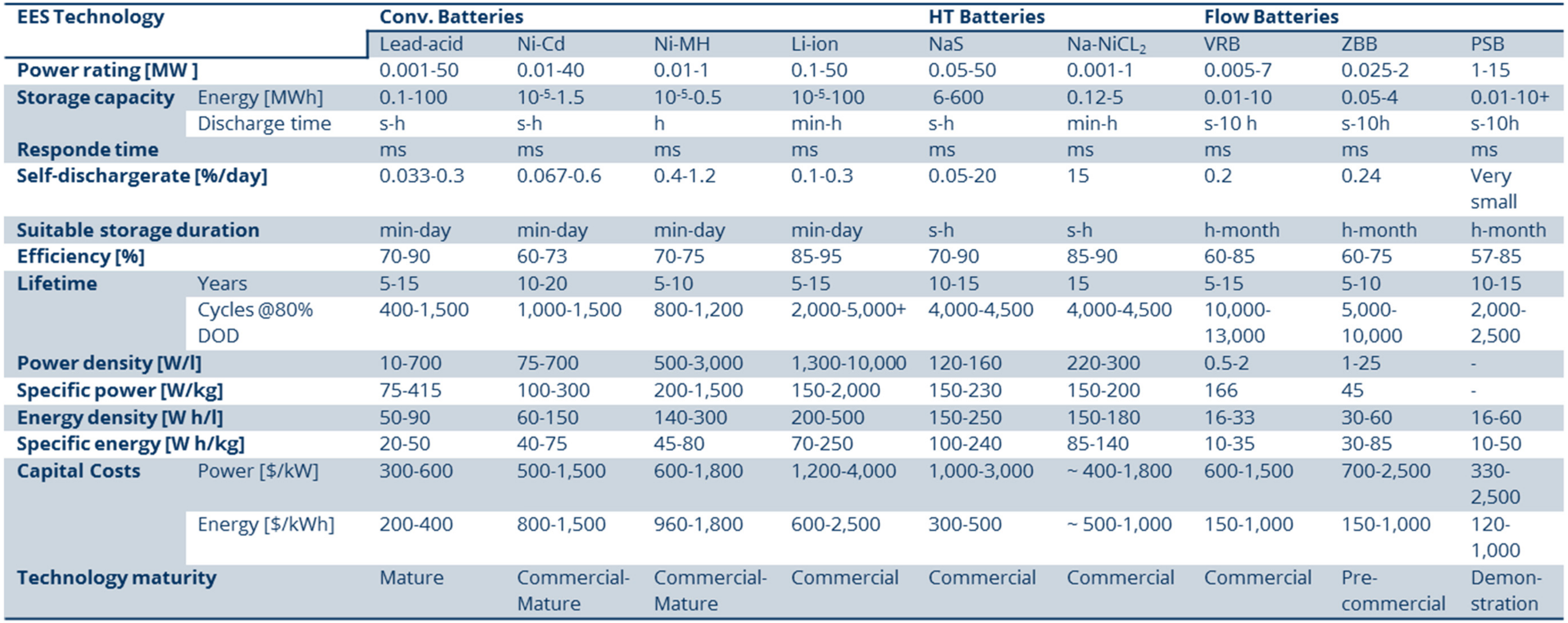
[33] The extremely low number is implausible and is a result of existing lead-acid batteries being undocumented. This lack of visibility must be taken into account when considering the table.

[34] 188 MW_{el} decentralised LiBs (home storage units) are also recorded for 34,000 PV systems at 2 kW apiece.

Table 40: Overview of key figures for battery systems [3]



EES Technology		Conv. Batteries				HT Batteries		Flow Batteries		
		Lead-acid	Ni-Cd	Ni-MH	Li-ion	NaS	Na-NiCL$_2$	VRB	ZBB	PSB
Power rating [MW]		0.001-50	0.01-40	0.01-1	0.1-50	0.05-50	0.001-1	0.005-7	0.025-2	1-15
Storage capacity	Energy [MWh]	0.1-100	10^{-5}-1.5	10^{-5}-0.5	10^{-5}-100	6-600	0.12-5	0.01-10	0.05-4	0.01-10+
	Discharge time	s-h	s-h	h	min-h	s-h	min-h	s-10 h	s-10h	s-10h
Responde time		ms	ms	ms	ms	ms	ms	ms	ms	ms
Self-dischargerate [%/day]		0.033-0.3	0.067-0.6	0.4-1.2	0.1-0.3	0.05-20	15	0.2	0.24	Very small
Suitable storage duration		min-day	min-day	min-day	min-day	s-h	s-h	h-month	h-month	h-month
Efficiency [%]		70-90	60-73	70-75	85-95	70-90	85-90	60-85	60-75	57-85
Lifetime	Years	5-15	10-20	5-10	5-15	10-15	15	5-15	5-10	10-15
	Cycles @80% DOD	400-1,500	1,000-1,500	800-1,200	2,000-5,000+	4,000-4,500	4,000-4,500	10,000-13,000	5,000-10,000	2,000-2,500
Power density [W/l]		10-700	75-700	500-3,000	1,300-10,000	120-160	220-300	0.5-2	1-25	-
Specific power [W/kg]		75-415	100-300	200-1,500	150-2,000	150-230	150-200	166	45	-
Energy density [W h/l]		50-90	60-150	140-300	200-500	150-250	150-180	16-33	30-60	16-60
Specific energy [W h/kg]		20-50	40-75	45-80	70-250	100-240	85-140	10-35	30-85	10-50
Capital Costs	Power [$/kW]	300-600	500-1,500	600-1,800	1,200-4,000	1,000-3,000	~ 400-1,800	600-1,500	700-2,500	330-2,500
	Energy [$/kWh]	200-400	800-1,500	960-1,800	600-2,500	300-500	~ 500-1,000	150-1,000	150-1,000	120-1,000
Technology maturity		Mature	Commercial-Mature	Commercial-Mature	Commercial	Commercial	Commercial	Commercial	Pre-commercial	Demon-stration

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18. Gas engines/gas turbines for hydrogen combustion

18.1. Technology description

This chapter considers the use of hydrogen in conventional engines and gas turbines. Here, in contrast to the fuel cell, chemical energy is first converted into thermal energy and then into mechanical energy. The basic physical and technical principles of gasoline and diesel engines and gas turbines are not considered in depth. The aforementioned technologies belong to the state of the art and are mature in the sense of their TRL. Even so, it is worth considering the co-combustion (mixed with natural gas or as synthesis gas) or pure combustion of hydrogen for the following reasons: the implementation of the power-to-gas process, in the simplest case, leads to (local) hydrogen enrichment in the natural gas network, and it is generally desirable to use the existing infrastructure.

The use of hydrogen in internal combustion engines has certain advantages. The exhaust gas consists of nitrogen oxides, which can be controlled via the air/fuel ratio, and water [1]. Small quantities of carbon compounds (from the engine oil) are released, but no particulates are produced [1]. “The efficiency of hydrogen engines is higher than gasoline engines because the greater combustion speed better approximates an Otto-cycle process.” [1] In research engines, efficiencies of around 50 % at the crankshaft have been achieved [2]. Comparison values for various internal combustion engines are given in Table 41 for classification of the efficiency.

Table 41: Efficiencies of internal combustion engines [3]

Type	ε	Rotational speed (rpm)	Power/displacement ratio (kW/dm³)	η (%)
Gasoline engines				
Racing engine	12–16	14,000–20,000	110–500	
Car engine	7–12	4,000–7,500	35–100	23–34
Diesel engines				
Car with indirect injection	20–24	3,500–5,000	20–40	27–39
Car engines	18–20	4,000–4,500	35–60	42–44
Commercial vehicle engines	15–18	2,000–4,000	10–20	31–42
Medium speed 4-stroke engines	13–15	350–750	5–12	41–46
Large 2-stroke engines	12–14	75–250	2–8	52

It is clear that comparable efficiencies can also be achieved with large, slow-running diesel engines [4]. The lower volumetric heating value of hydrogen and a large excess of air mean that only a lower power-to-volume ratio is achieved for hydrogen engines [1].

For gas turbines, several research projects in the recent past have focused on increasing the hydrogen content in fuel gas [5]. The main objective was to increase fuel flexibility so that synthesis gases with high hydrogen and carbon monoxide contents (from the gasification of coal, biomass, waste, etc.) can also be used in efficient and flexible gas turbines. The process is known internationally as the “integrated gasification combined cycle", in short, IGCC. The following commercial gas turbines for synthesis gas applications were listed in [6] as of 2014 (Table 42):

Table 42: Gas turbines for synthesis gas [6]

OEMs	**Siemens**	**GE**	**Alstom**
GT adapted low BTU fuels	SGT5-2000E (LC)	9F syngas	GT13E2 2012
Combustion system	Non-premixed flame with limited premixing (hybrid burners)	Multi-nozzle quiet combustion – non-premixed system	Annular combustor – modified EV type – partially premixed
Fuel	Syngas – low BTU fuels	Syngas (up to 95 % H_2) – low BTU fuels	Syngas (up to 50 % H_2) – low BTU fuels (615 MJ/kg)
Pressure ratio	12:1	17:1	
Capacity (SC–CC) MW	172–253	290-880	202-565
Efficiency (based on LHV, SC–CC)	35.3–52.5	40–57.4	38–53.8
NO_x in ppm (at 15 % O_2)	≤25	25	22

What these turbines have in common is that the essential component requiring adaptation is the burner technology. The turbines shown operate with systems where the fuel gas and air are not premixed, i.e. they operate with diffusion flame. The background here is the high combustion speed of hydrogen. Thus, the flame cannot flash back into the fuel-gas line because no oxidizing agent is present in it.

For ratings of up to 290 MW_{el}, the gas turbines of this type that are commercially available are also technically mature.

18.2. Estimation of potential

a) Technical development potential

This section examines the current state of the art and further development options for internal combustion engines and gas turbines. Here, internal combustion engines serve primarily as the basis for use in decentralized engine-based CHP units. Fuel-cell-based CHP units (or stationary fuel cells) have already been considered in the chapter on fuel cells.

Internal combustion engines

According to [1], both gasoline and diesel engines can be adapted to run on hydrogen. There has long been experience in converting gasoline engines for cars. In 2006, a small series of 100 units was produced with the BMW Hydrogen 7 (approximately 190 kW engine power) [1]. The first BMW hydrogen engine was introduced as early as 1979 [2].

Conversion of diesel engines is also possible and is considered more promising for commercial vehicles, where longer ranges can be achieved based on hydrogen. According to [2] with reference to [7], the effort involved in conversion is comparable to the conversion to a natural-gas vehicle. According to [7], the main adaptations concern the following:

- H_2 ignition and fuel system, exhaust-gas post-treatment, charging assembly, exhaust-gas recirculation, compression ratio, combustion chamber and engine control
- Adjustment of materials for valves and valve seats

Accordingly, the adaptations relate to injection, exhaust-gas recirculation and turbocharging. The necessary adaptations are covered in detail in [8]. In summary, the challenge when converting (natural-gas) engines is in optimizing the fuel-air mixture and ignition timing of an engine for any composition of hydrogen-enriched compressed natural gas (HCNG). Stoichiometric combustion of hydrogen would result in extreme combustion temperatures, so the formation of thermal NO_x has to be reduced by using an excess of air and recirculation of exhaust gas into the combustion chamber. For gasoline engines converted for natural gas, the ideal proportion of hydrogen is around 20–30 % [8].

Gas turbines

Gas turbines can already deal with very high proportions of hydrogen in the fuel gas by means of a diffusion flame (see section 18). However, very high exhaust gas temperatures can occur locally, leading to the formation of thermal NO_x emissions. In the state of the art, this is countered by the addition of inert gases (nitrogen, water vapour). However, in order to achieve low NO_x emissions comparable to those for conventional natural-gas turbines[35], up to 50 vol-% of inert gases have to be added, thus leading to higher plant complexity and further infrastructure requirements [9]. The development of gas turbines with premixed fuel and variable fuel-gas composition is therefore a subject of current research. Here, fuel gas and the oxidizing agent – air – are mixed in ratios defined as closely as possible even before they reach the reaction front. The combustion process requires that the gas supply speed and the flame speed are kept in balance. However, the flame speed varies with variable fuel-gas composition and supply. If the flame speed is too high (such as with high proportions of hydrogen), then the flame will flash back to the burner (flashback); if it is too low, the flame will be extinguished (blowout). Both conditions have to be avoided and represent a key challenge in the development of burners with variable hydrogen content in the fuel-gas supply. The technical background, advantages and disadvantages are discussed in detail in [6] and summarized in Figure 76:

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[35] Premixing burners that operate with lean, premixed fuel gas (lean premixed combustion – LPC) are used here [9].

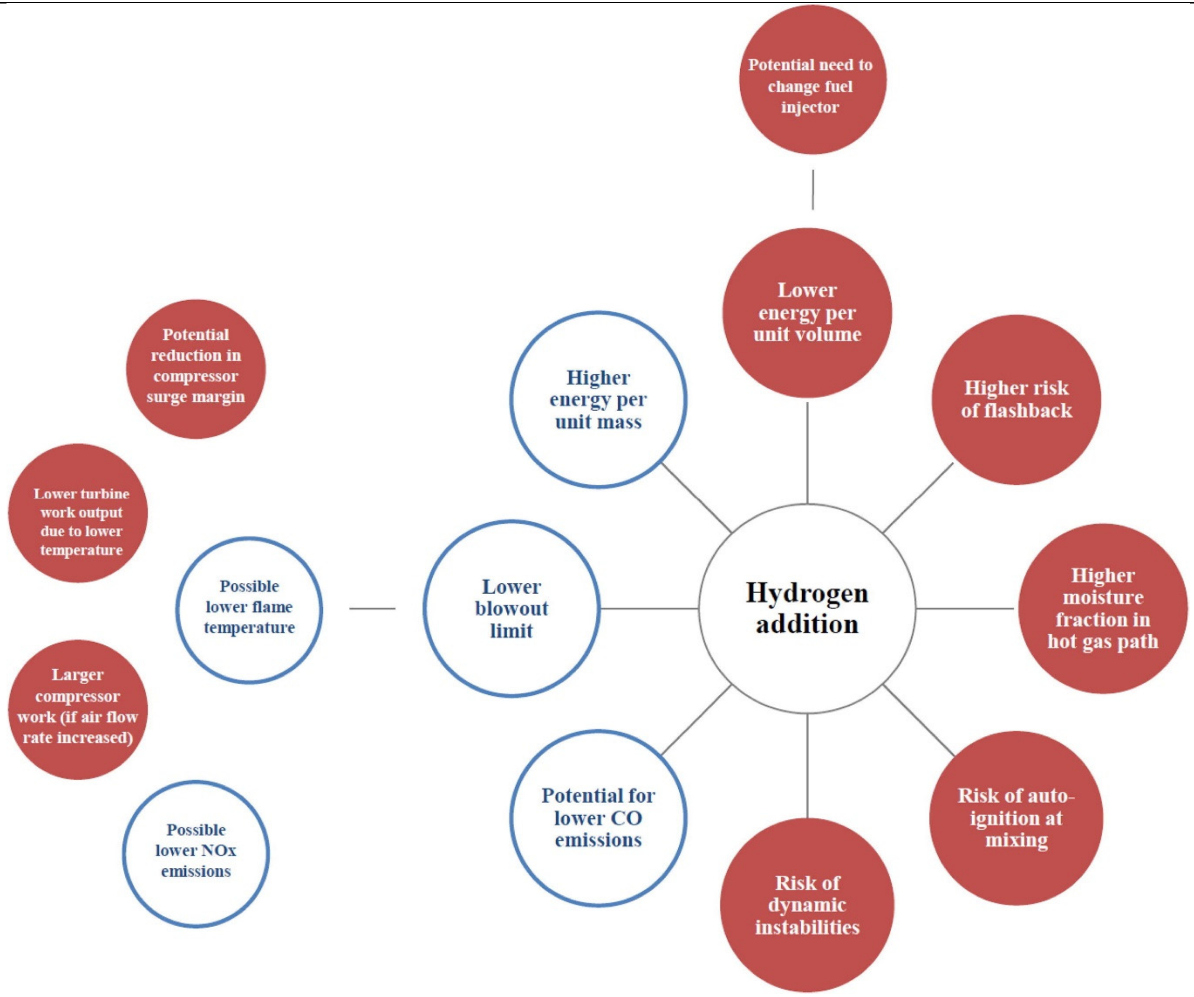

Figure 76: Advantages (light coloured) and disadvantages (red) of hydrogen enrichment of natural gas in gas turbines [6]

Modified variants of premixing burners are being investigated on pilot-plant scale, whereby the inert gases are already added to the mixture and the high dilution, combined with the large combustion chambers, leads to a large-volume but moderated combustion reaction. These processes are referred to as flameless oxidation (FLOX) or flameless or mild combustion [10]. The advances in FLOX burners are detailed in [11] and [12].

