Chapter 1

Storage of Renewable Energy – Introduction and Scope

1.1 Motivation and Objectives

Transition from fossil to renewable energy. The German "Energiewende" policy encourages the construction of power plants for renewable energy such as wind farms, photovoltaic (PV), or biomass power plants. The political goal is to reach a share of at least 80 % renewables in the electrical energy supply by 2050 [Bundesministerium für Wirtschaft und Technologie and Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, 2012]. The ambitious goal to reduce green house gas emissions comes along with major technical [Scholz et al., 2014] and regulatory/economic challenges [Dehmer, 2013; Narbel and Hansen, 2014]. Hence, it is possible that the politically set timetable is a too short period and that the project of restructuring the overall energy system might take a century or so. However, a general feasibility of 100 % renewable energy supply of all energy sectors (electricity, industry, mobility and heating) is confirmed by regional back-casting scenarios [Faulstich et al., 2016b]. Yet, wind and solar power, which are the two fastest growing renewables, generate electricity naturally intermittent, i.e. not demand-oriented. Thus, new strategies to balance electricity generation and demand are required. In the last decades many solutions, such as increasingly flexible generation capacities, demand side management, sectoral interlinking, and various energy storage options have been suggested. The energy system has to meet many different requirements. It is found that a multitude of different new technologies will have to be used, including several energy storage options for different applications, such as grid stability (short term storage or ancillary electric grid services), intra-day or weekly energy balancing (intermediate storage), and seasonal energy balancing (long term storage) [Beck et al., 2013; Sørensen, 2007; Schulz, 2015].

Required storage capacities. The future storage capacities needed in Germany and other countries depend on a large number of variables and are unknown. Estimates cover a wide range of possible values; e.g. Pape et al. [2014] estimate that in the German grid no electrical energy storage is required for a renewable share of up to 90 % as long as other flexibility options, such as flexible gas turbines and demand side management, are used. Weiss [2013] estimates that an electrical energy storage capacity of 1 to 1.5 TWh is needed in an 80 % renewable energy system and emphasizes that the ratio of wind to PV capacities is a decisive factor for storage assumptions. Scholz et al. [2014] estimate for a 100 % renewable system in Germany a required energy storage capacity of 191 TWh. To date such large energy storage capacities are feasible with chemical energy storage only [Scholz et al., 2014]. Based on a back casting scenario developed in [Faulstich et al., 2016b], Faulstich et al. [2016a] investigate the trade off between long-term chemical energy storage (with relatively low round trip efficiencies) and intermediate-term energy storage with higher round trip efficiencies based on a simulation of the overall energy system of Lower Saxony, a region in northern Germany. They [Faulstich et al., 2016a] estimate that a 100 % renewable energy supply of Lower Saxony requires 33.5 TWh of long-term energy storage capacity in the form of hydrogen storage in addition to 146 GWh intermediate-term energy storage capacity of the pumped hydro energy storage-type or similar. The energy needs of Lower Saxony correspond to approximately 1/10 of the German ones. Hence, it can be deduced that the estimates in [Faulstich et al., 2016a] correspond to a required storage capacity for a 100 % renewable German energy system (comprising electricity, industry, heating and mobility sectors) of 335 TWh long-term and 1.5 TWh intermediate-term storage. Faulstich et al. [2016a] state that for a lower share of renewables (approximately 80 to 90 %) the required storage capacity for Germany is drastically lower of around 11 TWh.

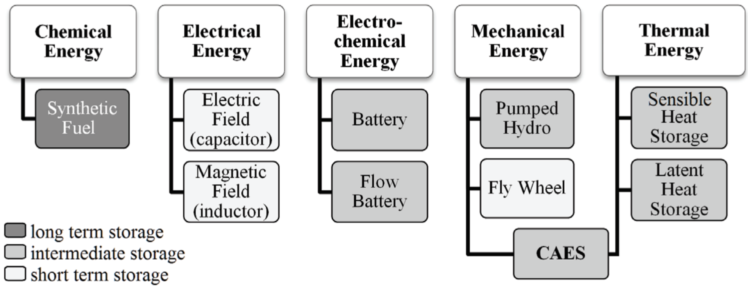

FIGURE 1.1: Electrical energy storage options sorted by form of energy in the storage state