MHPS is also currently investigating gas turbines (up to 700 MW_{el}) with up to 30 % hydrogen enrichment and premixing burners [13]. The same source states that existing gas turbines are still usable with up to 20 % hydrogen. Only at higher levels is it necessary to make further adaptations, in particular to the burner geometry. Flashbacks can be avoided by avoiding slowly flowing areas in the burner centre. Practically all gas turbine manufacturers (GE, Alstom, Siemens, etc.) are continuing to develop the hydrogen compatibility of their systems [9].

b) Expansion potential

The expansion potential for hydrogen-based internal combustion engines in Germany is equivalent to the existing internal combustion engines in vehicles and stationary CHPs. The expansion actually achieved will essentially depend on the ongoing development of fuel cells. Ultimately, the efficiencies and costs of the two systems will determine their further use. The currently heavily funded development of fuel cells gives an obvious advantage for fuel-cell technology for the mobile and decentralized CHP sector. On the other hand, existing gas turbines are already suitable for the use of hydrogen in the power-generation sector with up to 20 % hydrogen in the fuel gas. Due to the existing ratings of modern gas turbines with electrical outputs > 400 MW_{el}, a large proportion of regeneratively produced hydrogen could initially be used directly in existing gas-fired power stations by admixture [13]. An increase in hydrogen compatibility to 30 % in premixing burners for gas turbines further extends this usability and, in the long term, will secure both the flexibility and stability of conventional power generation. There are no plans for larger demonstration projects in Germany at the moment, since there is not enough hydrogen available from electrolysers. The basic feasibility has already been demonstrated in the IGCC projects presented in the following section.

18.3. Representation of the achieved state of expansion

As previously stated, the operation of internal combustion engines using hydrogen has been demonstrated and implemented in small-series production by BMW. The KEYOU start-up mentioned in [2] is still in an early development stage for the conversion of diesel engines. The present research did not find any hydrogen-suitable gas engines for CHP use. In the generating sector, according to the Germany Federal Network Agency (BNetzA) list of power plants, there are currently approximately 12,200 MW_{el} of newer natural-gas power plants (commissioned since 2000, output > 15 MW_{el}) operating. Thus, even assuming lower hydrogen admixtures, there is initially sufficient potential for the co-combustion of hydrogen.

Worldwide, there are several IGCC demonstration plants operating on a commercial scale using fuel gases with very high hydrogen contents (> 70 %). A selection of current plants in the US, Japan and China can be found in [14]. The gross outputs of the plants are typically more than 200 MW_{el} and they are coupled with CCS processes[36]. As stated in [9], the processes require further development because the high plant complexity limits availability (see also the example of IGCC Tianjin [15]).

18.4. TRL assessment

The conventional combustion engines presented here can only be used with hydrogen to a certain degree in their current forms. In the automotive sector, the conversion of engines is generally possible, but may have to compete with fuel-cell vehicles. Gas turbines with outputs > 100 MW_{el} have already been developed for use with synthesis gas. Further development of premixing burners is ongoing and permits the use of hydrogen/natural-gas mixtures.

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[36] CCS = carbon (dioxide) capture and storage

The TRL classification in Table 43 below can be derived from the aspects presented in this chapter:

Table 43: Results of the TRL analysis

Technology	TRL	Supplementary sources
Hydrogen engines		
• **Gasoline engines up to 200 kW_{el}**	8	
• **Diesel engines**	4	
Gas turbines		
• **For synthesis gas with diffusion burner (up to 95 % H_2) > 200 MW_{el}**	8	
• **With premixing burner (< 30 % H_2); > 400 MW_{el}**	6	
• **With premixing burner (> 30 % H_2); for 10–30 MW_{el}**	6	[9]
• **FLOX burner for hydrogen**	5	[12]

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19. Chemicals-to-Power – Fuel cells

19.1. Technology description

This chapter discusses the direct conversion of chemical energy into electrical and thermal energy. The technology required for this is the fuel cell (FC). Fuel cells represent the second conversion stage for providing final energy in the storage chain illustrated in Figure 2. Their advantage is that they operate at high levels of efficiency even in the case of small output units. The interface to the end application makes it necessary to consider the area of application when determining the degree of maturity. First, the technical basis of the various types of fuel cells will be presented. Section 19.2 then addresses further developments with a focus on the centralized supply of electrical energy. The representation of the achieved state of expansion according to areas of application (section 19.3) will cover more than just Germany in this chapter. FC technologies have achieved varying degrees of penetration around the world, and countries such as Japan and the U.S., for example, offer a better representation of the technological state of the art than a perspective focusing only on Germany.

Basic principle

Similar to electrolytic cells, FCs consist of a cathode and an anode that are separated by an ion-conducting electrolyte. The known FCs today can be broken down according to their electrolyte material and the operating temperature:

- Alkaline fuel cell (AFC)
- (High-temperature) proton exchange membrane fuel cell ((HT-)PEMFC)
- Direct methanol fuel cell (DMFC)
- Phosphoric acid fuel cell (PAFC)
- Molten carbonate fuel cell (MCFC)
- Solid oxide fuel cell (SOFC)

The key characteristics of these fuel cells are compiled in Table 44. As a general rule, FCs with a higher working temperature (PAFCs, MCFCs, SOFCs) tend to be more suitable for stationary, ongoing operation due to their thermal inertia. PEMFCs and DMFCs are utilized to meet the needs of mobile, intermittent applications.

Table 44: Types of fuel cells and operating temperatures, supplemented, based on [1], [2], [3]

Fuel cell	Electrolyte	Temperature	System efficiency	Fuel	Ion transport
AFC	Caustic potash solution	20–90 °C	62 %	H_2	OH^-
PEMFC **HT-PEMFC**	Proton-conducting plastic membrane	60–80 °C 120–200 °C	43–50 % (natural gas with reformer), 50–68 % (cell)	H_2	H^+
DMFC	Proton-conducting membrane	20–130 °C	20–30 % (cell)	CH_3OH	H^+
PAFC	Phosphoric acid	200–250 °C	40 % (natural gas with reformer system), 55 % (cell)	Natural gas (CH_4), biogas, H_2	H_3O^+
MCFC	Alkali carbonate melt	600–700 °C	60–65 % (natural gas with internal reformer)	Natural gas (CH_4), biogas, H_2	CO_3^{2-}
SOFC	Yttria-stabilized zirconia (YSZ)	700–1,000 °C	52–60 % (natural gas), 60–65 % (with internal reformer)	Natural gas (CH_4), biogas, H_2	O^{2-}

The theoretical efficiency of a fuel cell can be calculated based on the enthalpy and the enthalpy of reaction. In the case of the reaction of hydrogen and oxygen to form water, the maximum electrical efficiency is 83 % with respect to the higher heating value and 94 % with respect to the lower heating value at a pressure of 1 bar and temperature of 25 °C. [3]. The system efficiency is defined by equation (22) [3]:

$$\eta_{eff} = \frac{ac\text{-}power - power\ loss}{lower\ heating\ value\ of\ fuel} \tag{22}$$

It will not be possible to cover the subject of fuel cells in its entirety in this study. For this reason, only the key facts relating to the different types of fuel cells will be presented. [4] and [3], for example, discuss the subject area in great detail and these sources should be consulted for in-depth information if required.

Alkaline fuel cell

Alkaline fuel cells (AFCs) typically use aqueous potash as the electrolyte and were already being used during the Apollo space mission. Alkaline FCs generally achieve high levels of efficiency and normally operate in the low temperature range [6]. However, they are very sensitive to CO_2 on the catalysts of the electrodes and in the electrolyte (carbonate formation). High gas purity (H_2, O_2) is therefore required on the anode and cathode sides [7]. The formation of product water occurs at the anode, and the product water that condenses in the electrolyte is removed via evaporation [6]. The overall power density is less than that of a PEMFC. For this reason, AFCs can generally only be applied in a useful manner in niche applications [6].

Proton exchange membrane fuel cell (PEMFC)

PEMFCs are operated at 60–70 °C with a proton-conducting polymer membrane as the electrolyte (Nafion from Dupont, other products from GORE, BALLARD, FUMATEC) and platinized carbon paper electrodes. The structure of a cell stack is illustrated in Figure 77 and shows the key components [6]:

- The membrane electrode assembly (MEA) – active components – comprises electrodes and the electrolyte membrane
- The gas diffusion layers (GDLs) – carbon fibre substrate (fleece, paper, or woven fabric) with good thermal and electrical conductivity – support the homogeneous supply of gas (via diffusion), water management, heat transfer to the bipolar plate
- Bipolar plates (BPPs) – mass transfer via flow, current collection, thermal management (cooling)

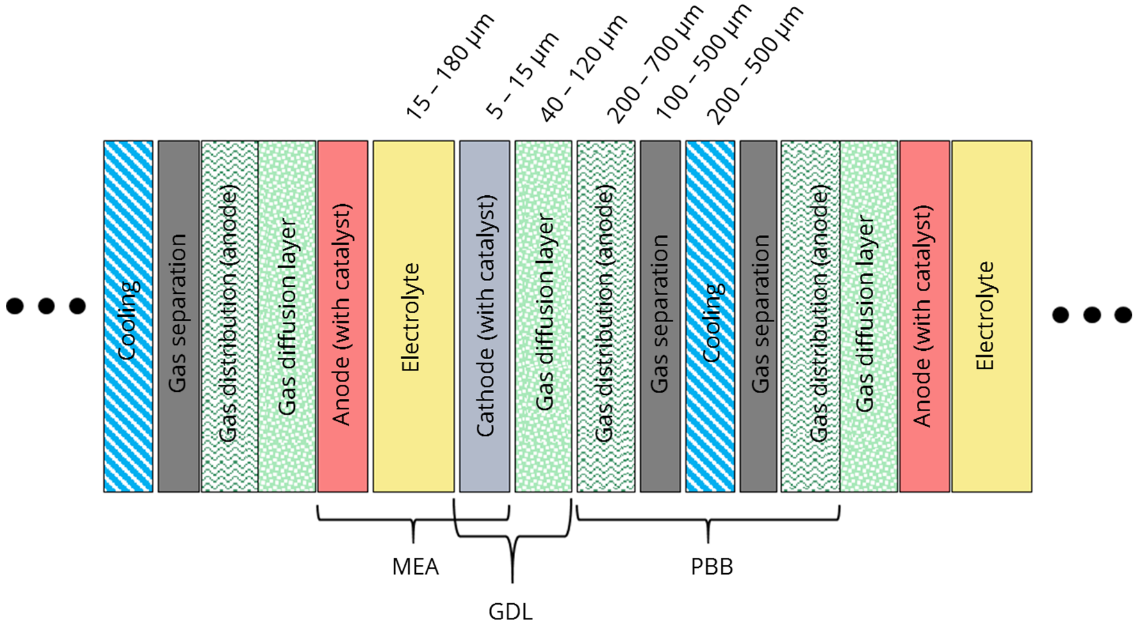

Figure 77: Structure of a PEMFC based on [6], translated

A power density of ~ 1,000 W_{el}/kg is achieved thanks to the high number of thin layers. Because of the lower operating temperature, the product water accrues in liquid form and the water balance must be restored in the cell. This means that water needs to be added to the anode and removed from the cathode. The pores of the electrode material should be neither too wet nor too dry, and so a stable three-phase boundary is essential for the operation of the PEMFC. The cathode output improves with excess air ($\lambda \approx 2$), and water is evacuated from the channels more efficiently with positive pressure (approx. 3 bar). PEMFCs are tolerant to CO_2 on the air side, so they can operate with air. CO_2 in the fuel gas (e.g. from a reformer) “irreversibly reduces [...] the cell tension slowly over time, presumably due to the gradual contamination of the platinum catalyst by CO.” [5] The two main issues with PEMFCs are their sensitivity to CO and the risk of desiccation or freezing of the membrane [5].

Phosphoric acid fuel cells (PAFC) and high temperature PEFCs

PAFCs are operated at temperatures of 160–250 °C with concentrated phosphoric acid (H_3PO_4) as the electrolyte. The acid is conducted through a micro-porous ceramic matrix (silicon carbide). Due to the high operating temperatures, PAFCs are tolerant to fuel impurities (1 % CO, 20 ppm H_2S) which arise or are retained during the reformation of natural gas. A portion of the phosphoric acid evaporates during operation, and the exhaust gas is cooled for the purpose of condensation. Platinum is used as the catalyst on the anode and cathode sides ($0.25\ mg \cdot cm^{-2}$ or $0.5\ mg \cdot cm^{-2}$; stable in H_3PO_4). "The strong adsorption of phosphoric acid on the platinum surface has a negative impact on the kinetics of oxygen reduction in particular. PAFCs therefore operate at considerably lower output densities than PEFCs." [6]. The electrical efficiency is ~ 40 %. Efforts should be made to utilize heat in order to increase the overall efficiency. Stationary power plants are therefore the main area of application for PAFCs. However, because their output figures are comparable to those of cheaper, conventional CHP plants, the marketability of PAFCs is limited. The largest PAFC power plant, with an output of 11 MW_{el} (eighteen 670 kW_{el} stacks), was operated from 1984–94 in Tokyo [5], and the longest-lasting systems were operated for up to 65,000 h [6].

HT-PEFCs operate with phosphoric acid-modified polybenzimidazole (PBI), and thereby achieve lower current densities than Nafion in PEMFCs but are more tolerant to carbon monoxide (3–5 % in the fuel gas) [5]. The overall service life of the two types of cells is determined by the phosphoric acid inventory and the corrosion of the catalyst.

Direct methanol fuel cells (DMFC)

DMFCs function in essentially the same way as PEMFCs and can be operated with a (properly metered) mixture of methanol and water. Although there is no CO in the exhaust gas, CO does sometimes form on the anode side, reducing the current density and limiting the efficiency of the cell. DMFCs are therefore only used for decentralized applications up to 500 W (traffic technology, environmental technology, camping, recreation) [8].

Molten carbonate fuel cells (MCFC)

MCFCs are operated at 650 °C with a molten electrolyte (62 mol-% Li_2CO_3 + 38 mol-% K_2CO_3 or 52 % Li_2CO_3–48 % Na_2CO_3) and nickel-chromium electrodes. Further carbonate additives (including potassium, magnesium) improve their conductivity, corrosion resistance and gas solubility. The electrolyte is stored in a micro-porous matrix (lithium aluminate). Methane can be reformed internally due to the high temperatures. "The heat required by the reformation reaction contributes to the cooling concept of the MCFC. In order to prevent soot formation, higher levels of hydrocarbons must be removed or converted into methane by a so-called pre-reformer before reaching the cell." [6] The MCFC can anodically oxidize CO slowly and regenerate minor sulphur poisoning of the catalysts, resulting in very high fuel gas compatibility. Because CO_3^{2-} ions are used for charge transport and steam with CO_2 is formed on the anode side, it is necessary for the anode exhaust gas to be afterburned, CO_2 separated and the cathode supply air fed back in again. MCFCs are generally developed for the operation of stationary power plants [6].

Solid oxide fuel cells (SOFC)

SOFCs are operated at temperatures of around 1000°C with yttria-stabilized zirconia as a solid oxide electrolyte, nickel on YSZ as anode material and Pt/Pd-doped perovskite as cathode material. Their key advantages are that they require few noble metals, have a high tolerance to CO and H_2S and are easier to manage as a system (no electrolyte leakage, no water balance issues), provided that good thermal management is provided (temperature resistance of materials/seals, thermo-electric voltages, slow start-up/shut-down) [5]. Because of the high temperature, SOFCs are direct fuel cells as they can use internal reformation to recycle hydrocarbons (indirectly via upstream reformers or directly on the anode) in addition to hydrogen and CO. SOFCs are operated with preheated compressed air (3 bar), while excess air is used for cooling. The arrangement of the cell components can be designed as a tubing concept (from SIEMENS-WESTINGHOUSE, also in MHPS stacks – sealing is straightforward, low output density ~ 100 W/kg), flat cell concept (higher output densities, sealing is more difficult) or as a monolith concept (high output density ~ 8,000 W/kg due to self-supporting, wave-type stack of layers consisting of cathode, solid electrolyte, anode). The high exhaust gas temperatures with residual fuel gases enable hybrid versions with (micro) gas turbines to increase efficiency [5]. Thus far, SOFCs have been primarily used for micro CHP applications [6].

19.2. Estimation of potential

a) Technical development potential

This section examines the possibilities for further development of some of the FCs mentioned above. Overall, the research approaches are strongly focused on the materials used. There are a number of interrelated reasons and factors behind this:

- The thinner and more compact the design of the cells, the lower their internal resistance. This results in higher efficiency, greater output density in the system and overall material savings.
- The more delicate the design of the cells, the greater the risk that they will be unable to withstand mechanical and thermal loads, and the overall service life decreases. The structural stability of the cell is reduced and may need to be compensated for elsewhere in the system (stack design).
- The use of various material combinations can increase the tolerance to contaminants; however, the materials also interact with one another. For example, the molecules from the silicone seals in PEMFCs may diffuse into the cells and render the catalytic elements there inert.