Electrical energy storage. Electricity cannot be stored. However, electric energy can be transformed into storable energy forms such as mechanical energies (kinetic or potential energy), thermal energy, chemical energy, and others. A general overview of electrical energy storage systems sorted by energy form in the storage state is given in Figure 1.1. An example for chemical energy storage is the hydrogen path: Electrical energy is used to produce hydrogen via water electrolysis as a synthetic fuel. Hydrogen can then be stored in its gaseous or liquid form and contains chemical energy. When a deficit in the electric grid occurs, hydrogen can be turned into electric energy via fuel cells or via combustion turbines using oxygen from the air. This hydrogen path allows for large storage capacities and long storage periods due to the stability and storability of fuels such as hydrogen, synthetic natural gas, or Fischer-Tropsch products. However, conversion efficiency is comparatively low. On the other hand, the electrical energy storage in electric fields of capacitors or the magnetic field of inductors has very high conversion efficiencies but storage duration is limited due to high self discharging rates. Thus, together with flywheels which belong to the category of mechanical energy storage systems, these technologies are only applicable to short term storage in the order of milli seconds to minutes. In the section of intermediate term energy storage several technologies are available. Pumped Hydro Energy Storage (PHES) accounts for 99 % of the installed power and capacity in the electric grid [Rehman, Al-Hadhrami, and Alam, 2015; Dötsch, Kanngießer, and Wolf, 2009]. It is in use as bulk energy storage for intra day load shifting for around 100 years. The electrical round trip efficiency is today around 80 %. Compressed Air Energy Storage (CAES) is another option to store energy for intermediate term (storage durations of hours or days). It is often listed in the category of mechanical energy storage due to its seemingly similarities with PHES (e.g. comparable machinery, such as pump or compressor and water or gas turbine, respectively, and similar power and capacity ranges). However, energy flows, efficiencies, and storage mechanisms are different because of the compressibility of the working fluid *air* compared to the incompressible *water* in PHES. Thus, thermodynamic considerations and thermal cycling within the CAES process are also crucial. This makes CAES a thermo-mechanical system. The fact that enthalpy of compressed air at ambient air temperatures is close to zero emphasizes the thermal energy storage characteristics. Without thermal energy storage external heat sources such as natural gas have to be used, turning the overall concept into a combined generation and storage unit.

Compressed Air Energy Storage. The first fuel-driven CAES plant was successfully commissioned in Huntorf in 1978. Today, there are only two commercial plants worldwide - in Huntorf (Germany) and in McIntosh (USA). Due to the switch from fossil to renewable energies CAES gained interest over the last few years and proliferation of publications can be observed; Several pilot plants of next generation CAES systems are recently being tested; Some economic forecasts expect a "dramatic growth" of "more than 11 GW of CAES" until 2023 [Martin, 2013-08-19].

Objectives. In this thesis forthcoming CAES concepts are examined based on steady state calculation methods validated with data from the reference CAES plant Huntorf. Time-dependent aspects of the processes are calculated. Hydrogen as a fuel option is discussed. The calculation methods are validated with a unique set of measured operational data from the reference CAES plant in Huntorf. A hydrogen-fueled CAES model system is tested in a 100 % renewable energy system simulation.

1.2 Previous Publications

In this section previously published literature is summarized sorted by three key topics: CAES in general, time dependent CAES, and hydrogen options for CAES.

1.2.1 Design and Steady State Thermodynamics of CAES

[1] The first patent of CAES dates back to the 1940s [Gay, 1948]. The first plant went in operation in 1978 in Huntorf, Germany [Quast and Crotogino, 1979; Brown Boveri & Cie, 1980; Hoffeins, Romeyke, and Sütterlin, 1980; Quast, 1981; Brown Boveri & Cie, 1986; Crotogino, Mohmeyer, and Scharf, 2001-04-15; Crotogino, 2003]. In the 70s and 80s a research program was conducted in the U.S. to examine underground storage options, in which the concept of CAES was investigated and a large number of potential sites for CAES was identified. Reports of this 'Underground Energy Storage Program' prepared by the Pacific Northwest Laboratory for the U.S. Department of Energy are given in [Drost, Zaloudek, and Loscutoff, 1980; Hendrickson,

[1] This subsection has previously been published in [Kaiser, Weber, and Krüger, 2018].

1981; Hobson et al., 1981; Kannberg, 1981; Wiles and McCann, 1981; Allen, Doherty, and Fossum, 1982; Allen, Doherty, and Thoms, 1982; Reilly and Schainker, 1982; Wiles, 1982; Zaloudek and Reilly, 1982; Fort, 1982; Fort, 1983; Beckwith & Associates, 1983; Erikson, 1983; Hostetler, Childs, and Phillips, 1983] and summarized among others in the annual report [Kannberg, 1983]. Fort [1982] presents the program 'CAESCAP' that was developed by Pacific Northwest National Laboratories (U.S.) in the early 80s and shows methods comparable to those presented in Chapter 3 of this thesis [Fort, 1982; Fort, 1983]. The program serves to evaluate different CAES plant configurations in steady-state conditions including adiabatic CAES (ACAES). Subsequent to these theoretical studies, in the early 90s a CAES plant was commissioned in McIntosh, Alabama, which remains the only operated underground energy storage facility in the U.S. [Goodson, 1993; Pollak, 1994]. Osterle [1991] presents a thermodynamic analysis of a basic CAES configuration based on Clapeyron equation of state (EOS). Compression and expansion are assumed to be irreversible and exergy is used to define a process efficiency.

Seventeen years later, in the context of renewable energy new studies on adiabatic CAES (ACAES) are elaborated. Grazzini and Milazzo [2008] consider various design criteria for ACAES such as the storage pressure and the number of compression or expansion stages. The considerations are based on Clapeyron equation of state (EOS) and reversible thermodynamics. For ACAES a round trip storage efficiency of 72 % has been found [Grazzini and Milazzo, 2008]. In 2011 a more detailed study of ACAES was presented by Wolf [2011] discussing several EOS that might be suitable for CAES calculations. Wolf [2011] questioned the applicability of ideal gas law models for their insufficient representation of the air storage state in which a high pressure together with a low temperature occur. Furthermore, heat storage optimization was a focus in his study.

Hartmann et al. [2012a] analyse different ACAES concepts using again ideal gas EOS and considering reversible and irreversible ACAES with a variation of the number of compression stages (1 to 3 stages). Some dynamic elements are added, since the effect of rising cavern pressure on compression side during the charging process is taken into account. This effect is neglected during discharging, where no throttle is modeled but the turbine power remains constant over a wide pressure range. The main conclusion of Hartmann et al. [2012a] is that the literature value of 70 % ACAES efficiency applies only to reversible models and that 60 % figure seems to be a suitable estimate for an actual plant. Kim et al. [2012] present a thermodynamic analysis of several CAES concepts using both energy and exergy. The calculations are again based on ideal gas law and take irreversibility into account but neglect pressure variations inside the reservoir by evoking isobaric storage solutions. The steady-state calculations [Kim et al., 2012] consider a diabatic plant that resembles the McIntosh plant. Furthermore, isothermal configuration, tri-generation micro-CAES with storage, heating and cooling, micro-ACAES, and isobaric CAES plus a pumped hydro energy storage-hybrid system are considered. Kim et al. [2012] introduce a new CAES storage efficiency based on exergy and conclude that for CAES a figure of around 70 % is applicable. Less optimistically, Pickard, Hansing, and Shen [2009], using ideal gas law, irreversibility, and exergy calculations too, estimate that ACAES attains a cycle efficiency of roughly 50 % to 60 % only. Nielsen [2013] gives an overview of several CAES configurations and describes in detail several variations of an isobaric plant ('ISACOAST-CC'). Furthermore, heat transfer processes inside a salt cavern are considered. The calculations include a dynamic simulation that takes into account a part load operation. Zhao, Wang, and Dai [2015] present a steady-state calculation of CAES combined with a Kalina process where Clapeyron EOS is used. Several parameter variations are presented to show the effect of changing ambient conditions or turbine inlet temperatures. Again exergy is used. Safaei Mohamadabadi [2015] compares several CAES concepts including the conventional CAES, a cogeneration CAES, adiabatic, and hydrogen fired CAES. Although thermodynamic irreversibilities are accounted for, Clapeyron EOS is used and specific heats are taken as constant. The concept of exergy is used to asses efficiencies. An economic assessment is the main focus.