- The interplay between the materials and their impact on the stability, degradation (efficiency and loss of output over time) and service life of a FC can therefore only be thoroughly examined on an application-specific basis and over a longer testing period.

These factors slow down the process of stack development considerably, and lead to setbacks and numerous restarts with various materials. They also have a corresponding impact on the publishing landscape, which is too vast to be addressed within the scope of this study. We will instead touch upon the further fields of research in the area of industrial-scale FCs. The following types of FCs will not be discussed in depth:

- AFCs: this type of FC has a high efficiency at low operating temperatures, but its use is restricted by the high gas requirements. According to [9], however, GenCell has developed a 5 kW_{el} AFC, which can also be operated with air and without the use of noble metal catalysts.
- PEMFCs: these have already reached series maturity at outputs of up to 100 kW_{el} and are produced in large quantities for automobiles (see also section 18.3).
- Microbial fuel cells (MFCs): these could be used to generate energy directly from waste water; the stage of development is limited to early laboratory experiments (TRL 3) [10].
- DMFCs: these are not taken into consideration for large plants due to their low level of cell efficiency.

The high-temperature fuel cells MCFC, PAFC and SOFC tend to be more suitable for stationary applications due to their fuel compatibility and the high temperatures. However, any increase in the level of efficiency must bear in mind the thermodynamic constraints. The figure of 94 % mentioned above only applies at room temperature. At high temperatures, the free enthalpy of reaction and the reversible efficiency of the cell decrease. This behaviour is illustrated in comparison with the Carnot efficiency in Figure 78. The reversible reaction efficiency is the ratio of Gibbs energy to enthalpy of formation.

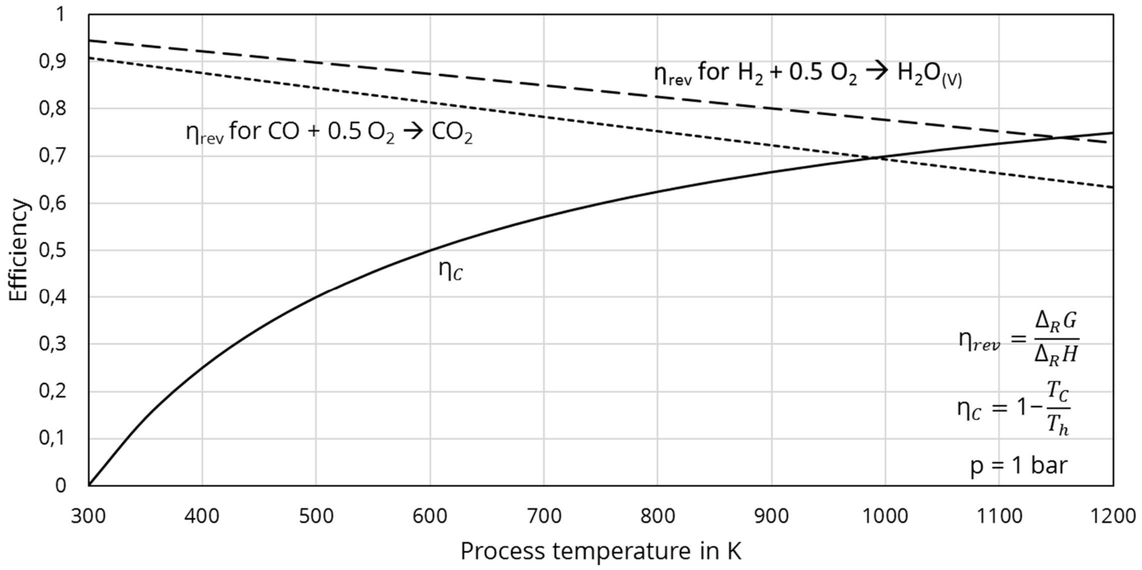

Figure 78: Reversible efficiency of the reactions and Carnot efficiency above the process temperature; data calculated with FactSage [11]

It should be noted that an SOFC operating with internal reformation, achieving 60–65 % system efficiency (see Table 44) and operating at 800–900 °C is already running very close to its maximum degree of efficiency. Research into the structure of the cells will also continue to be carried out at the high temperatures of an SOFC. For example, the solid electrolyte is normally the carrying element of the cell, but the anodes can also fulfil this function. Micro-tubular cells are likewise in the development stage [12]. Furthermore, the options for using nano materials to reduce the inner resistance at lower temperatures (400–700 °C) are also being investigated for SOFCs [13].

Hybrids represent a further area of research. These can be built based on several types of cells (e.g., combining anionic, alkaline and acidic polymer membranes [14]) or by integrating conventional combustion technology such as (micro) gas turbines. With respect to SOFC-GTs, [15] notes that while numerous model-based studies and simulations have been performed, little experience has been gained with installed systems and their operation under dynamic conditions.

A further branch of research is focused on unitized reversible/regenerative hydrogen fuel cells (URFCs). Not only can these cells convert hydrogen into electricity, they can also be used as electrolysers. Every fuel cell can also function as an electrolyser in principle; however, the operating conditions are adapted to a conversion direction in order to maximize efficiency. The simplest form of reversible system uses at least two stacks (one for electrolysis and one for FC operation), which share the remaining system technology (discrete regenerative fuel cell system). Merging the stacks in this manner results in savings with respect to cost and mass. An overview of PEM systems is presented in [16] and cites a number of demonstrators up to the kW range. The flow-to-electricity efficiency of these systems is 20–30 %.

b) Expansion potential

The expansion potential for FCs in Germany should be considered in terms of substitution potential. Depending on the area of application, FCs could achieve output magnitudes in the TW_{el} range. This can be easily illustrated using the mobility sector as an example. There are 46.5 million cars in Germany [17]. If just 25 % of these were designed as FC vehicles with a 100 kW drive in future, this would result in a cumulative output of approximately 1163 TW_{el}. According to the Federal Environment Agency's list of power plants [18], there is approximately 15 GW_{el} of installed capacity in gas turbines/gas and steam power plants > 100 MW_{el} in the power plant sector. In the area of decentralized power and heating supply within homes, 7.8 million gas-fired heating boilers, 5.3 million gas-fired condensing boilers and 5.1 million oil-fired boilers, that is, a total of approximately 18 million systems, could be replaced by FCs in Germany [19].

The expansion potential could therefore be significant but would also mean that the demand for fuel gas would be maintained. The CO-tolerant FCs can and will be operated with (desulphurized) natural gas via integrated reformers. A pure H_2 supply from renewable sources would of course be beneficial in terms of sector coupling; however, the generation capacities of the renewable energy sources would need to be consistently higher than the values noted in the above sections, which only took account of electricity supply.

19.3. Representation of the achieved state of expansion

In terms of representing the level of expansion that has been achieved, this section's scope cannot be limited to Germany, as FC technology is achieving stronger market penetration in the U.S., Japan and South Korea due to large-scale funding programmes. An overview of this is provided in Figure 79. It is evident at first look that a high number of FCs are sold in Asia, but these apparently have very small output. This can be partially attributed to the ENE-FARM project in Japan, which, among other things, supports FC-based home CHP systems, and also partially to portable FC systems with a small output (< 100 W_{el}, e.g. PEMFCs myFC mobile batteries [20]), which are used to supply modern, portable technologies in the communications and recreation sectors, etc. [9]. Furthermore, several thousand electric cars and buses in China and Japan are included in the statistics (Toyota and Honda are responsible for approximately 250 MW_{el} of the delivered PEMFCs).

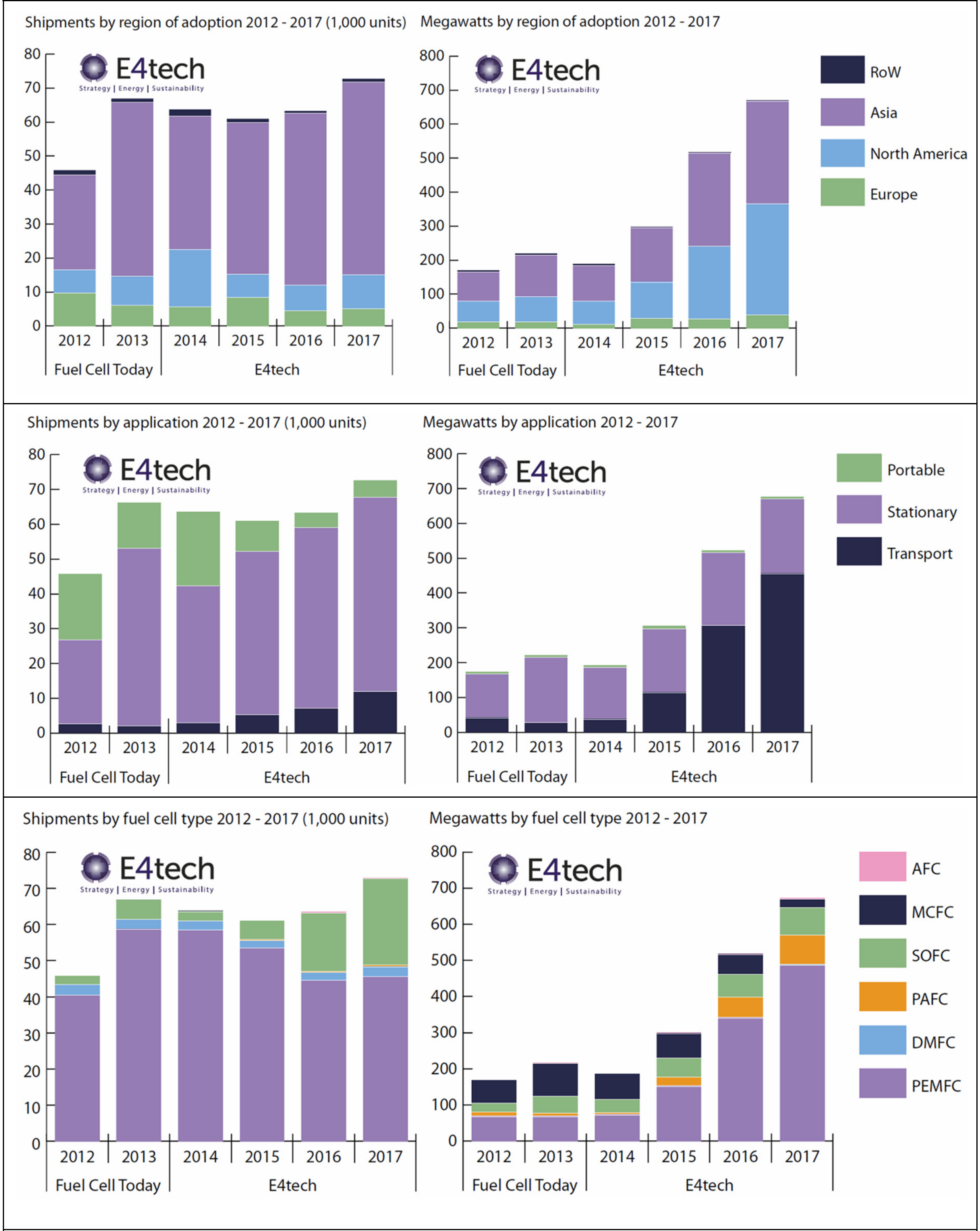

Figure 79: Global sales of FCs by region and application [9]

The illustrated correlations are supported by line 2 in Figure 79, which shows that the largest increases in output are achieved by the transport sector, where PEMFCs are primarily used (line 3 Figure 79). According to the information in [9]:

- 90 % of PEMFCs are used in the transport sector

- SOFCs represent a continually increasing share of the ENE-FARM project in Japan (~ 40 % of the 50,000 units in 2017); PEMFCs with methanol reformers account for the remainder
- The majority of the 76 MW_{el} of SOFCs sold worldwide was nonetheless operated in the USA by Bloom Energy for industrial CHP applications
- DMFCs are used almost exclusively in portable units < 100 W
- Approximately 80 MW_{el} of PAFCs were sold primarily to South Korea for use in power plants
- The global MCFC production capacities amount to approximately 25 MW/a and are not currently utilized to capacity
- The largest contiguous FC plants in South Korea are operated on an MCFC basis (58 MW_{el} in Hwasung, a further 20 MW_{el} plant is to go into operation in 2018).

In Europe, efforts are being made to advance FC technology with the Ene.field (expired in 2016) and PACE projects, focusing on decentralized fuel cell heaters. PEMFCs are seeing increasing use in forklifts in the U.S. (> 16,000 units @ 6 kW) [21]. With respect to larger output ranges, hybrid 1 MW_{el} SOFC systems are being developed at MHPS on a tubular basis. These systems will use micro gas turbines to subsequently recover fuel gas that has not been utilized [22].

19.4. TRL assessment

The majority of the fuel cell systems presented here have reached market maturity up to a certain magnitude. There is a direct correlation between the desired output classes and the areas of application. For example, thousands of flexible PEMFCs that operate at comparatively cool temperatures are already being used for vehicles up to 100 kW_{el}. These cells are also utilized for buses and fork lifts. In Germany, they are still being used as part of funded demonstration projects. The same also applies for decentralized micro CHP systems (up to approximately 5 kW_{el}) for household applications or small businesses. Given that there are over 200,000 installed PEMFC and SOFC plants in the ENE-FARM project in Japan, these systems must be classified as tried and tested in the kW range as well. The breakthrough to large-scale hybrid SOFC systems with module sizes of up to 1 MW_{el} is being tested. In contrast, stationary MCFCs, which have been tested with module sizes of 1.4 MW_{el}, have become better established. During the interview [23], it became clear that a continued focus must be placed on the intelligent use of these systems. The key strengths of fuel cells are their high level of efficiency at even the smallest outputs as well as low partial loads. To this end, corresponding reaction surfaces must be provided. However, the space required for this results in high material costs when the output is intended to be scaled. For this reason, the area of use may be restricted to only decentralized applications with smaller outputs in comparison to conventional power plant technology. Future deployment as large-scale power plants with outputs of several hundred MW_{el} is reserved for other technologies which are significantly more scalable and are likewise sufficiently flexible for the power plant sector (e.g. gas turbines) [23].

The following TRL classification in Table 45 can therefore be derived from the aspects presented in this chapter:

Table 45: Results of the TRL analysis

Technology	TRL	Supplementary sources
AFC		
• **Industrial power plant, implemented up to 240 kW_{el}**	6	[24]
• **Decentralized back-up system, up to 5 kW_{el}**	7	[25]
PEMFC, HT-PEMFC		
• **HT-PEMFC for stationary/marine application up to 5 kW_{el}/module**	9	[26]
• **URFC up to 4 kW_{el}**	4	
• **Mobile sector up to 100 kW_{el}**	9	
• **Micro CHP with methanol**	9	
• **Power plant sector up to 1 MW_{el}**	7	
DMFC		
• **Portable applications up to 50 W_{el}**	8	
PAFC		
• **Decentralized up to 100 kW_{el}**	9	
• **Centralized up to 11 MW_{el}**	7	
MCFC		
• **On modular basis up to 1.4 MW_{el}**	9	
• **Power plant up to 58 MW_{el}**	7	
SOFC		
• **SOFC for micro CHP**	9	
• **Hybrid SOFC-GT up to 1 MW_{el}**	6	

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20. Interim conclusion for TRA

The maturity of the different technologies is highly heterogeneous across the different areas. A visualization of the TRLs in conjunction with a respective scale is proposed in section 27.2 of the appendix.

There are high TRLs for biomass conversion in combined heat and power applications. The same applies to hydropower and electricity distribution. Despite their maturity, technologies can always be further optimized. These optimization measures are aimed at expanding life cycles or reducing costs. In photovoltaics, certain solar cell types are simply mature, mass-produced and connect to pv power plants. The use of more efficient multilayer pv cells is reserved for special applications. A significant breakthrough on the use of large building surfaces by DSC or organic cells is still pending (TRL 6). It could significantly increase the available surfaces and thus the PV expansion potential. In other areas, such as the geothermal energy and wind power, there is still the potential for technological development, which enables existing plants to be made larger or more efficient. Onshore wind turbines are also durable and technically mature. Although further scaling is desirable, it is reaching limits in terms of transportation, height regulations and weight for the nacelle. The shortcomings of offshore wind power relate to the need for foundations in deep water and grid connection over long distances. Floating foundations could solve many challenges, but so far they have only been built and tested as demonstration projects in full scaling (TRL 8). The network connection by submarine cable is technically mature. In geothermal power the main components of the power train are mature, have proven themselves in continuous operation and are used worldwide, but other complementary fields lag behind. Here, the challenge lies in the exploration and drilling of suitable geothermal sources. However, this does not represent a central problem with the energy technology itself.