Budt et al. [2016a] present both an overview of CAES history and recent developments. The publication includes considerations on exergy, efficiencies, and fluid properties. Huntorf and McIntosh plants are described using generally available (literature) process data and several advanced CAES systems are elaborated upon in more detail. Castellani et al. [2015] present experimental data on CAES with considerations on heat storage options based on phase changes. Additionally, Tessier et al. [2016] provide theoretical considerations for such an ACAES. Mazloum, Sayah, and Nemer [2016] present a steady-state and dynamic calculation of ACAES resulting in a round trip efficiency of 66 % based on irreversible thermodynamics. Briola et al. [2016] present thermodynamic calculations for the Huntorf CAES plant (original 290 MW configuration before the retrofit to 310 MW) with air treated as real gas and irreversible thermodynamics. The main focus is on dynamic plant behavior based on characteristic curves of the turbo machinery. Even though Huntorf and McIntosh plants play a key role in the above cited literature, thermodynamic insights are often limited to the citation of (generally available) literature values of the process parameters. Only when it comes to dynamic aspects, such as the transient behavior of the cavern the existing plants are considered more thoroughly. Thermodynamic data of the Huntorf air storage cavern was originally presented in [Hoffeins, Romeyke, and Sütterlin, 1980; Quast, 1981] and has been analyzed in works of Raju and Khaitan [Raju and Khaitan, 2012; Khaitan and Raju, 2012; Khaitan and Raju, 2013], Kushnir et al. [Kushnir, Ullmann, and Dayan, 2012b; Kushnir, Dayan, and Ullmann, 2012] and Xia et al. [2015]. Recently, Briola et al. presented dynamics of turbo machinery in more detail [Briola et al., 2016]. Nakhamkin et al. [1989] discuss the transient thermodynamics of McIntosh's cavern.

Conclusion. The corollary of the above literature review on thermodynamics of CAES is that no detailed thermodynamic steady-state analyses has been carried out in which the gas is treated as real and a consistent method validated with measured operational data is used to handle process irreversibilities for both, the existing CAES plants and the forthcoming (conceptual) CAES designs.

1.2.2 Time Dependent Thermodynamics of CAES

CAES and its transient aspects are subject of research and development since the 1970s. Recently, the combined operation of CAES together with renewables is of major interest, but also thermodynamics of the air storage cavern, the heat storage as well as part-load behavior have been addressed in a number of projects and scientific papers. CAES related subjects that require time dependent calculation are:

- Combined operation of CAES with renewables,
- Thermodynamics of compressed air storage cavern (CAS),
- Thermal energy storage (TES) for ACAES,

- Part load, start-up and run down procedures.