The initial conversion stage also includes many mature power-to-heat and power-to-cold technologies. Most of them have a capacity up to several MW_{el}. The development of heat pumps has also improved recently: they run more efficiently, on a larger scale and at higher temperatures (>130 °C TRL 4-6). A major drawback is the ongoing low flow temperature for industrial applications. New refrigerants are still in R&D while CO_2 seems to be usable but necessitates larger compression units and requires pilot scale plants to gain experience. Using combined heat pumps for cooling and heating extends energy efficiency even further but can rarely be implemented. Power-to-cold technologies are still dominated by compression cooling. The drawbacks of absorption/adsorption cooling technologies are low thermal efficiency and the large size of the systems concerned. Power-to-gas and power-to-chemicals are closely linked by the hydrogen both produce from electrolysis. The maturity of chemical pathways to convert syngas (mixture of CO, H_2, CO_2) to fuels via methanol or Fischer-Tropsch-synthesis is undisputed when using steam reforming and natural gas. Large-scale water electrolysis has even been used in the past to produce fertilizer. The challenge of today's electrolysers is (cost-)efficiency and durability in the context of dynamic and intermittent operation.

PEMECs support rapid load changes, but the system efficiency at high pressure does not match the efficiency of SOEC systems. However, SOECs should not be shut down completely to avoid thermal stress on the material. Further research topics are currently catalytic and biological methanation. Especially biological reactors are neither optimized nor available on the MW scale (TRL 5).

Storage solutions have been the subject of numerous research projects and offer a wide range of options. Mechanical storage methods present a bottleneck with their low energy density, which results in large land usage. New approaches try to either "hide" the problem underground (underground water storage) or remedy the storage density problem by lifting heavy rocks. The technology underlying water pumps and turbines is mature. The concepts themselves only reach TRL 2 since none of them have been built (mostly for economic and regulatory reasons). Compressed air energy storage solutions face similar problems. In addition, they are more complex and require high temperature thermal storage for adiabatic operation, which are of limited availability in the required MW-scale. Molten salt storages on a MW scale (up to 350 °C) are available worldwide in commercial pilot projects (TRL 8) in conjunction with CSP-plants. For thermal power, sensible storage solutions based on water and gravel dominate amongst the mature approaches. Higher storage densities (and temperatures) can be achieved with latent or thermo-chemical storage (TRL 3-6), but most of them are still in R&D (= max. TRL 4) and research continues to focus on new, cheap, durable and available materials. The comparative simplicity of water and gravel are hard to overcome. Chemical storage methods also have a strong focus on hydrogen due to the abundant experience in transportation and storage of (fossil) gases, fluids and solids (TRL 9). The hydrogen tolerance of existing storage components is still in question and there are only a few demonstration units for large-scale underground storage solutions (TRL 8). The same applies to transportation technologies such as metal hydrides, LOHC, liquid hydrogen or adsorption materials (TRL 4-6). Although there have been numerous research projects, particularly in the automotive sector, the main drawback is the thermal management of these technologies. Discharging requires temperatures at the range of 200 °C which are difficult to provide in the context of highly intermittent and flexible operation.

In the field of electrochemical storage, there are also mature, large-scale, proven battery types (lead-acid, high temperature NaS, lithium-ion). Their weak point is their capacity-wise scalability. Even redox flow batteries that might overcome this hurdle are only available up to 1 MW_{el} (TRL 9). If battery storage capacity in the magnitude of GW (or at least > 100 MW per module or system) is needed for the energy transition, no battery type reaches TRL > 6. However, the widespread use of battery electric vehicles and several projects around the world demonstrate a TRL 9 for scale-ups to several MW_{el}.

In the second conversion stage, both global research efforts and the present study are dominated by fuel cells for the reasons set out above. In this last stage, end use is more important than the maturity of fuel cell types. While PEMFCs are produced in large quantities up to 100 kW_{el} to provide the power train for fuel cell vehicles, there are far fewer PAFCs, MCFCs and SOFCs for large-scale stationary operations in the MW-class (TRL < 7). However, over 200,000 PEMFCs and SOFCs are shipped in Japan under the ene-farm-project for small-scale home applications in the kW-class (TRL 9). The remaining drawbacks are the longevity of the cells in unfavorable conditions (gas purity) and the general high costs for large-scale stacks (based on materials and production).

An alternative approach is the use of hydrogen in conventional power technologies such as gas turbines and gas motors. Internal combustion engines can be basically adapted to use hydrogen (TRL 8). However, recent research on this topic is scarce and interest has dropped over the last decade with the technological progress made by fuel cells. With regard to large-scale gas turbines, the greatest progress has been made with non-premixed burners for syngas operation in conjunction with IGCC (TRL 8). For premixed burners the possible hydrogen fraction in hydrogen-enriched natural gas has been increased to about 30 %. The main problems remaining in this field are high flame velocity (complicating flame stability and causing flashbacks) and high temperatures when burning hydrogen, causing NO_X emissions without lean-burn technologies. The injection of water to lower temperatures during combustion and therefore lower NO_X emissions is being investigated.

21. Evaluation of system integration[37]

21.1. Modelling approach

The previous TRL rating has made it clear that the assessment must consider the technical environment of operation and the necessary scaling. For this reason, in an abstracted approach, the supply of the German final energy demand mainly through electric primary energy using volatile RES is modeled. The aim of this model is to estimate the necessary magnitude of the power ratings and capacities for this energy concept. The approach is based on Figure 1 and could be referred to as "waterfall model" in which the energy flow from the primary energy supply covers the energy demand first and excesses successively fill storage units. These storages take over in case of shortages. The principle is shown in Figure 80.

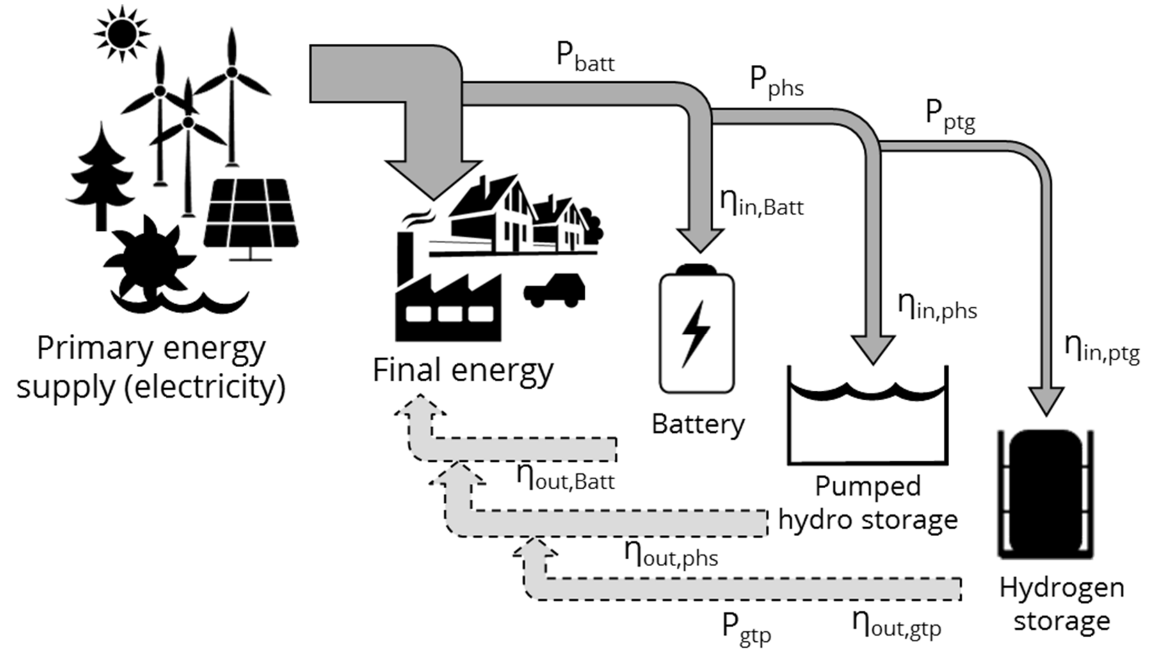

Figure 80: Logic of the model

The primary energy sources include photovoltaics, wind energy (onshore and offshore separately), biomass and hydropower. The final energy demand considers only the electrical energy demand. The theoretical power demand for heating purposes (mainly heat pumps) as well as mobility (covered by electromobility with batteries, fuel cells or gas engines) is also taken into account in different scenarios. The energy storages are simplified battery storages, pumped hydro storages and underground caverns for hydrogen. The conversion losses for charging and discharging are recognized via efficiencies. It is further assumed that there is an ideal power transmission and distribution (no transmission losses).

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[37] The used model is based on the following research project carried out by Simon Schwab and supervised by myself: "Energy storages for a renewable energy supply",student thesis, TU Dresden, 2018.

In the following, the most important boundary conditions and assumptions of the model are presented and scenarios are derived. However, the purpose of this model is explicitly a rough estimation of necessary dimensions for a renewable power supply with further sector coupling taken into account. Therefore, not all imaginable combinations or efficiency technologies are subject of this model.

a) Creation of a reference year for electricity demand

For a profound model, the load profiles of the electricity demand and the renewable feed-in over a reference year is necessary. Therefore, the net load profiles in 2015, 2016 and 2017 of Germany are used. They are taken from the transparency platform of the Association of European Transmission System Operators (entso-e) [1]. For a more accurate mapping of power peaks, the quarter-hour resolution of the data was chosen. These are mean values of a power measurement over a period of 15 minutes. The load profile is calculated by the transmission system operator (TSO) from the sum of net feed-in plus import minus export and electricity for pumped hydro power. The following steps have been taken to process and improve the data:

- Gaps in data tables:
  - Short periods: mean of the previous and following data point
  - Long periods (several hours): mean profile of the day before and after the gap; occurrence is only sporadically and is balanced over the averaged three years.
- Weekday influence (cf. Figure 82):
  - The reference year starts simplified with Monday. The values of the considered years were shifted accordingly. In order to retain the weekday characteristics, in a leap year the last day was removed.
- Pump storages:
  - Since pump storage demand does not represent final energy, the load is reduced by the pump storage power in each time step.
- Deviation in total energy demand:
  - The total electricity demand of 477 TWh_{el} results from the averaged entsoe data. It is smaller than the final energy demand for electricity (about 515 TWh_{el} [2]) and much smaller than the gross electricity generation of about 650 TWh_{el}. The difference results from 50 TWh_{el} of exports, 85 TWh_{el} from grid losses and power for auxiliary systems (not part of the consideration) and 7.5 TWh_{el} for pump storages. The remaining deviation of approximately 6 % (477 TWh_{el} / 507.5 TWh_{el}) is acceptable for the overall assessment, when assuming further efficiency gains and energy saving measures until 2050.

The resulting load profile for a reference year is shown in Figure 81. There, seasonal fluctuations as well as the "band-shaped" trend can be seen, which reflects the large daily fluctuations (minima at 30-40 GW_{el}, maxima at 70 GW_{el}). Averaging eliminates extreme situations. For example, the annual maximum load in the grid development plan 2017 [3] is given as approx. 84 GW_{el}. The characteristic course of the weekly or daily load profile is shown in Figure 82 for an August and February week. The courses differ seasonally in their maxima and minima. The influence of the weekends is clearly visible.

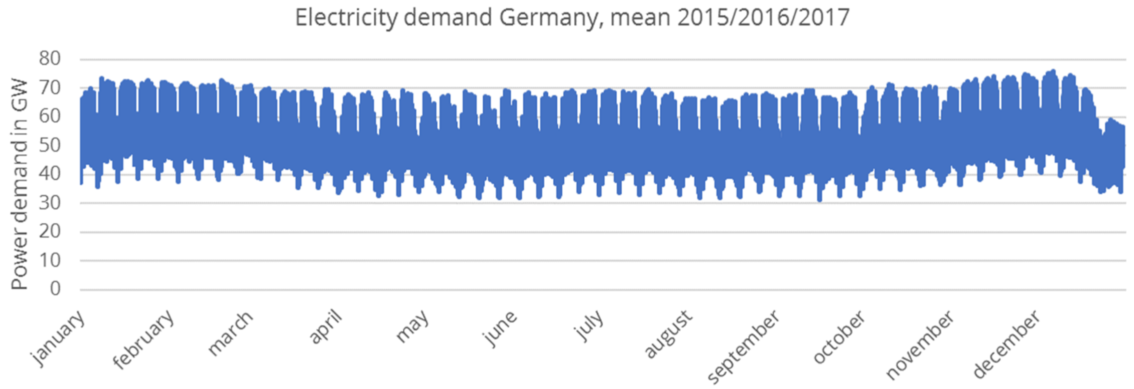

Figure 81: Load curve of the reference year, maximum load 76 GW, minimum load 32 GW, based on [4]

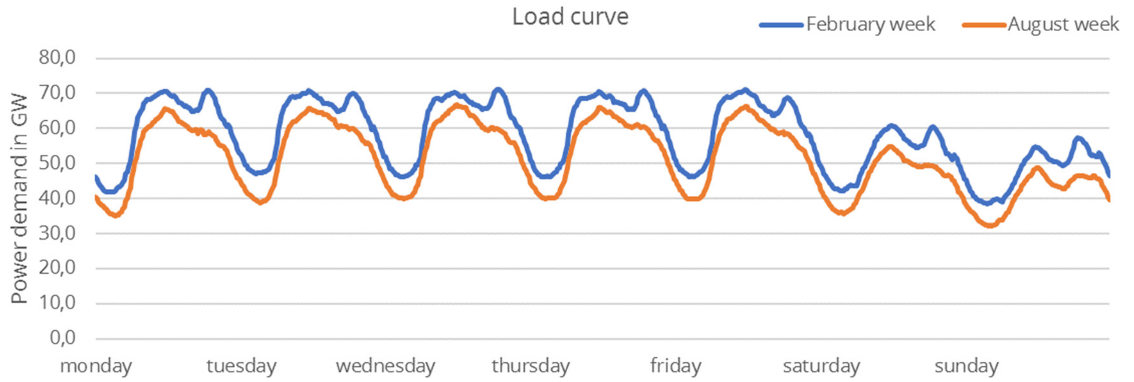

Figure 82: Load curves of two reference weeks, based on [4]

The feed-in profile of the RES is the counterpart of the load profile. The synthetization of a reference year can be simplified, since weather is the main factor for seasonal fluctuations and is not tied to weekdays. For biomass power plants and hydropower fixed, averaged feed-in data is used, as their expansion potential limited (see Figure 85). The supply from pump storages is not considered here, since it is part of the later simulation. The most significant further expansion of RES is expected from intermittent sources of photovoltaics and wind power (separated into onshore and offshore). For further consideration, a reference year was created in which the supply from these three sources is mapped as dimensionless values. They are calculated as the ratio of quarter-hourly power supply to installed power capacity. Afterwards, the mean value of relative power supply of the three years was used for further calculations. It is therefore assumed, that similar weather prevails in the future and it implicates a similar utilization of the existing photovoltaic and wind power plants. This way, the future installed power capacity of volatile RES can be scaled at will. The course of the relative power supply is shown in Figure 83 and Figure 84. Assuming equal capacity capacities for wind and PV expansion (e.g. 100 GW_{el} PV and 100 GW_{el} wind power onshore), the courses correspond to an absolute feed-in. The photovoltaic power compensates a comparatively low supply of onshore wind power during summer. Wind power shows a characteristic weak phase in summer and (especially offshore) a noticeable peak supply in winter. Thus, a combination of both sources with similarly power capacities seems promising. In addition, Figure 83 shows that the share of generating pv plants and onshore wind turbines is mostly below 60 %. On the other hand, offshore wind turbines show a higher mean capacity utilization and a more even generation. Another important feature is the short drop at the end of January, which coincides with a weak phase of onshore wind energy. The maximum power ratio is up to 80 %. However, the current spread area of today's offshore plants is still limited and therefore regional weather differences do not dampen the relative values. This is a minor factor in the calculation, as the future expansion area is anyway geographically restricted to the German Baltic Sea and North Sea.

Missing data points were supplemented by mean values, similar to the load profile, in case of short gaps. For longer periods, the available prediction values were used.

This design results in fixed full load hours (t_{full}) for the RESs in this model, which are summarized in Table 46 below. The determined values of the reference year deviate from the previously described state of expansion of the respective RES as a result of averaging. The current values are also listed based on [5]. The average number of full load hours for onshore wind power is considerably lower than current values. In addition to the influence of weather, the technical development towards low-wind turbines plays a systematic role in this deviation. According to data in [6] new turbines may achieve full load hours > 2,700 h/a. This value cannot be generalized, but it is indicative that the future onshore wind turbines will make better use of the installed capacity on average, what possibly leads to a more frequent supply. As a result, the necessary expansion for subsequent conversion stages must decrease.