Combined operation of CAES with renewables. Due to the unsteady nature of the renewable energy sources wind and solar power, time-dependent analysis of energy systems becomes ever more important. There are several publications dealing with combined operation of **wind power and CAES** [Greenblatt et al., 2007; Ibrahim et al., 2007; Ibrahim et al., 2012; Wolf, 2011; Fertig and Apt, 2011; Mason and Archer, 2012; Mauch, Carvalho, and Apt, 2012; Madlener and Latz, 2013; Maton, Zhao, and Brouwer, 2013; Gu et al., 2013; Yang et al., 2014b; Zhao et al., 2015; Saadat, Shirazi, and Li, 2015; Ramadan et al., 2015; Bosio and Verda, 2015], **solar power and CAES** [Arabkoohsar et al., 2015], **renewables in general and CAES** [Grazzini and Milazzo, 2008; Garvey, 2012] (renewable produce directly compressed air) [Marano, Rizzo, and Tiano, 2012; Berrada and Loudiyi, 2016], CAES on different energy markets [Lund and Salgi, 2009] (spot market), [Drury, Denholm, and Sioshansi, 2011] (energy and reserve market), or, in more general terms, **energy storage with renewables** e.g. [Kondoh et al., 2000; Sundararagavan and Baker, 2012; Weiss et al., 2016]. These studies often aim at an economic optimization of the combined system using a technical plant model that is reduced to a set of characteristic values such as cost, heat rate, and full load operation duration. Some of these characteristic values are presented in the Table 1.1. The CAES heat rate is commonly set to 1.17 kWh/kWh, which corresponds to the $hr_2 = Q_{fuel}/W_{el,turb}$ of the McIntosh CAES plant (see Chapter 3). An electrical turnaround ratio of around 150 % is often used which indirectly includes fuel contribution and corresponds to the formulation $\eta_{rt1} = W_{el,turb}/W_{el,comp}$ (Eq. 2.11 in Chapter 2). In such a ratio the contribution of fuel energy (Q) is not considered which leads to 'efficiency' values > 1. For adiabatic CAES a round trip efficiency of around 70 % is commonly used. In addition, Mason and Archer [2012] use load dependent heat rates in their calculations and are, thus, one of the advanced economic studies. However, despite this seemingly consistent use of η_{rt1} and hr_2 the origin of these values is handled in different manners: When splitting the round trip efficiency η_{rt1} into two efficiencies of charging (compression) and discharging (expansion in turbines) the estimates are quite different (see Table 1.1) which may lead to a significantly different evaluation of the overall process, e.g. Foley and Díaz Lobera [2013] base their considerations on a fuel-driven CAES plant with a realistic heat rate combined with the round trip efficiency of an adiabatic plant. In consequence, resulting considerations must underestimate the potential of CAES by far. Due to these unambiguous treatment of CAES characteristics in literature it is useful to examine CAES efficiency values in detail (see Chapter 2) based on fundamentals of thermodynamics.

Thermodynamics of air storage caverns. Compressed air can be stored in all kinds of pressure vessels [Budt et al., 2016b]. Underground salt cavern have proven their reliability for large scale CAES facilities in Huntorf and McIntosh. There are several articles dealing with the time dependent behavior of air storage. Langham [1965] is the first publication describing simulation of the dynamics of air storage for CAES. Langham [1965] describes a system where compressed air is cooled and stored inside excavated rock tunnels assuming air leakage through fissures and faults. The calculations assume complete mixing of the air; Specific heat capacity is constant. Langham [1965] concludes that air leakage has a major impact on the overall storage set-up. The first CAES plant Huntorf (Germany) was commissioned in 1978 using a salt cavern for air storage. It was found that air leakage of salt caverns is negligible. Some operational data is published in the form of diagrams [Quast and

TABLE 1.1: Characteristic values of CAES used in different studies

Efficiencies charge ·	discharge =	η_{rt1}	hr_2 $\frac{kWh_{th}}{kWh_{el}}$	Reference
		1.50	1.17	Greenblatt et al. [2007]
		1.35	1.17	Mauch, Carvalho, and Apt [2012]
0.80	1.93	1.54	1.22	Mason and Archer [2012]
0.70	2.00	1.40	1.17	Gu et al. [2013]
0.60	2.49	1.49	1.17	Madlener and Latz [2013]
0.75	0.82	0.62		Maton, Zhao, and Brouwer [2013]
0.80	0.90	0.72	1.20	Foley and Díaz Lobera [2013]
adiabatic:		0.68		Wolf [2011]
		0.68		Kaldemeyer, Boysen, and Tuschy [2016]
		0.80		Liu, Woo, and Zarnikau [2017]
McIntosh:		1.36	1.2	Kaiser, Weber, and Krüger [2018]
Huntorf:		1.19	1.7	Kaiser, Weber, and Krüger [2018]

Crotogino, 1979; Hoffeins, Romeyke, and Sütterlin, 1980; Quast, 1981; Crotogino, Mohmeyer, and Scharf, 2001-04-15]. This operational data was used several times to validate calculations of CAES cavern thermodynamics [Raju and Khaitan, 2012; Kushnir, Ullmann, and Dayan, 2012a; Kushnir, Ullmann, and Dayan, 2012b; Kushnir, Dayan, and Ullmann, 2012; Quast and Crotogino, 1979; Khaitan and Raju, 2013; Xia et al., 2015; Zhao, Wang, and Dai, 2015; Marano, Rizzo, and Tiano, 2012; Maton, Zhao, and Brouwer, 2013; Hartmann et al., 2012a]. Raju and Khaitan [2012] calculate the cavern behavior based on the Huntorf values presented in [Brown Boveri & Cie, 1980] and [Crotogino, Mohmeyer, and Scharf, 2001-04-15] which are mainly originally published earlier by Quast and Crotogino [1979]. Almost all later publications refer to [Crotogino, Mohmeyer, and Scharf, 2001-04-15] and [Raju and Khaitan, 2012], whereas original data from Hoffeins, Romeyke, and Sütterlin [1980] and Quast [1981] seem to be rather untouched in recent literature.

Another approach is presented by Schwoeppe, Gose, and Scholz [2008] who investigate a CAS model in order to estimate temperature and pressure values for geo-mechanical stability considerations in the context of an offshore CAES system in Germany.

Besides afore mentioned Huntorf data Osterle [1991] and Marano, Rizzo, and Tiano [2012] refer to McIntosh data for validation purposes. The working group of Marano et al. focuses on hybrid models consisting of a combination of CAES and wind and/or PV [Arsie et al., April 5-7, 2005] [Marano, Rizzo, and Tiano, 2012]. A few other dynamic calculations of CAES do not contain validation data such as [Garvey, 2012; Nielsen, 2013; Zhang et al., 2013]. Tada et al. [1998] show a numerical analysis of the temperature distribution inside the air storage cavern during charging and discharging.

Furthermore, the thermodynamic behavior of gas storage caverns has been extensively studied in the context of natural gas storage and sophisticated tools for cavern design exist, see Table 1.2. These programs have been adapted to the simulation of compressed air. Thus, user manuals and specialist literature is extensive, e.g. the user's manual "Salt Cavern Thermal Simulator" (SCTS) by RESPEC contains extensive formulas on gas storage thermodynamics [Nieland, 2004]. This study includes an analysis to proof that one single bulk temperature and pressure (such as in [Langham, 1965]) represents the gas storage behavior in an appropriate manner. Numerous research articles are dealing with the thermodynamics of salt caverns in the context of natural gas storage and often in the context of rock stability or production rates such as [Hagoort, 1994; Berest and Brouard, 2003; Lux, 2009; Dresen, 2010; Leuger and

Beutel, 2012; Rutqvist et al., 2012a; Rutqvist et al., 2012b; Kruck, Zander-Schiebenhöfer, and Johansen, 2013; Park et al., 2016].

TABLE 1.2: Simulation software of gas thermodynamics in salt caverns

Software Name	Company	Country
SCTS Salt Cavern Thermal Simulator	RESPEC	USA
COS Cavern Operation Simulator	TRANSITION	Poland
GUSTS v2	GEOSTOCK	France
n.a.	KBB	Germany