Table 46: Comparison of full load hours for RES in 2017 and the reference year

	Reference year			Actual values 2017		
RES	$P_{inst.}$ In GW_{el}	W_{el} in TWh_{el}	t_{full} in h	$P_{inst.}$ In GW_{el}	W_{el} in TWh_{el}	t_{full} in h/a
Hydropower	5.6	15.7	2,803	5.6	19.8	3,536
Biomass	8	36.2	4,525	8	51.4	6,425
Wind onshore	50.5	80.6	1,596	50.5	88.7	1,750
Wind offshore	5.4	18.0	2,889	5.4	17.9	3,320
Photovoltaic	42.4	36.4	859	42.4	39.9	941

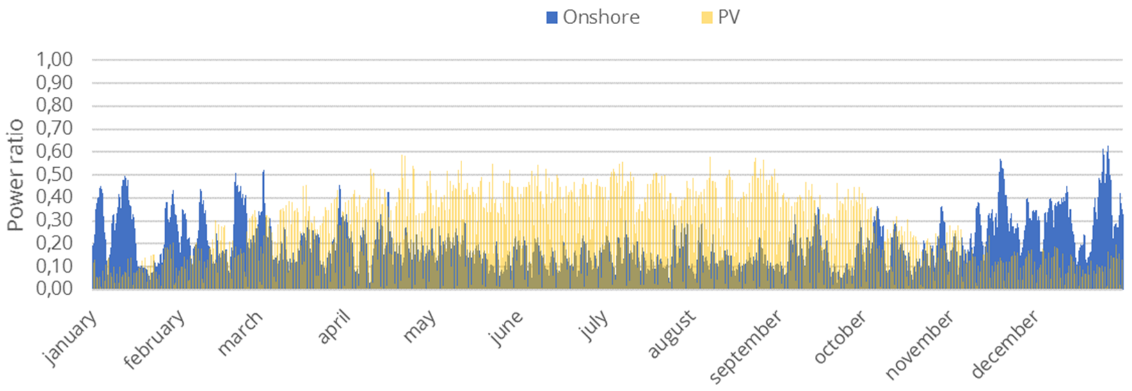

Figure 83: PV and onshore wind power ratio over a year, based on [4]

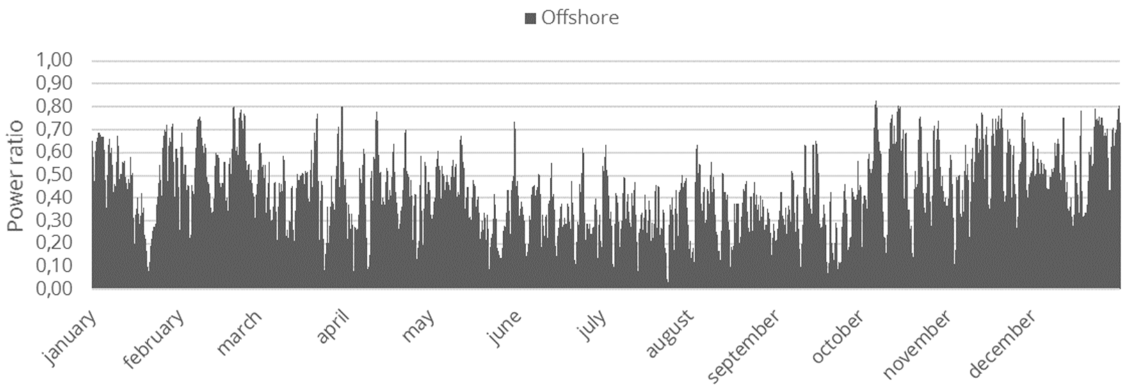

Figure 84: Offshore power ratio for the reference year, based on [4]

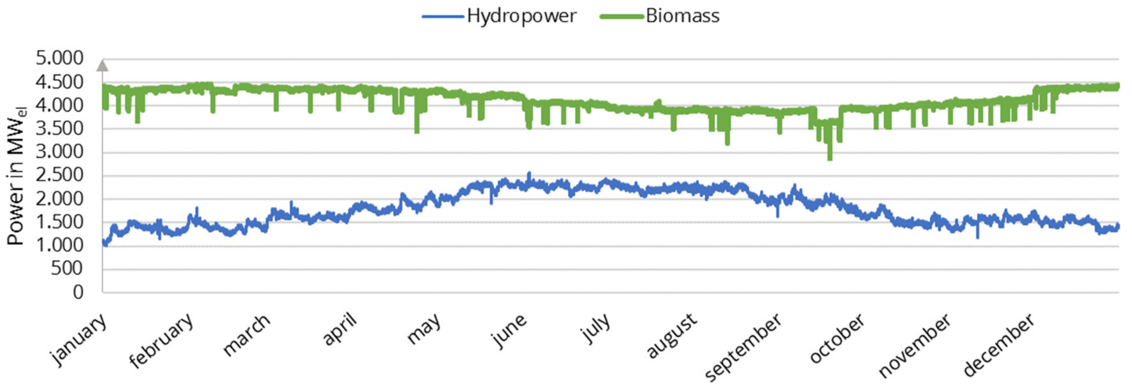

Figure 85: Power supply from hydropower and biomass – simulation with absolute values, based on [4]

b) *Power curtailment*

The existing, but not considered, grid does not have to transport any power feed-in at any time. It has been calculated that a temporary curtailment of renewable energy from wind and PV systems can substantially reduce grid expansion. The effect of curtailment is significant: "It is sufficient to cutail the annual feed-in of these renewable energy plants by 1 % in order to reduce grid expansion requirements by around 30 %. A curtailment of 3 % of the annual energy would be sufficient to save more than 40 % of grid expansion." [7]. Therefore, the created model includes the option of a 3 % curtailment. The option works with perfect foresight, i.e. the model calculates the minimum possible power limit, where less than 3 % of the annual energy from wind and PV is curtailed. Since the power ratio of the reference year is already averaged, the potential peaks are further dampened.

c) *Energy demand for heating*[38]

To examine a further sector coupling, the electrical load of heat pumps for low-temperature heat is considered. The energy demand is divided into space heating, hot water and process heat in the statistics of the BMWi [2]. Heat for industrial processes counts for "process heat" and is not considered at this point, since very high temperatures are required in many areas, which cannot be supplied by heat pumps (cf. section 11.4). Therefore, the substitution of fossil fuels for space heating and hot water via sector coupling by means of electric heat pumps is a priority.

The seasonal performance factor of heat pumps indicates the mean annual COP, since the COP depends on the temperatures of the heat sources and sinks. The SPF for air-water heat pumps is currently at an average of 3.0 and for brine-water heat pumps at 3.8. Therefore, the necessary electricity demand changes depending on the distribution of installed heat pumps. With 50 % brine-water heat pumps and 50 % air-water heat pumps, the average SPF is 3.4. The basis for these values are surveys from 2014 [8].

The ratio and SPF may change significantly by 2050, as air-water heat pumps are independent from geological conditions and in addition, efficiency gains increase the SPF. The course of the hot water demand is assumed as constant over the year. If the hot water demand of approx. 83 TWh_{th} currently covered by oil, natural gas, district heating and coal in industry, commerce and households would be covered by heat pumps with a SPF of 3.4, then 24.4 TWh_{el} would be required, leading to a constant power demand of 2.79 GW_{el} [2].

The space heating demand, in contrast, is dependent of ambient temperature, so that constant power demand is not applicable. Nevertheless, the current space heating demand of 710.3 TWh_{th} minus the existing coverage by electricity and RES of 126 TWh_{th} results in a remaining heating demand of 584.3 TWh_{th} coverable by heat pumps. With the above SPF of 3.4 an electricity demand of 171.9 TWh_{el} is deduced. That increases the total primary electricity demand for hot water and space heating by 196.3 TWh_{el}.

In this approach, several developments are neglected: efficiency gains of heat pumps (cf. chapter 11), improved insulation (reduction of heating demand), possible shifts of load curves (storage units), influence of CHP or waste heat recovery and seasonal long-term storage of solar thermal energy (cf. chapter 15). Therefore, the value is an estimation and may be subject to a more profound analysis with additional data. For the distribution of the electrical load, the heating demand was calculated on the basis of an average ambient

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[38] The compilation of temperature data and resulting hourly heat load is based on a research project carried out by Moritz Seibt and supervised by myself: “Energy storages for a renewable energy supply”, diploma thesis, TU Dresden, 2018.

temperature for the year 2017. In accordance with [9] and [10] the respective daily heating demand is covered by heat pumps and the power load distributed hourly. A yearly distribution of the heating demand is shown in Figure 86.

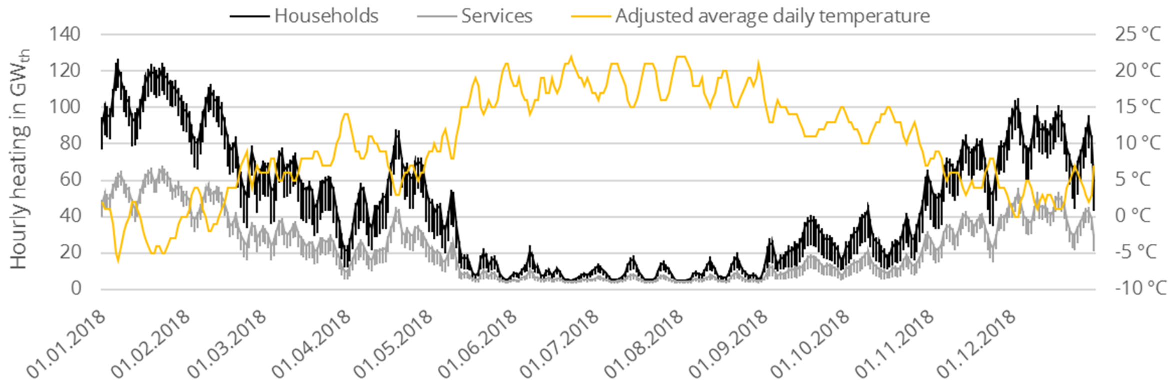

Figure 86: Hourly heating demand and mean temperature, based on [11]

d) *Energy demand for mobility*

Another component of sector coupling is electromobility or renewable fuels (from biomass or power-to-liquids). Today's electric vehicles represent only a small share of the German vehicle fleet. This results in a lack of representative, long-term data for charging behavior or even implemented strategies. For hydrogen or PtL vehicles, a conventional refueling behavior can be assumed. For this model a continuous demand is assumed, that neglects pumps and other auxiliary equipment. The demand is covered by primary electric energy if available, or fed from the storage units.

According to [12], 732.9 billion kilometers (including 630.5 billion km of passenger cars, 66.3 billion km of lorries) were covered on German roads in 2017. The average energy consumption of an electric passenger car is currently approx. 170 Wh_{el}/km ([13], [14]) and 880 Wh_{el}/km for lorries [15]. This results in a purely electromotive energy demand of 165.5 TWh_{el}. Regarding battery vehicles, a 90 % efficiency for charging and discharging results in 204 TWh_{el} total demand. Using hydrogen for fuel cell vehicles increases the demand to 345 TWh_{el} (hydrogen production efficiency 80 % with SOEC; efficiency of PEMFC in vehicle 60 %). The future demand will depend on the distribution of the drive types and the actual value will be something in between. If the electric energy demand of 204 TWh_{el} were to be temporarily stored in large batteries (some type of "gas station"), the primary electricity demand would increase even further (251.9 TWh_{el}). A continuously operated system would require a constant power of 28.8 GW_{el}. The value might increase drastically with further hydrogen conversion (PtL processes). A reduction of demand is not foreseeable, especially if today's final energy demand for inland waterway transport (3.3 TWh), air traffic (100.6 TWh) and rail traffic (15.6 TWh) is taken into account. The electrification of air traffic is also not foreseeable, due to longer product life cycles and the requirement of high energy densities for fuels [16]. Therefore, PtL processes are irreplaceable for this. However, the long conversion chains lead to efficiencies that reach

at best about 65 %, i.e. meeting the demand of 100.6 TWh_{chem} will require 154.8 TWh_{el} additional primary electrical energy. The necessary permanent power feed for continuous PtL is 17.7 GW_{el} just for air traffic supply.
The assumptions described above are used to derive the additional primary electrical energy demand for the most important mobility sectors (Table 47):

Table 47: Energy demand for mobility

Mobility sector	Primary electrical energy demand in TWh_{el}
E-Mobility (private, public, transportation) Battery vehicles – fuel cell vehicles	204 - 345
Rail traffic	15.6
Air traffic	154.8
Sum	374.4 – 515.4

e) Assumptions for expansion potentials and efficiencies

To modelling, the values for assumptions are of the essence. Therefore, the expansion limits for RES and conversion efficiencies are shown below in Table 48. The indices are based on the results of the respective technology chapters. There will be no further expansion of the hydropower and biomass power plants. The pumped hydro storages will not be expanded. The battery storage is generalized assuming a capacity to power ratio of 4 (based on [17]). The target power ratio of wind power to photovoltaics is 60/40 as long as the energy demand of the scenarios allows it, since that ratio minimizes the storage demand according to [18].

Table 48: Assumptions for the energy scenarios

Primary electricity supply	Min. installed power capacity P [GW_{el}]	Max. installable power capacity P [GW_{el}]	Full load hours [h/a]
Photovoltaic modules	43.4	275	859
Onshore wind turbines	51.5	189	1,596
Offshore wind turbines	5.4	54	2,803
Biomass	7.4	7.4	4,525
Hydro power	5.5	5.5	2,889
Storages	**Installed power capacity P [GW_{el}]**	**Storage capacity C [GWh_{el}]**	**Efficiency in/out**
Battery	Variable	C/P = 4	0.9/0.9
Pumped hydro	6.5	40	0.88/0.91
Hydrogen storage	According to demand	Max. 35,4 $TWh_{ch,H2}$	-/-
Conversion	**Installed power capacity P [GW_{el}]**		**Efficiency**
Electrolysis	According to demand		0.8
FC or hydrogen combustion	According to demand		0.6
Heat pumps	Not examined		SPF 3,4

The following Table 49 summarizes the potentials of RES based on literature data as presented in the respective chapters above.

Table 49: Summary of RES potentials

	2017		**2050**			
	GW$_P$	**TWh$_{el}$/a**	**GW$_P$**	**TWh$_{el}$/a**	**GW$_P$**	**TWh$_{el}$/a**
Onshore wind turbines	51	90				
2 % land use			189	390		
8 % land use					722	1,495
Offshore wind turbines	18	5	54	258	54	258
Photovoltaic modules	43	40	275	248	275	248
Hydro power	5.5	21	6.2	24	6.2	24
Biomass	8	51	4	24	4	24
Geothermal power	0.04	0.2	8	64	8	64
Sum	126	207	536	1,008	1,069	2,113

21.2. Scenarios for a renewable energy supply

To examine the quantitative requirements of the primary energy supply, conversion steps and storage units, several scenarios are calculated for the model presented above. The final energy demand is successively increased by expansion of sector coupling. The starting point is the net electrical energy consumption of the reference year (scenario 1). Scenario 1 is calculated in two versions: a) low battery storage capacity and b) excessive battery storage capacity. Thus, the influence of the short-term storages on the long-term storage needs becomes visible. In scenario 2, the demand from scenario 1 is extended by the energy demand of electric heat pumps for heating purposes. Finally, in scenario 3, the mobility demand (minimum value from Table 47) is added and the full load hours of the RES are significantly increased (PV 1,000 h/a, offshore wind 4,000 h/a, onshore wind 2,400 h/a, cf. Table 50).

Table 50: Scenarios for a renewable energy supply system

Scenario	**Electricity demand**	**Heating demand**	**Mobility demand**	**Total demand**	**Battery storage**
1a	477 TWh$_{el}$	0 TWh$_{el}$	0 TWh$_{el}$	477 TWh$_{el}$	40 GWh$_{el}$
1b	477 TWh$_{el}$	0 TWh$_{el}$	0 TWh$_{el}$	477 TWh$_{el}$	200 GWh$_{el}$
2	477 TWh$_{el}$	196.3 TWh$_{el}$	0 TWh$_{el}$	673,3 TWh$_{el}$	40 GWh$_{el}$
3+	477 TWh$_{el}$	196.3 TWh$_{el}$	374.4 TWh$_{el}$	1,047.7 TWh$_{el}$	40 GWh$_{el}$

21.3. Results of the simulation

The results of the simulation are summarized in the following Table 51. The table gives an overview of basic system behavior. The most prominent results are discussed in detail below.

Table 51: Scenario results

Scenario	1a	1b	2	3+
Onshore wind power	126 GW$_{\text{el}}$	122 GW$_{\text{el}}$	190 GW$_{\text{el}}$	190 GW$_{\text{el}}$
Offshore wind power	54 GW$_{\text{el}}$	54 GW$_{\text{el}}$	54 GW$_{\text{el}}$	54 GW$_{\text{el}}$
PV power	120 GW$_{\text{el}}$	119 GW$_{\text{el}}$	260 GW$_{\text{el}}$	275 GW$_{\text{el}}$
Total primary energy demand	477 TWh$_{\text{el}}$	477 TWh$_{\text{el}}$	673 TWh$_{\text{el}}$	1,047 TWh$_{\text{el}}$
Total primary electricity supplied	536 TWh$_{\text{el}}$	529 TWh$_{\text{el}}$	758 TWh$_{\text{el}}$	999 TWh$_{\text{el}}$
Maximum load	76 GW$_{\text{el}}$	76 GW$_{\text{el}}$	128 GW$_{\text{el}}$	171 GW$_{\text{el}}$
Minimum load	32 GW$_{\text{el}}$	32 GW$_{\text{el}}$	38 GW$_{\text{el}}$	81 GW$_{\text{el}}$
Maximum RES feed in	138 GW$_{\text{el}}$	136 GW$_{\text{el}}$	224 GW$_{\text{el}}$	285 GW$_{\text{el}}$
Minimum RES feed in	11 GW$_{\text{el}}$	10 GW$_{\text{el}}$	12 GW$_{\text{el}}$	14 GW$_{\text{el}}$
Maximum residual load	49 GW$_{\text{el}}$	49 GW$_{\text{el}}$	94 GW$_{\text{el}}$	131 GW$_{\text{el}}$
Minimum residual load	- 87 GW$_{\text{el}}$	- 85 GW$_{\text{el}}$	- 145 GW$_{\text{el}}$	- 163 GW$_{\text{el}}$
Curtailed primary electricity	5 TWh$_{\text{el}}$	4 TWh$_{\text{el}}$	0 TWh$_{\text{el}}$	0 TWh$_{\text{el}}$
Electrolysis capacity	48 GW$_{\text{el}}$	48 GW$_{\text{el}}$	145 GW$_{\text{el}}$	163 GW$_{\text{el}}$
Full load hours	1,894 h/a	1,574 h/a	1,172 h/a	906 h/a
Fuel cells/gas turbines	50 GW$_{\text{el}}$	50 GW$_{\text{el}}$	94 GW$_{\text{el}}$	131 GW$_{\text{el}}$
Full load hours	800 h/a	651 h/a	935 h/a	1,530 h/a
Hydrogen storage capacity	15 TWh$_{\text{chem}}$	14 TWh$_{\text{chem}}$	80 TWh$_{\text{chem}}$	250 TWh$_{\text{chem}}$
Hydrogen charged	73 TWh$_{\text{chem}}$	60 TWh$_{\text{chem}}$	136 TWh$_{\text{chem}}$	118 TWh$_{\text{chem}}$
Hydrogen discharged	67 TWh$_{\text{chem}}$	54 TWh$_{\text{chem}}$	147 TWh$_{\text{chem}}$	334 TWh$_{\text{chem}}$

a) Scenario 1a

Scenario 1a describes a basic scenario where the electricity demand of today is covered mainly with volatile RES. The yearly final energy demand of 477 TWh$_{\text{el}}$ is covered with 536 TWh$_{\text{el}}$ primary electricity. The surpluses are stored for later usage. As expected, the minima and maxima of load correspond to today's values and only a small amount of 5 TWh$_{\text{el}}$ had to be curtailed due to lacking conversion capacitites and completely filled storages. The 3 % curtailment option is not used in this case, since it requires higher RES power capacities and this model does not consider bottlenecks in the transmission grid. The theoretical influence of a curtailment with perfect foresight is shown in Figure 87. It limits the feed-in from PV and wind power to 85 GW$_{\text{el}}$ and thus avoids peaks of approx. 141 GW$_{\text{el}}$. These peaks occur during winter months with high shares of wind power. The battery storages work well during summer month, when they balance the daily PV peaks. At the beginning of a year (February) the batteries are depleted for a longer period and at years end they are permanently full (cf. Figure 88). The pumped hydro storages show a similar behavior as short-term storages (cf. Figure 89). The state of charge of the hydrogen storage shows a remarkable and characteristic course over a year. Along with the short-term storages, it is depleted in January and February. During spring it is filled up and keeps a balanced SOC over summer. It is gradually depleted in autum and refilled in December (cf. Figure 90).

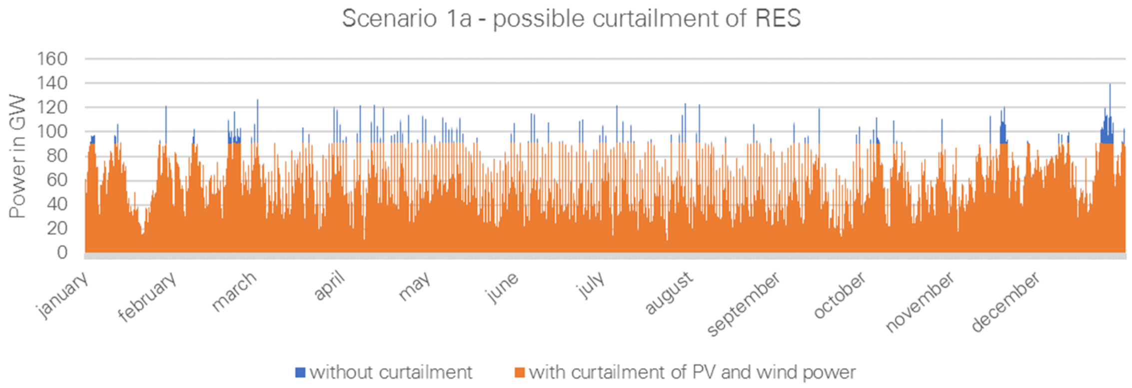

Figure 87: Scenario 1a – influence of curtailment

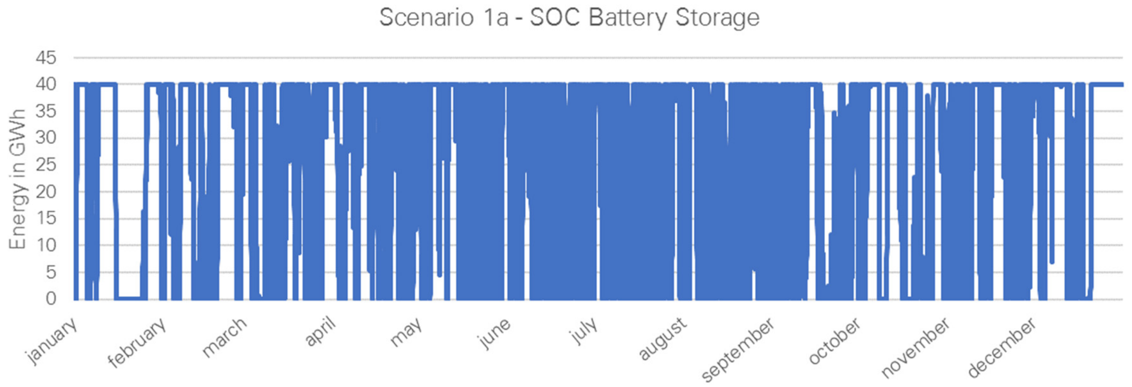

Figure 88: Scenario 1a - SOC of battery storage over a year

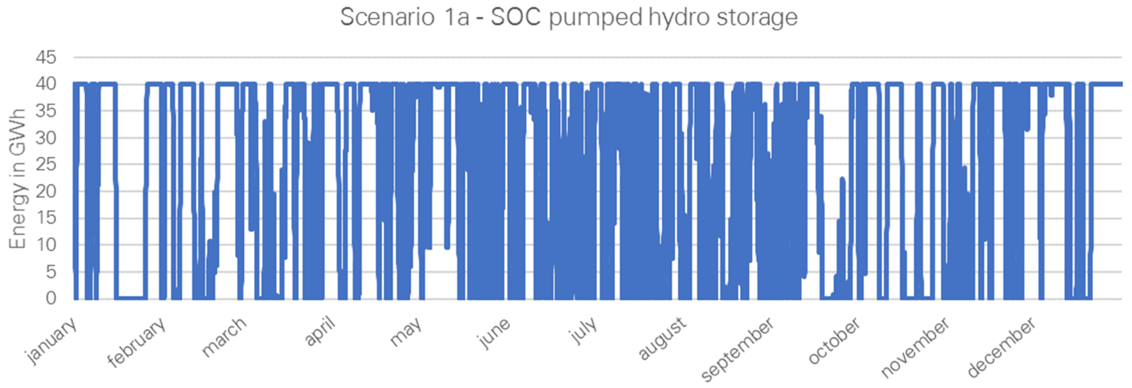

Figure 89: Scenario 1a - SOC of pumped hydro storage over a year

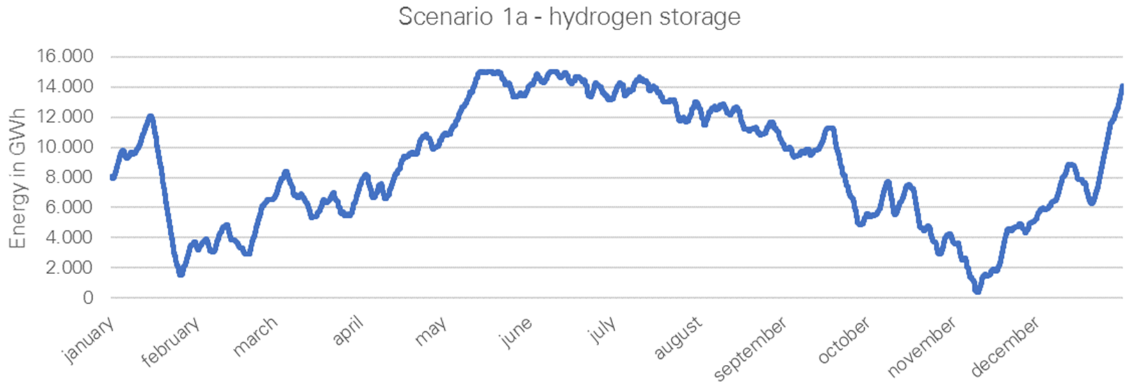

Figure 90: Scenario 1a - SOC of hydrogen storage over a year

The necessary conversion capacities for electrolysis are close to 50 GW_{el}, the same magnitude as the "backup" - capabilities (highly efficient hydrogen gas turbine or more decentral fuel cells). The full load hours for electrolysis are 1894 h/a and only 800 h/a for conventional power. The required hydrogen storage capacities of 15 TWh_{chem} are in range of the expansion potential for cavern storages (35 TWh_{chem}, cf. section 16.3). Since the storage is filled at years end, the scenario 1 proposes a sustained supply system.

b) Scenario 1b

In scenario 1b the battery storage capacities are expanded to examine the impact on the required long-term storages and conversion capacities. The energy/power-ratio is unchanged at 4 and the power is quintupled (50 GW_{el} instead of 10 GW_{el}). This expansion has only minor effects on the necessary primary RES (-5 GW_{el} for wind and PV) and storage capacities (-1 TWh_{chem}) (cf. Table 51). It has no effect on the power capacity of electrolysis and backup plants. However, it significantly reduces the utilization of the third step in the waterfall model. Full load hours drop by ~ 19 % and the hydrogen storage is less cycled. The curtailed primary electricity decreases slightly to 4 TWh_{el}, however the smaller hydrogen storage is earlier filled in spring and less hydrogen is discharged over the year (cf. Figure 91 and Figure 92).

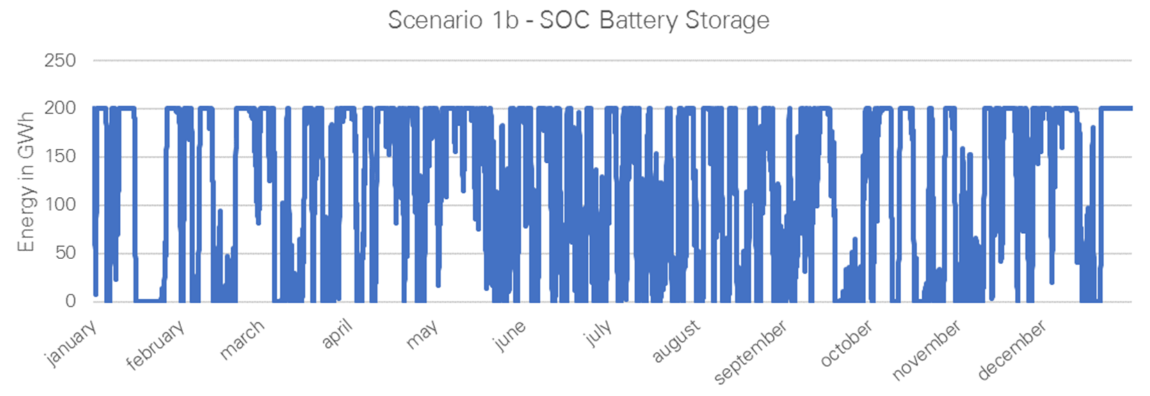

Figure 91: Scenario 1b - SOC of battery storage over a year

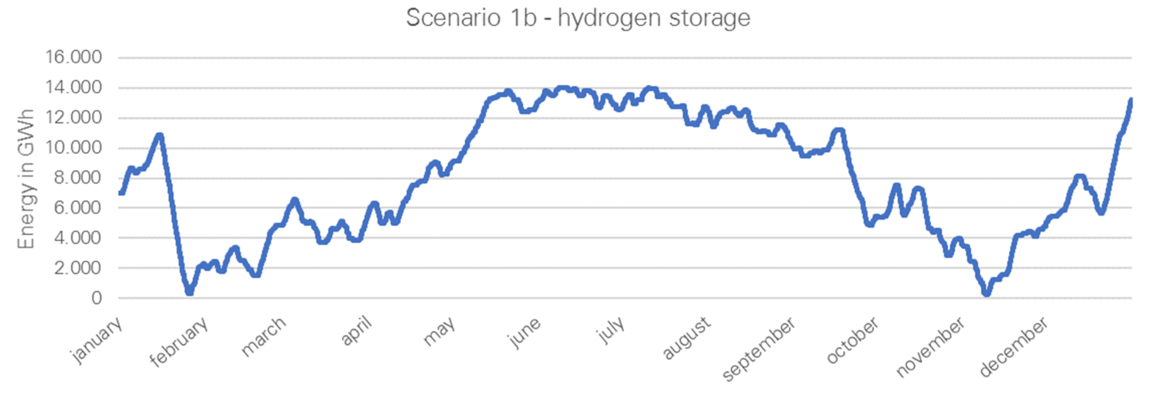

Figure 92: Scenario 1b - SOC of hydrogen storage over a year

c) *Scenario 2*

In scenario 2 the electricity demand for heat pumps to fulfill low-temperature heating purposes is added to the total demand. As a result, the RES capacities are nearly maxed out to their expansion limit. The RES provide 758 TWh_{el} to cover 673 TWh_{el} demand. The installed PV and wind power leads to extreme feed-in peaks that have to be utilized in order to modestly fill the hydrogen storage towards years end. The course of the hydrogen SOC is shown in Figure 93 and it points out the impact of the high PV share that does not correspond to the 60/40 ratio mentioned above (here: 48,4 % wind power to 51,6 % PV). The large solar surpluses in summer in conjunction with low heating demands lead to the continuous charging from May to October. However, even the strong wind months do not cope with the excess additional heating demand in winter. This way, the hydrogen storage would deplete in the following period and the system is not sustainable. Further, the hydrogen storage capacities set to 80 TWh_{chem} exceed today's theoretical cavern capacities by far.

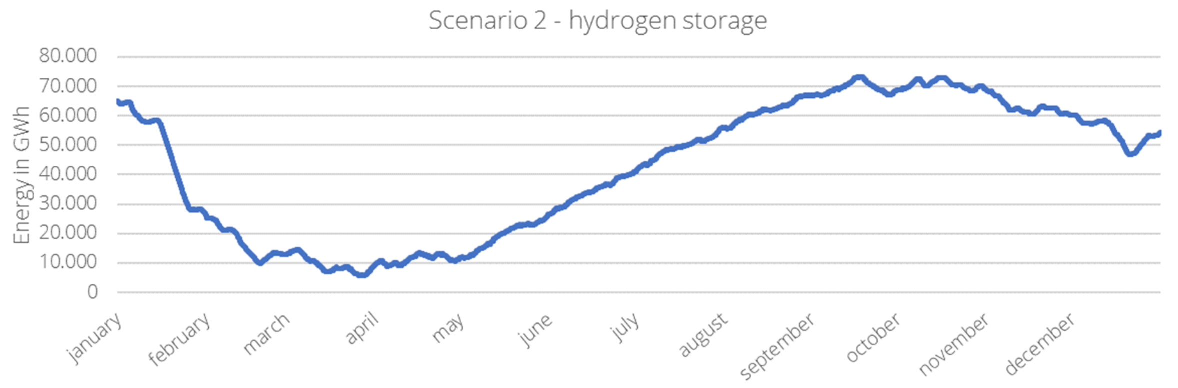

Figure 93: Scenario 2 - SOC of hydrogen storage over a year

d) *Scenario 3+*

In this scenario the demand for electricity-fueled mobility (including air traffic and goods traffic) is added to the total energy demand. That itself is not rational as scenario 2 already converged the limits of expansion potentials. Therefore, this scenario is suited to theoretical discuss the possibilities of improved full load hours on the RES side. These have been increased (PV 1,000 h/a, 4,000 h/a offshore, 2,400 h/a onshore, cf. Table 51) and result in a primary electricity supply of 999 TWh_{el} compared to 771 TWh_{el} at the expansion limits. As the total energy demand for the electrification of the named sectors is still larger (1,047 TWh_{el}) than the supply, the system cannot work in its current configuration. It has to depend on additional imports of energy (fuels or electricity), as the Figure 94 shows a continuous depletion of the hydrogen storage, even if all possible excess power from RES is stored. Within this scenario another finding is important. As the full load hours are increased the maximum RES feed-in rises further from 224 GW_{el} in scenario 2 to 285 GW_{el}. That implicates a further increase in necessary grid expansion. However, the minimum feed-in of RES rises slightly from 11 GW_{el} to 14 GW_{el}. This necessitates higher backup-power capabilities of 131 GW_{el} that are more often utilized with 1,530 h/a compared to the scenario 2 (94 GW_{el}, 935 h/a).

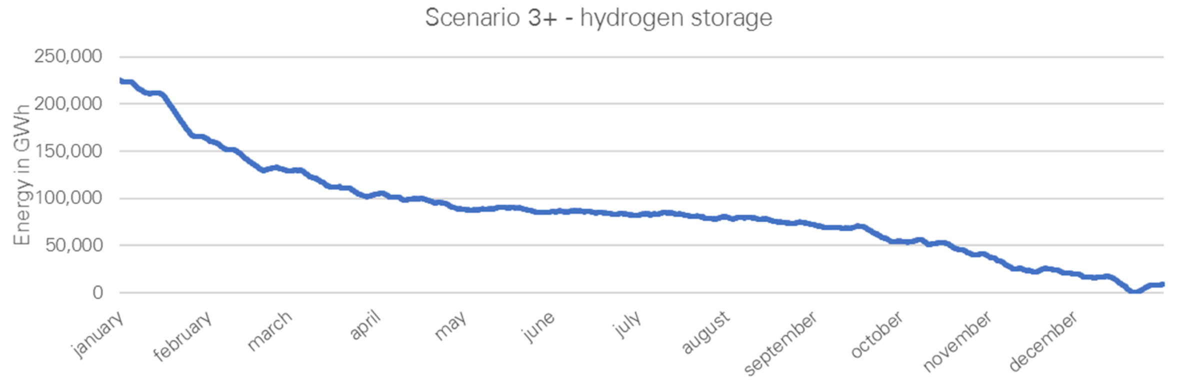

Figure 94: Scenario 3+ - SOC of hydrogen storage over a year

21.4. Consequences

The results, shown above, imply a series of consequences for the TRL rating as well as the German energy transition in its entirety. On the one hand, several major conclusions of previous studies can be confirmed. The VGB study concerning the wind power supply [19] (also cf. chapter 5.2b) can be sustained. Even if PV power is taken into account, there are times of minimum peak power supply from RES, where only a minute fraction of the installed power capacity is available. That leads to an energy supply system, according to Figure 1, that depends on a second parallel power supply, fed by long-term chemical storages (i.e. synthetic fuels; hydrogen at least). The magnitude of this parallel, long-term backup corresponds to the current average load of 50 GW_{el}. The results also sustain the proposition that a renewable power supply of today's electricity demand is within range of the expansion potential and technical possibilities.

On the other hand, these findings lead to consequences for the TRA. In any way, the necessary scale for the energy storage capacity is in TWh. From the above presented storage technologies only chemical storages potentially provide this magnitude. Further, the power capacities for conversion technologies lies in the two-digit GW range. The future development of short-term storages has a minor influence on this fact. The high round trip efficiency of battery systems is a bright spot for the storages at this point, as it covers the widest variety of end use areas. However, according to current knowledge, batteries cannot reasonably provide the TWh capacity and at least hydrogen storages are necessary for this.

However, a resolute sector coupling towards an electrification of heat supply and mobility will considerably increase the total electricity demand to a degree where it exceeds the expansion potential (even with efficiency gains and higher full load hours) of the German volatile RES capabilities. The steep increase of necessary conversion capacities makes this transition no less difficult. The energy demand for industrial high temperature processes is not even considered in this examination. Therefore, it is to deduce, that a "decarbonization" of the energy sector or rather the final energy demand (cf. chapter 2) is not possible with the given boundary conditions. It would require a tremendous reduction of the total energy demand. More efficient consumption technologies will do their part, but the mentioned rebound effect (e.g. ever increasing traveled kilometers per year) will negate the efficiency gains. Further, the necessary transmission and distribution capacities have to grow, but these are not subject to this examination.

For a new energy system, the transformation chains must be kept as short as possible, otherwise the concatenation of efficiencies leads to high amounts of dissipated energy, which in turn must be compensated by even more renewable primary energy. Thus, the direct use of the primary electricity has the highest priority. Any detour via conversion steps and storages is to be avoided.

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22. Summary and Outlook

In conclusion, this thesis contributes to the questions aroused in chapter 1:

- What are necessary technologies for an at least secure supply of energy?
- What are the options for the energy system and how can different technologies be implemented?
- What is the current state of the art and what technologies need further development?
- What is the necessary expansion for the respective technologies?
- Are the given goals and timeline for the energy transition feasible?

In summary, the TRL of the different systems examined varies widely. For every step in the direct or indirect usage of renewable intermittent energy sources, technologies are available that are commercially available in the MW-scale. However, RESs potentially provide power in the GW-scale. Thus, conversion technologies and energy storage systems also have to be available in the GW-scale. Since the scale of testing is an essential criterion in technology readiness assessment, it reduces the TRL of essential technologies such as battery storage and power-to-gas conversion significantly. A further bottleneck is the intermittent power supply and thus operation of the technologies. Comparatively slow and thermally inert processes (e.g. power-to-gas/chemicals) are more suitable for continuous operation. Therefore, the environment criterion under current conditions for most demonstration projects has to be assessed as “relevant” or “operational with limited range” and thus limits the TRLs.

Another bottleneck is the restricted availability of RESs and their dependence on natural conditions. Germany has long periods with high temperatures (reducing the efficiency of solar pv modules) or low radiation combined with poor wind conditions. In these cases, even large wind and pv capacity provide low power outputs. Those conditions pose a threat to the energy supply system, which has to be countered by large-scale (GW) conversion and storage capacity. Such capacity cannot be installed on a short-term basis and therefore requires conventional power supply technologies to bridge the gap towards a RES-dominated energy supply system.

The study shows that there are significant bottlenecks in terms of security of supply. Although the conversion of solar and wind energy into electrical energy has a very high TRL and is also highly scalable (land use, environmental impact and costs are neglected here), the intermittent availability of wind and solar energy is a natural bottleneck and requires storage solutions and backup systems. Of course, sector coupling may contribute to security of supply, but storage solutions on a GW and/or TWh scale are essential. Their TRL and scalability are still considered to be low, so that at least a decade of further development will be required to reach TRL 9. At that point nationwide implementation can begin, which in turn will take several decades to complete. The last energy transition towards nuclear power, presented shortly in chapter 1, gives a clue about the time frame for a (partial) transformation of an industrial nations energy system.

As an outlook, the assessment of TRLs should be repeated on a regular basis, as the validity period is limited. This study is a snapshot of the current expectation on technologies and the future. It underlies permanent change. On the other side, certain boundary conditions, e.g. the laws of thermodynamics, remain constant and force a critical view on ideas and concepts regarding the energy system.

23. Abbreviations and symbols

η	Energy conversion efficiency	P	Power
dt	Change in time	$\dot{Q}, \dot{q}$	Heat flow, specific heat flow
dx	Change in position	Q	Electric charge
E	Energy	S	Surface, Area
F	Faraday constant	$\dot{V}$	Volume flow
g	Gravitational acceleration	V	Volume
G	Gibbs energy	z	Valency number of ions of the substance (electrons transferred per ion)
h	Specific enthalpy	Δ	Change in …
H, $\dot{H}$	Enthalpy, enthalpy flow	ν	Velocity
$\dot{m}$	Mass flow	ρ	Density
m	Mass		

$(NH_4)_2SO_4$	Ammonium sulfate
a	Year
A	Ampere
AC	Alternating current
ACAES	Adiabatic compressed air energy storage systems
ACCR	Aluminiun Conductor Composite Reinforced
AEE	Agency for Renewable Energies
AEL	Alkaline electrolysis
AFC	Alkaline fuel cell
AGFW	Energy Efficiency Association for heating, cooling and CHP
AGM	Absorbed glass mat
Agora	Agora energy revolution
AIT	Austrian Institut of Technolgy
Al_2O_3	Aluminium oxide
approx.	Approximately
BAFA	German Federal Office for Economic Affairs and Export Control
BBPIG	German Federal Requirement Plan Act
BDEW	German Federal Association of Energy and Water Industries
BiSCCO	Bismuth strontium calcium copper oxide
BMWi	German Federal Ministry for Economic Affairs and Energy
bn	Billion
BNetzA	Germany Federal Network Agency
BPP	Bipolar plates
BTU	British Thermal Units
BVG	German Geothermal Association
BWE	German Wind Energy Association
CAES	Compressed air energy storage
CC	Convection cooling
CcH_2	Cold- and cryo-compressed hydrogen
CCRP	Clean Coal Research Programm
CCS	Carbon Capture and Storage
CdTe	Cadmium telluride

cf.	Compare
CGH_2	Compressed gas hydrogen
CH3OH	Methanol
CH4	Methane
CHP	Combined heat and power plant
CIGS	Copper indium gallium selenide
CIP	Continuous improvement processes
cm^2	Square centimeter
CO	Carbon monoxide
CO2	Carbon dioxide
COP	Coefficient of performance
CPV	Concentrator photovoltaics
C-rate	Discharge rate
CSP	Concentrated Solar Power
CTE	Critical Technology Elements
CTL	Compact transmission line
CuO	Copper oxide
DBFZ	German Biomass Research Centre
DC	Direct current
DC CTL	Compact Transmisson Line for Direct Current
DCSP	German Association for Concentrated Solar Power
dh	District heating
DLR	German Aerospace Center
DMFC	Direct methanol fuel cell
DoD	United States Department of Defense
DOD	Depth of Discharge
DOE	United States Department of Energy
DSC	Dye-sensitized solar cell
DTS	Distributed Temperature Sensing
DWS process	Dry-wet simultaneous fermentation
E	Energy
e.g.	For example
EEG	German Renewable Energy Sources Act
EGS	Enhanced Geothermal Systems
el.	Electrical
energet.	Energy-related
engl.	english
EnLAG	German Energy Line Extension Act
EnWG	German Energy Industry Act
FACTS	Flexible AC transmission systems
FC	Fuell cell
$FeCl_2$	Iron(II) cloride
FLM	Overhead line temperature monitoring
FLOX	Flameless oxidation
FNR e. V.	Agency for Renewable Resources
FRT	Fault Ride Through
FSC	Fixed series compensation
FTS	Fischer-Tropsch-synthesis
GaAs	Gallium arsenide
GAO	Government Accountability Office
GaP	Gallium phosphide
GDL	Gas diffusion layers

Ge	germanium
GIL	Gas-insulated pipe or transmission line
GIS	Gas -insulated switchgear
GT	Gas turbine
GtL	Gas -to-liquid
GW	Gigawatt
GWh	Gigawatt hour
GWP	Global Warming Potential
h	Hour
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen sulphide
H_2SO_4	Sulphuric acid
H_3PO_4	Phosphoric acid
HAWT	Horizontal Axis Wind Turbine
HCl	Hydrochloric acid
HCNG	Hydrogen enriched compressed natural gas
H-Gas	High (calorific) gas
HHV	Higher heating value
HP	High pressure
HSO^{4-}	Hydrogen sulfate
HT	High temperature
HTB	High-temperature battery
HTEL	High temperature electrolysis
HTLS	High-temperature low-sag conductors
HVAC	High voltage alternating current
HVDC	High voltage direct current
I-CAES	Isothermal compressed air energy storage systems
ICT	Information and communications technology
IGBT	Insulated-gate bipolar transistor
IGCC	Integrated Gasification Combined Cycle
IHX	Internal Heat Exchanger
incl.	Inclusive
IRL	Integration Readiness Level
ISE	Fraunhofer Institut for solar energy systems
ISFOC	Instituto de Sistemas Fotovoltaicos de Concentraión
IWES	Frauenhofer Insititut for wind energy and energy systems technology
J	Joule
K	Kelvin
K2CO3	Potassium carbonate
km	Kilometer
KNO3	Potassium nitrate
KOH	Potassium hydroxide
kV	Kilovolt
kW	Kilowatt
LAES	Liquid air energy storage
LCC	Line Commutated Converter
LCO	Lithium cobalt oxide
LFP	Lithium iron phosphate
L-Gas	Low [calorific] gas
LH_2	Liquid Hydrogen
LHV	Lower heating value

Li_2CO_3	Lithium carbonate
LiB	Lithium-ion battery
$LiCoO_2$	Lithium cobalt oxide
$LiMnO_2$	Lithium manganese oxide
LMO	Lithium manganese oxide
LNO	Lithium nickel oxide, $LiNiO_2$
LOHC	Liquid Organic Hydrogen Carriers
LP	Low pressure
LSD	Low self-discharge
LTO	Lithium titanate
LVR	Line voltage regulator
m	Meter
m^2	Square meter
m^3	Cubic meter
MCFC	Molten carbonate fuel cell
MEA	Membrane electrode assembly
MENA	Middle East & North Africa
MgO	Magnesium oxide
MHI	Mitsubishi Heavy Industries
MHPS	Mitsubishi Hitachi Power Systems
MHS	Metal hydride storage
Mio.	Millions
MNQC	Multi-Nozzle Quiet Combustor
MOF	Metall Organic Framework
MOSFET	Metal-oxide semiconductor field-effect transistor
MP	Medium pressure
MRL	Manufacturing Readiness Level
MSCDN	Mechanically Switched Capacitor with Damping Network
MW	Megawatt
N	Newton
N_2	Nitrogen
Na_2CO_3	Sodium carbonate
Na_2S_5	Sodium polysulfide
$NaAlCl_4$	Sodium tetrachloroaluminate
NaCl	Sodium chloride
$NaNiCl_2$	Sodium-nickel chloride
$NaNO_3$	Sodium nitrate
NaS	Sodium-sulphur
NASA	National Aeronautics and Space Administration
NCA	Lithium Nickel Cobalt Aluminium Oxide
NiCd	Nickel-cadmium
$NiCl_2$	Nickel(II) chloride
NiCr	Nichrome
NiMH	Nickel -metal hydride
NMC	Lithium Nickel Cobalt Manganese Oxide
NOVA	German acronym for “grid optimization before reinforcement and expansion”
NOx	Nitrogen oxide
NREL	National Renewable Energy Laboratory
O_2	Oxygen
OLM	Overhead line monitoring
ORC	Organic-Rankine-Cycle
OSC	Organic solar cell

P	power
p. a.	Per year
PAFC	Phosphoric acid fuel cell
PAN	polyacrylonitrile fibres
Pb	Lead
PbO_2	Lead oxide
$PbSO_4$	Lead sulfate
PCM	Phase Change Materials
PEM	Proton exchange membrane
PEMEL	Proton exchange membrane electrolysis
PEMFC	proton exchange membrane fuel cell
PHS	Pumped Hydro Storage
PJ	Petajoule
ppm	Parts per million
PtC	Power-to-Chemicals
$PtCH_4$	Power -to-methane
PtG	Power-to-Gas
PtH	Power-to-Heat
PtH_2	Electrolysis processes
PtL	Power-to-Liquids
PV	photovoltaic
R&D	Research and development
RES	Renewable Energy System
ReWP	Operating Reserve from Wind and Photovoltaic Farms
RFB	Redox flow battery
RHO	Rated heat output
RLGT	Regulated local grid transformers
RoHS	Restriction of Hazardous Substances
RRWK	Regional Regulating Power Station
s	Second
SC	Series compensation
SF_6	Sulphur hexafluoride
SFC	Static frequency converters
SH_2	Slush Hydrogen
SiO2	silicon dioxide
SMDS	Shell Middle Distillate Synthesis
SOC	State of Charge
SOEC	Solid oxide electrolysis cell
SOFC	Solid oxid fuel cell
SPE	Solid polymer electrolyte
SPF	seasonal performance factor
SRL	System Readiness Level
SST	Solid state transformer
STATCOM	Static synchronous compensator
STC	Standard Test Conditions
SUMR	Segmented ultralight morphing rotor
SVC	Static var compensator
SWNT	Single walled nanotube
t	Metric ton
TAL	Thermal-resistant aluminium
TCSC	Thyristor-controlled series compensation
TEC	Thermoelectric cooler

ThH_2	Torium hydride
TiH_2	Titanium hydride
TiO_2	Titanium dioxide
TMP	Technolgy Maturity Plan
TRA	Technology Readiness Assessment
TRL	Technolgy Readiness Level
TSO	Transmission system operator
TW	Terrawatt
TWh	Terrawatt hour
UBA	German Federal Environment Agency
U-CAES	Uncooled compressed air energy storage systems
UPS	Uninterruptible power supply
URFC	Unitized reversible/regenerative hydrogen fuel cells
V	Volt
V_2O_5	Vanadium pentoxide
VAWT	Vertical Axis Wind Turbine
vol.%	Volume percent
VRFB	Vanadium redox flow battery
VSC	Voltage-Sourced Converter
W	Watt
WT	Wind turbine
Y_2O_3	Yttrium(III) oxide
YBCO	Yttrium barium copper oxide
YSZ	Yttria stabilized zirconia
ZEBRA	Zero Emission Battery Research Activities
ZnO	Zinc oxide
ZrO_2	Zirconium dioxide

24. Indices

C	Carnot	MeOH	Methanol
cell	Cell	min	Minimum
chem, ch	Chemical	module	Module
cycle	Cycle	net	Net
eff	Effective	out	Output
el	Electrical	R	reaction
End	Final	rev	reversible
Gross	gross	RHO	rated heat output
Gt	Geothermal	Sorbent	Sorbent
H2	Hydrogen	th	thermal, theoretical
in	Input	tn	thermoneutral
irr	Irradiation	u	upper
l	lower	W	water
lignite	Lignite	Wi	wind
max	Maximum		

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27. Appendix

27.1. DOE TRL definition and description

Based on U.S. Government Accountability Office (Hrsg.): Technology Readiness Assessment Guide - Best Practices for Evaluating the Readiness of Technology for Use in Acquisition Programs and Projects, GAO-16-410G, August 2016, online: http://www.gao.gov/assets/680/679006.pdf, retrieved 15.08.2018.

TRL	Definition	Description
1	Basic principles observed and reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology's basic properties or experimental work that consists mainly of observations of the physical world. Supporting Information includes published research or other references that identify the principles that underlie the technology.
2	Technology concept and/or applications formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies. Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The step up from TRL 1 to TRL 2 moves the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL 1 work.
3	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative tested with simulants. Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected on simulants. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments.
4	Component and/or system validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small scale tests on actual waste. Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4-6 represent the bridge from scientific

		research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.
5	Laboratory scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory scale system in a simulated environment with a range of simulants1 and actual waste. Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.
6	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology’s demonstrated readiness. Examples include testing an engineering scale prototypical system with a range of simulants. Supporting information includes results from the engineering scale testing and analysis of the differences between the engineering scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.
7	Full-scale, similar (prototypical) system demonstrated in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology’s demonstrated readiness. Examples include testing an engineering scale prototypical system with a range of simulants. Supporting information includes results from the engineering scale testing and analysis of the differences between the engineering scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.

8	Actual system completed and qualified through test and demonstration. Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development.	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system with actual waste in hot commissioning. Supporting information includes operational procedures that are virtually complete. An Operational Readiness Review (ORR) has been successfully completed prior to the start of hot testing.
9	Actual system operated over the full range of expected conditions. Actual operation of the technology in its final form, under the full range of operating conditions.	The technology is in its final form and operated under the full range of operating mission conditions. Examples include using the actual system with the full range of wastes in hot operations.

27.2. Visualized summary of TRLs

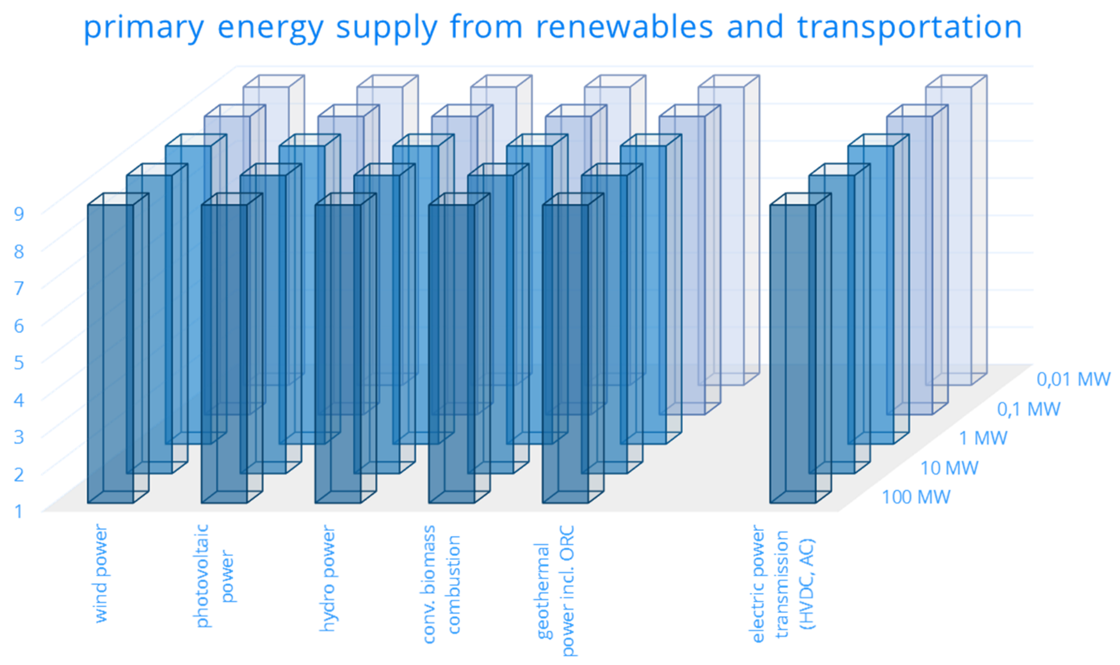

Figure 95: TRLs of primary energy supply from renewables and electric power transmission

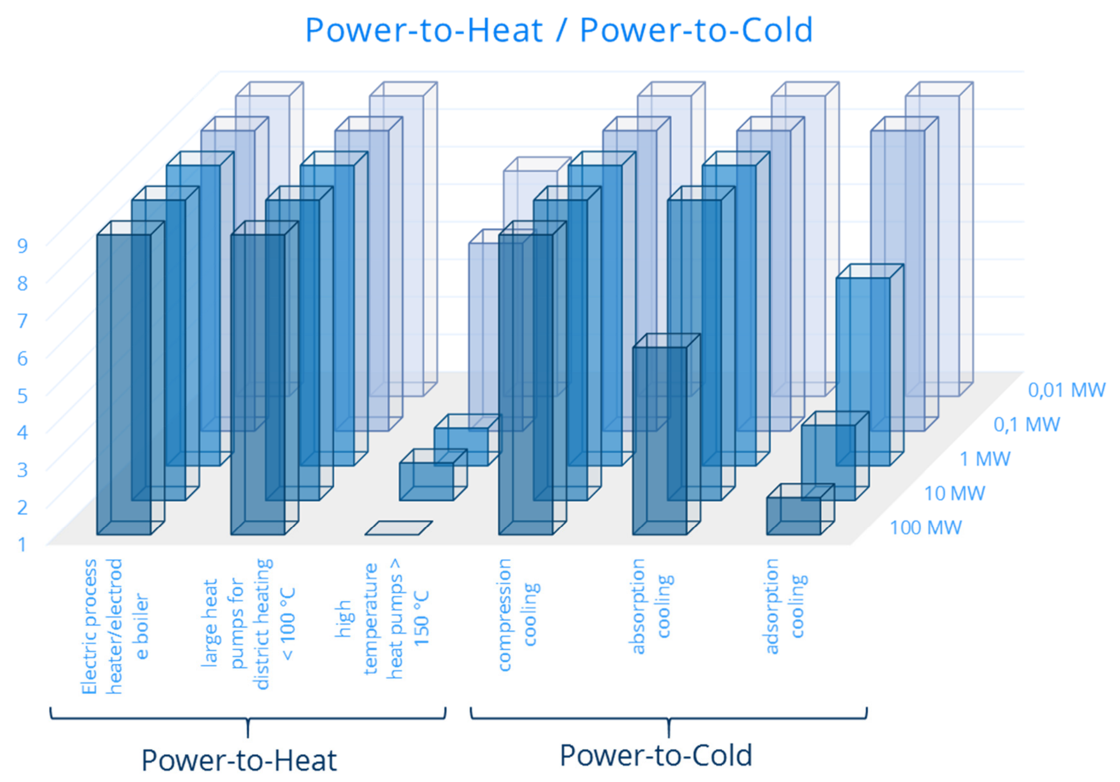

Figure 96: TRLs of power-to-heat and power-to-cold

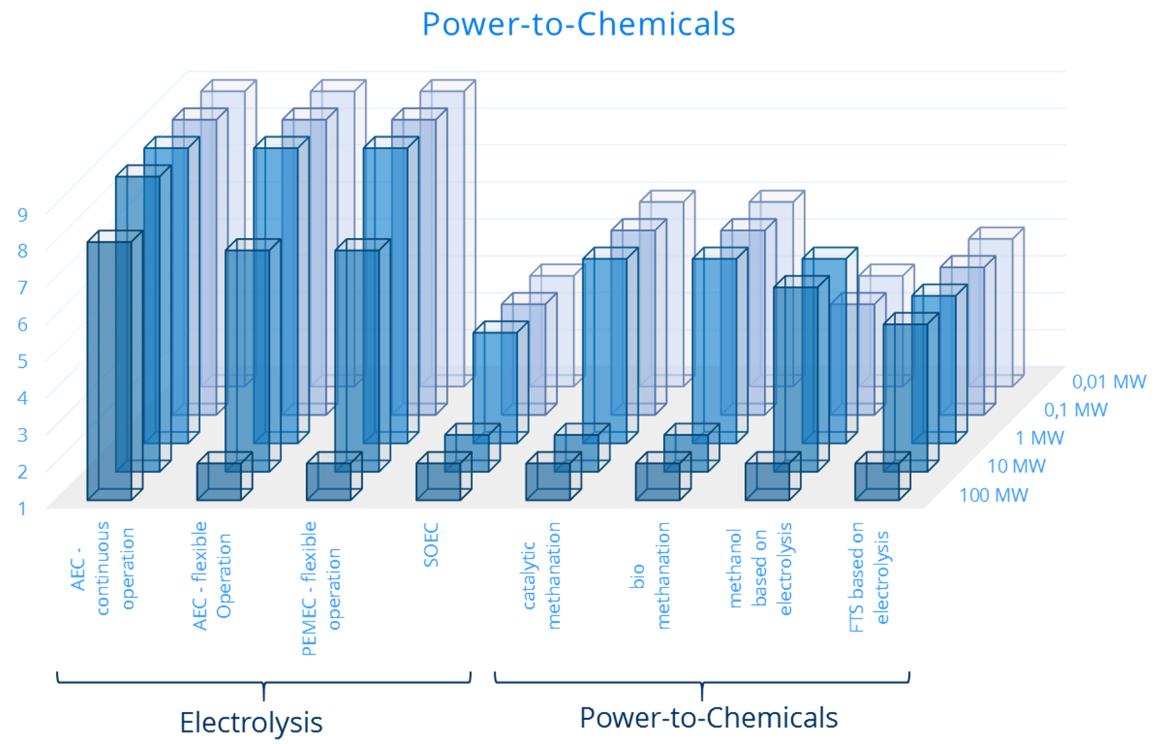

Figure 97: TRLs of power-to-chemicals

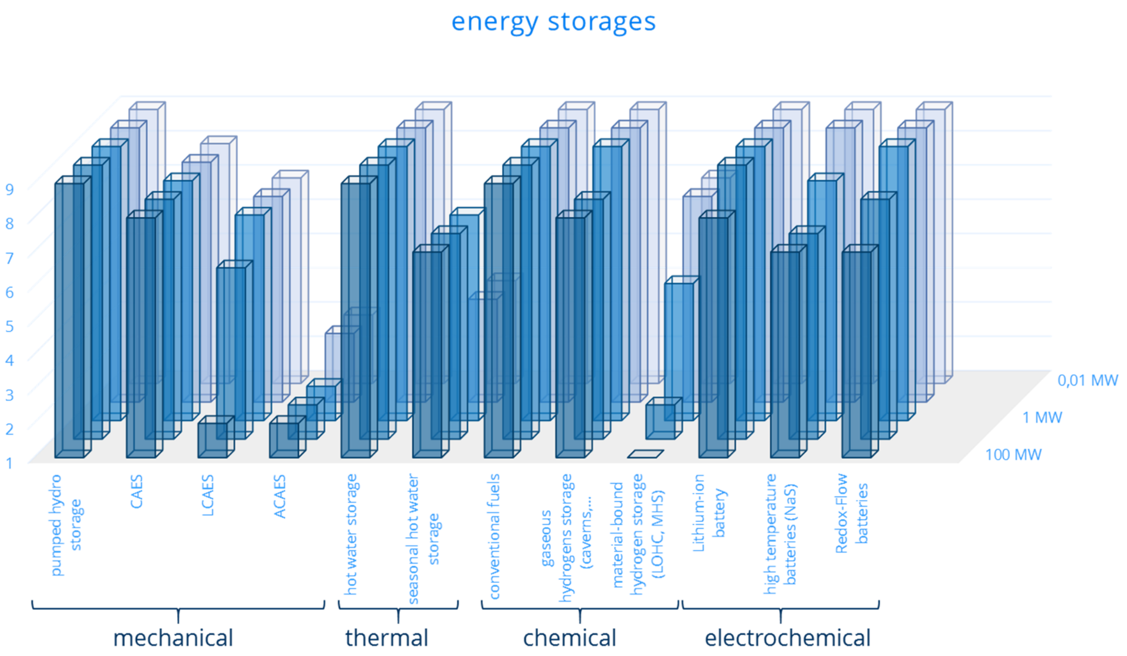

Figure 98: TRLs of energy storages

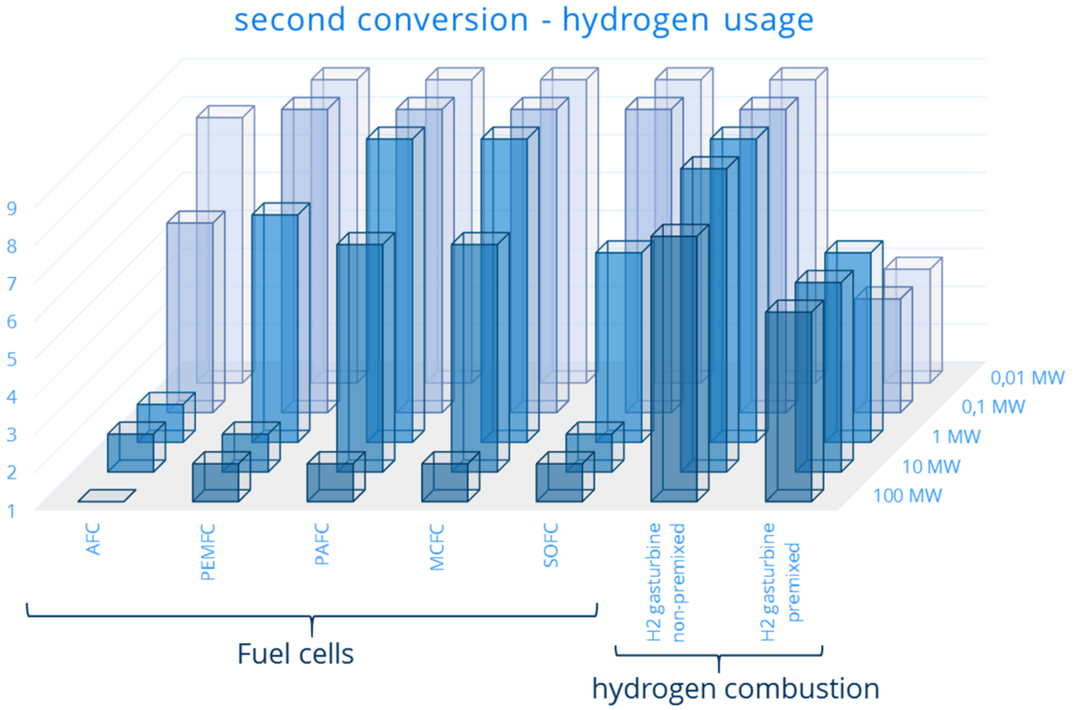

Figure 99: TRLs of hydrogen conversion - chemicals-to-power