Thermal energy storage (TES) for ACAES. In the existing CAES plants approximately 95 % of the electric energy taken from the grid is dissipated as heat losses during compression of air (see Chapter 3 and [Kaiser, Weber, and Krüger, 2018]). Thus, recent literature is often focusing on adiabatic CAES (ACAES) solutions that avoid these losses by using a thermal energy storage (TES) unit and enables storage and re-use of compression heat. Yet, the temperatures within the TES fall or rise during charging and discharging, respectively, making the heat transfer inherently time dependent. Possible technical solutions to achieve satisfactory efficiency values have been largely explored. In the 1970s and 1980s a US research program addresses ACAES technical and economic issues [Kreid, 1976; Kreid, 1977; Drost, Zaloudek, and Loscutoff, 1980; Hobson et al., 1981]. Kreid [1976] confirms the general feasibility of ACAES but estimates that it will not be competitive with fuel-driven CAES. Kreid [1977] investigates several TES concepts such as a hybrid CAES system with TES and fuel-firing or the use of an aquifer as TES. However, conventional recuperator systems showed to be the most economic option. Thus, Kreid and McKinnon [1978] present a detailed thermodynamic analysis of ACAES and a hybrid CAES based on irreversible thermodynamics with extensive parametric studies on plant performance parameters, such as efficiency, system heat rate, and turbine heat rate. Drost, Zaloudek, and Loscutoff [1980] investigate six compressed air energy storage systems with an aquifer as thermal storage and assess economics. Hobson et al. [1981] review direct and indirect contact sensible heat storage, latent heat storage, and thermo-chemical energy storage for CAES. Hobson et al. [1981] show the effects of cyclic thermal storage and how the overall storage temperature slightly rises during the first cycles which entails a slight decrease of the overall efficiency. Similar results are obtained later by Wolf, Berthold, and Dötsch [16.06.2009] and Wolf [2011] who present the concept of excess heat that can occur in TES systems due to irreversibility of compression and expansion as well as humidity of ambient air. In [Wolf, 2011] detailed thermodynamic modeling of the overall ACAES process is presented with a one-tank thermocline TES system including some experimental validation of the model assumptions. However, Hobson et al.'s preferred TES system is a two stage direct contact sensible heat packed bed due to economic reasons (lower cost and commercial readiness) [Hobson et al., 1981]. Thus, various heat storage materials are presented; surface and subsurface storage solutions are discussed and design methods are elaborated in detail. Calculation of the TES is carried out with the "MIT-model" (Hamilton in [United States Department of Energy, Electric Power Research Insitute, and Pacific Northwest Laboratory, 1978-05-15], p.271-307). In 2003 to 2006 the EU-project "Advanced adiabatic compressed air energy storage" (AA-CAES) was initiated by Alstom Power LTD, UK [Bullough et al., 2004; Zunft et al., 2006; Jakiel, Zunft, and Nowi, 2007]. One of the outcomes of this project is that packed bed sensible heat (possibly combined with latent heat) TES are the preferable solution. Several follow-up studies exist [Alstom Power et al., 2007; Dietz, 2008]. Bullough et al. [2004] present some economic aspects and a broad range of technical challenges for ACAES: several turbo machinery options are discussed as well as a variety of TES options such as solid and liquid storage materials as well as phase change storage. Zunft et al. [2006] preferred TES solution was a cylindrical pre-stressed concrete vessel with a volume around $10,000m^3$ filled with solid or solid and phase changing storage materials. They [Zunft et al., 2006] present technical and economic results stating that a 300 MW plant (termed "Central Solution") reaches "thermo economic model efficiencies of more than 70 %, and power related investment costs of less than $800\ EUR/kW$". Yet, in following projects "ADELE" and "ADELE-ING" [Zunft et al., 2012; Moser et al., 2012; Zunft, 2015] higher investment cost were found: Zunft [2015] presents some of the TES systems in more detail, including regenerator storage (compressed air is in direct contact with a solid storage material), regenerator storage with a secondary loop (gaseous heat transfer medium to cool the compressed air and transfer heat to a solid heat storage material), several stages of liquid heat storage materials (thermal oil and molten salt) and low temperature thermal oil as heat storage (multistage process). Zunft [2015] states that the multi-stage low temperature variant is most promising in terms of risk and economics. The feasibility of pre-stressed concrete vessels has been proven experimentally and several other design aspects have been covered. In conclusion, for such a system a capital cost of $1300\ EUR/kW_{el}$ has then been found [Zunft, 2015]. Thus, a demonstration plant has not been realized due to unresolved economic challenges. Zunft [2015] re-affirms the estimated efficiency of (up to) 70 %, yet, some thermodynamic studies suggest lower values: Hartmann et al. [2012a] analyze different ACAES concepts using ideal gas equation of state. They compare reversible and irreversible calculation methods and consider several ACAES plant layouts. In conclusion they estimate that the overall energy storage efficiency of ACAES is around 60 % which is 10 percent point lower than generally estimated in the European and German CAES projects. Yang et al. [2014a] confirm these results by presenting a parameter variation of heat storage effectiveness and pressure loss for a thermodynamic ACAES system model. Their overall system efficiency is in the range of 52-60 % (when considering pressure losses and irreversibility) [Yang et al., 2014a].

Mei et al. [2015] present analysis and experimental data from an adiabatic system termed "TICC-500" that has been commissioned 2014 in a $420\ kW$ scale at Tsinghua University, Beijing. TES consists of three water tanks at different temperature levels. The energy storage efficiency achieved with TICC-500 system is 41 % [Mei et al., 2015].

The concept of packed bed as TES in the context of CAES is recently revisited by Park et al. [2014], Barbour et al. [2015], and Sciacovelli et al. [2017]. Park et al. [2014] propose a TES system underground in the form of a gravel-filled underground cavern. By comparing it to a conventional above ground thermal storage unit they find lower heat losses due to heating of surrounding rock. The concept of packed bed TES (not in the context of CAES) is also extensively investigated by Beasley and Clark [1984] who investigate several parameter of packed bed TES such as void fraction distribution, thermal wall effects as well as energy losses due to dynamic response. Experimental data of laboratory scaled packed bed TES is known from Meier, Winkler, and Wuillemin [1991], Bauer [2001], Anderson et al. [2015], and Cascetta et al. [Cascetta et al., 2015; Cascetta et al., 2016] who present data and corresponding mathematical models. These mathematical models are briefly presented e.g. by Singh, Saini, and Saini [2009] who compare several calculation methods for predicting thermal performance of packed bed TES systems. Bauer [2001] investigates in more depth several heat transfer mechanisms. Cascetta et al. [Cascetta et al., 2014; Cascetta et al., 2015; Cascetta et al., 2016] elaborated the topic quite extensively developing a 1D numerical model (Matlab-Simulink) and a 2D CFD model (Fluent) of the TES based on their measured data from laboratory scale.

The concept of latent heat energy storage for CAES has been re-investigated by Bullough et al. [2004], Tessier et al. [2016], and Castellani et al. [2015]. Tessier et al. [2016] present heat storage based on a cascade of phase changes. Air is treated as ideal gas; compression and expansion are considered as polytropic; the air storage place is considered as isothermal; efficiencies are based on exergy of enthalpy. The overall storage efficiency is estimated to be 85 %. Castellani et al. [2015] present experimental data of an expansion within a pressure vessel that contains phase changing material to estimate the amount of phase change material needed to attain near-isothermal expansion of air.

Qi [2012] presents a detailed study of two high-temperature heat storage systems for ACAES including some experimental validation. Liu and Wang [Liu and Wang, 2016] carry out an analysis of ACAES with exhaust enthalpy recuperation and estimate the use as a cogeneration unit, while Yao et al. [2016] analyze thermo-economic optima of ACAES (without detailed analysis of TES options).

Part load, start-up and run down procedures. When using CAES as a means for flexible compensation of wind or solar power fluctuations, short operation duration necessitate frequent start-up and run-down procedures as well as flexible power outputs by operation in a part load. Hence, these operation modes have to be handled properly to represent the overall process correctly. Operation characteristics of the Huntorf plant are presented in [Hoffeins, Romeyke, and Sütterlin, 1980]. Hoffeins, Romeyke, and Sütterlin [1980] discuss the commissioning protocols of the Huntorf machinery and describe start-up and part load characteristics of compressors and turbines. More general information is published for conventional gas turbines e.g. by Lechner and Seume [2010] and Marx [2012]. Nielsen [2013] describes start-up procedures of turbo machinery for CAES and takes into account part load behavior by using load dependent isentropic efficiency values corresponding to the manufacturer's characteristic diagrams of compressors and turbines (here: Alstom's GT26). Wolf [2011] (p.124) uses a similar approach by adopting a mass flow rate dependent effective isentropic turbine efficiency in equivalence to typical steam turbine performance characteristic. For compressor calculations Wolf [2011] (p.127) uses an approach based on polytropic efficiency.

Mazloum, Sayah, and Nemer [2016] presented a steady state and dynamic calculation of an adiabatic CAES system where start-up and rundown procedures are taken into account by estimating the effect of thermal inertia of heat exchangers and mechanical inertia of the rotational equipment (compressors and turbines). Processes are considered as polytropic and mechanical losses are taken into account. They conclude that the resulting efficiency of transient calculations is approximately 2 percent points lower than for steady state calculations, which is only valid for operation durations that are very long (more than 10 hours of continuous compression and expansion).

1.2.3 Hydrogen Options for CAES

There are three essential aspects when considering hydrogen for CAES: