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Article

Electric-driven underwater thermal energy storage: Commercial utilization of surplus fluctuating wind power for district heating

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Abstract: This paper investigates the potential of a concept for the commercial utilization of surplus intermittent wind-generated electricity for municipal district heating based on the development of an electric-driven heat storage. The article is divided into three sections: (1) A review of energy storage systems; (2) Results and calculations after a market analysis based on electricity consumption statistics covering the years 2005–2013; and (3) Technology research and the development of an innovative thermal energy storage (TES) system. The review of energy storage systems introduces the basic principles and state-of-the-art technologies of TES. The market analysis describes the occurrence of excess wind power in Germany, particularly the emergence of failed work and negative electricity rates due to surplus wind power generation. Based on the review, an innovative concept for a prototype of a large-scale underwater sensible heat storage system, which is combined with a latent heat storage system, was developed. The trapezoidal prism-shaped storage system developed possesses a high efficiency factor of 0.98 due to its insulation, large volume, and high rate of energy conversion. Approximate calculations showed that the system would be capable of supplying about 40,000 people with hot water and energy for space heating, which is equivalent to the population of a medium-sized city. Alternatively, around 210,000 inhabitants could be supplied with hot water only. While the consumer´s costs for hot water generation and space heating would be lowered by approximately 20.0–73.4%, the thermal energy storage would generate an estimated annual profit of 3.9 million euros or more (excluding initial costs and maintenance costs).

Keywords: thermal energy storage; district heating; surplus wind energy; latent heat; sensible heat; underwater storage

1. Introduction

A stable power supply is the foundation of our industrialized society. The political objective, with regard to the coming centuries in Germany, is directed toward increasing the fraction of renewable energy generation in the network, ideally leading toward full supply from renewable energy (Becker, 2013). Wind power is an intermittent energy source that is only available whenever the weather dictates, rather than on command; consequently, electricity generation does not necessarily correspond to demand. Furthermore, it is crucial to make it a requirement to have efficient energy storage systems that have the ability to store large amounts of energy at excessive supply, while also having the capability to render energy on demand, due to the certainty that the power drains under heavy wind energy fluctuations.

The root idea of research has been the fact that, considering the wind power supply in Germany, there are times of high demand and low electricity demand, in the same way that wind energy generation fluctuates depending on whether there is more or less wind. This possibly even tends to result in negative electricity rates from time to time, namely when there is an excess supply of wind power to the grid. In general, the concept could be based on buying wind energy in times of relatively low prices, for instance, at night or at oversupply. Since the energy is not intended to be used as ultimate energy yet, and is not converted into effective energy as a consequence of utilization, it needs to be stored somehow, thus becoming another secondary energy. In this context, so arose the idea of engineering a thermal energy storage (TES) able to provide energy for district heating at higher energy prices arose with reference to the previous energy rates of purchase. Due to these economic means of energy storage, heat rates are assumed to be offered at lower prices than heat from district heating networks, and at lower costs than conventional centralized fossil fuel combustion. Hence, a given time may have higher general heat and electricity rates, as well as higher demand, with TES, therefore offering a benefit for both the energy storage operator and the recipient. In other words, the concept is based upon practicing arbitrage, and it is actually not entirely new to the energy sector. **Figure 1** shows the schematic representation of a wind energy integrated thermal energy storage system for district heating purposes, which converts fluctuating surplus electricity into heat before utilizing a TES system to achieve short-term or long-term supply uniformity.

In addition to the benefits derived by the storage operator from arbitrage, energy storage generally contributes to greater efficiency, power quality, reliability, transmission optimization, and black-start functions. Thus, the work described below is of international interest as it deals with rational and efficient, as well as optimal, usage of available (renewable) resources.

Beyond that, the Boston Consulting Group (Pieper and Rubel, 2010) refers to energy storage on an industrial scale as undeniably one of the most interesting growth markets being investigated.

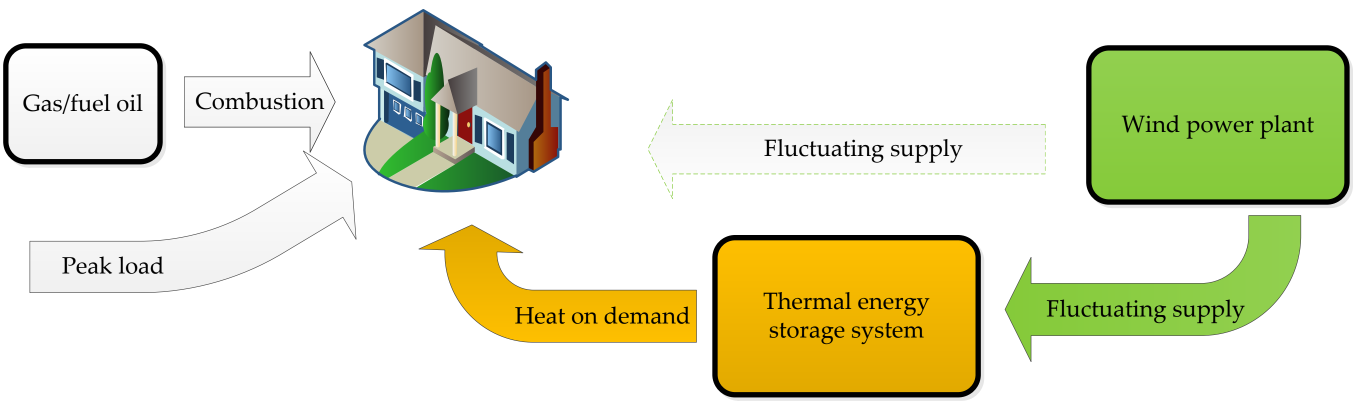

Figure 1. Schematic vision of an integrated TES system for a combined space heating and hot water supply system.

1.1. Objectives of research and approach

The central objectives were:

(1) To investigate the economic potential of taking fluctuating surplus wind power into storage and, afterwards, supplying heat energy to a potential recipient;

(2) To search for and plan an innovative and economic TES technology.

The approach of this scientific work was divided into three major sections of research. The first section was a literature review conducted on energy storage methods, particularly thermal energy storage, resulting in a brief overview of the basics of and on the state-of-the-art of energy storage. The second section of the approach was an electricity market analysis, comprising issues such as investigating the current amount of surplus energy within the Mecklenburg-Vorpommern (North-Eastern Germany) region and the whole of Germany, identifying the locations and times of where and when there is a surplus, as well as the approximate electricity rates related to excess wind energy. The third section of this approach was technology research in order to identify and to develop or redesign a suitable heat storage system. This also included considering the possible economic circumstances after future implementation, in the process from the purchase of surplus wind power to temporary storage as heat energy, and via integration into district heating systems or power supply systems for the transport and sale of the energy. This part of scientific work was based upon a detailed, advanced literature research in the field of energy storage technologies, of which there is an abridged version in the following chapter.

2. Review on energy storage methods

An energy storage unit is an energy engineering facility whose energy content rises due to the supply of energy (charging), meaning it acts as an energy vector. Then, the energy content of the storage unit is kept as non-dissipatively as possible for a certain, predetermined duration; on demand, the energy is released again in a controlled manner as the energy content of the storage unit decreases (discharging) (Rummich, 2009).

The demand for utilization of renewable energies and, to this effect, new technologies targeted on reducing CO_2 emissions, has been represented by a variety of social, political, and academic groups in the past years, granting a special significance to the theme of energy storage. Subsequently, this implies short-term energy storage systems concerned with time-of-day adjustment and long-term energy storage systems for seasonal fluctuations, as well as increased endeavors for the rational use of energy, linked tightly to the necessity of the implementation of storage systems. On behalf of the research aims described above, and the required dimension of plant capacity in this project, only energy storage systems that operate within the range of MW were an element of consideration. Given the investigated source of energy (wind energy) that technologically utilizes the kinetic energy of flowing air to generate electricity via wind turbines, this storage should be referenced as an electrical energy storage (EES) system.

EES refers to a process of receiving electrical energy from a power network and converting it into a form that can be stored over a period of time. When needed, the stored energy is reconverted into electrical energy or used immediately in its present form of energy (Chen et al. 2009).

Energy storages are intended for a range of differing functions, including:

(1) Stockage,
(2) Compensation of load fluctuations,

(3) Contribution to optimal energy conversion and utilization, augmentation of efficiency,
(4) Enhancement of supply security and quality of energy allocation,
(5) Covering peak loads in public power networks,
(6) Energy supply for mobile energy consumers,
(7) Temporary shifting of energy supply,
(8) Reduction of energy demand,
(9) Supply of energy for special purposes,
(10) Contribution to climate protection and sustainability (Rummich, 2009).

According to these key functions, the primary task of an energy storage is to interconnect available energy supply and energy demand, provided that both are temporally not congruent with each other.

Energy exists in various forms, of which several can be stored utilizing energy storage technologies. Depending on the types of energy, energy storage systems can be charged with mechanical, electrical, or thermal energy (Khartchenko, 1997).

Mechanical energy can be stored through the use of gravitational energy storage, pumped hydropower storage (PHPS), compressed air energy storage (CAES), and flywheels. PHPS and CAES store potential energy; flywheels, on the other hand, store kinetic energy (Rebhan, 2002).

Electrical energy, meanwhile, is stored through the use of batteries. Here, the battery is charged by connecting it to a source of direct electric current, converting the electrical energy into chemical energy, while discharging involves the reconversion of stored chemical energy into electrical energy (Sharma et al. 2009).

Thermal energy is stored as a change in internal energy of a material, which can be sensible heat, latent heat, or thermochemical, in addition to combinations of these (Abedin and Rosen, 2011). Thermal energy storage utilizes materials that are kept at high or low temperatures in insulated containers. Heat or coldness recovered is applied for heating purposes or for electricity generation through the usage of heat engine cycles (Chen et al. 2009). An overview of the major techniques of thermal storage is shown in **Figure 2**.

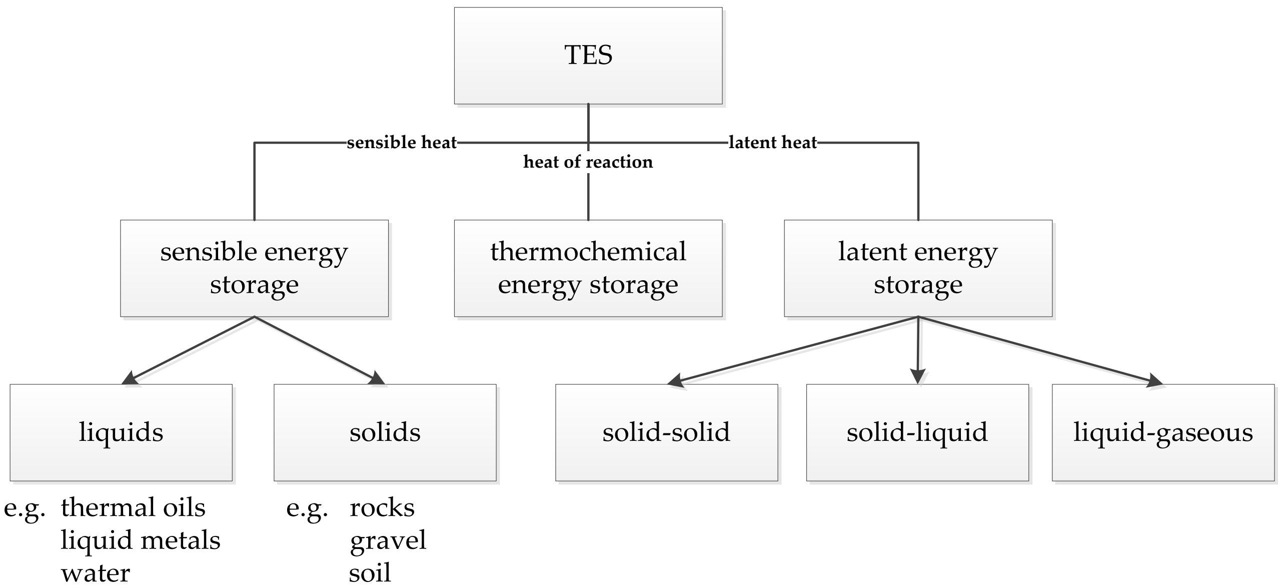

Figure 2. Types of TES.

Sharma et al. (2009) state that thermochemical energy storage relies on "the energy absorbed and released in breaking and reforming molecular bonds in a completely reversible chemical reaction." Accordingly, the heat stored depends on the quantity of storage material (reagent) obeying the law of mass action, the endothermic heat of reaction, and the extent of conversion (chemical turnover, yield, selectivity):

$$Q = m\,\Delta h_r\,a_r \tag{1}$$

Thermal energy storage (TES) systems in general, and sensible or latent heat storage in particular, have been at the center of research interests for the past 30 years. Although the information exists in enormous quantity, it is complex and difficult to find, for it is widely spread in literature (Zalba et al. 2003).

The following subsections provide a detailed description of sensible TES and latent TES, as these techniques were selected for this study on the grounds of the current state of research.

2.1 Sensible TES

Sensible TES is already applied in a wide spectrum of applications, such as in the chemical industry and energy industry (Chen et al. 2009), and represents a large group of heat stores in which energy intake and release is characterized by a change in temperature of the storage medium (Hasnain, 1998), while phase transformation is undesired. Hence, thermal energy Q imparted or removed is "sensible" by means of temperature change. This relationship is described as

$$Q \;=\; \int_{T_i}^{T_f} m\,c_p\,\Delta T \tag{2}$$

$$= m\,c_{ap}\,(T_2\text{-}T_1) \tag{3}$$

with the specific heat capacity c_p as the proportionality factor. This mass-specific constant of matter specifies the amount of heat per unit mass required in order to raise the temperature by 1 Kelvin, 1 degree Celsius, respectively, therefore represented by the unit $kJ{\cdot}kg^{-1}K^{-1}$. When it comes to the technical implementation of sensible heat storage, next to the mass of the storage medium, the storage volume is often of high importance, scilicet having the volumetric heat capacity as a key descriptive characteristic. The volumetric heat capacity indicates how much heat can be stored in 1 m^3 of a material if its temperature is increased by 1 K or 1 °C. This is calculated by multiplying the specific heat capacity c_p by the density ρ, thus extending the prior equation:

$$Q = V\,\rho\,c_{ap}\,(T_2\text{-}T_1) \tag{4}$$

Sensible TES are fed by high-temperature water from generators that, with respect to this project, use electricity (wind power) to drive an increase in the water´s average temperature.

The range of applications, in the cases of liquid storage materials and liquid heat transport media, is limited by their melting and boiling temperatures (Rebhan, 2002). Due to the temperature difference between the storage medium and the surrounding environment, excellent insulation of the storage system is mandatory.

Regarding the state of research, sensible TES is presently the most profound studied TES that can be applied multifariously, ranging from decentralized applications in apartments to centralized storage systems in buildings, and even entire residential neighborhoods (Institut für Regenerative Energietechnik, 2009).

In the case of liquid storage media, such as water, engineers distinguish between mass storage and stratified storage. Mass storage is characterized by the change of quantity of storage medium (mass, volume) during the charging or discharging processes. Whilst charging, the amount of storage medium increases, whereas during discharging, this factor decreases. In this technology of storing energy, the temperature of the storage medium remains constant (Rummich, 2009). It can therefore be described as:

$$m,\ V = variable,\ T \approx constant.$$

Stratified storage, on the other hand, is defined as a storage dependent upon the natural formation of temperature layers during charge and discharge. It is particularly suitable for liquids of low thermal conductivity since temperature equalization between the different layers is predicted to take place very slowly. Given that the density of a liquid storage medium at higher temperatures is lower than its density at lower temperatures, a natural formation of temperature layers occurs corresponding to the temperature levels (Rummich, 2009).

2.2 Latent TES

In contrast to sensible TES, stored energy in latent TES is latent or "hidden," and therefore not sensible as change in temperature since increasing energy content is not directly associated with a rise in temperature (Institut für Regenerative Energietechnik, 2009), but rather with the energy of phase transition (thus enthalpy). In other words, latent heat storage is based on heat release or absorption when a storage material undergoes a phase change from liquid to solid, gas to liquid, or vice versa (Sharma et al. 2009).

During phase transition, the temperature of pure substances is practically constant, meaning that the temperature remains virtually unchanged while charging, storing, and discharging (Rummich, 2009). Latent TES is therefore a particularly attractive technology, as it provides a high energy storage density, while offering the capacity of storing heat as latent heat of fusion at a constant temperature according to the phase transition temperature of the phase change materials (PCMs) that act as storage media. For instance, in the case of water, 80 times as much heat or energy is needed in order to melt 1 kg of ice as to increase the temperature of 1 kg of water by 1 K (Hasnain, 1998). Consequently, a much smaller volume and mass of storage material is required for storing a certain amount of energy. The relationship between energy and latent TES with a PCM as storage medium concerning the storage capacity is given by:

$$Q = \int_{T_i}^{T_f} m\, c_p\, \Delta T + m\, a_m\, \Delta h_m + \int_{T_m}^{T_f} m\, c_p\, \Delta T \tag{5}$$

$$Q = m\, [c_{sp}\, (T_m - T_i) + a_m\, \Delta h_m + c_{lp}(T_f - T_m)] \tag{6}$$

PCMs exhibit solid-solid, solid-liquid, and liquid-gas transformations, although relatively few solid-solid PCM applications have been developed that offer appropriate heats of fusion and transition temperatures with regard to its application in thermal energy storage. These materials change their crystalline structure from one lattice configuration to another at a certain defined temperature, absorbing or releasing latent heat during the transformation. Solid-liquid PCMs are the most common type of storage material in latent TES due to their ability to store a comparatively large quantity of heat over a narrow temperature range without the associated change of volume. Liquid-gas PCMs normally have substantially higher specific heats of transformation (enthalpies); nonetheless, they are rejected in most cases as a result of the large volume change during transformation (Hasnain, 1993). Owing to this intense change of density, which in the case of water/steam accounts for an approximate value multiplied by a factor of 1000, it is technically difficult to control and to put into practice (Institut für Regenerative Energietechnik, 2009). Usually, latent heat storage materials are useful over a small temperature range (International Energy Agency , 2008), however, there is significant potential for further research and development in this field.

PCMs that have already been applied include water/ice/steam, paraffin, and eutectic salts (Abedin and Rosen, 2001). In general, PCMs can be classified into organic, inorganic, and eutectic PCMs (Sharma et al. 2009). **Figure 3** displays the general classification of currently used or investigated PCMs with examples for each category.

A eutectic is a minimum-melting composition of two or more components, each of which melts and freezes congruently to form a mixture of the component crystals during crystallization (George, 1989). Eutectic PCMs usually freeze and melt without segregation of components, since they freeze to an intimate mixture of crystals, leaving little possibility for separation. On melting, both components liquefy again simultaneously; here, segregation is also unlikely (Sharma et al. 2009).

Concerning the state of research, in recent years, there have been numerous investigations focusing on the development and optimization of latent heat storage materials on the basis of paraffin and salt hydrates. In particular, the development of microencapsulated PCMs was found to be a key step in the production of commercial products. Salt hydrates are characterized by a higher density and a higher volumetric energy density compared to paraffin, but have not yet been successfully embedded into microcapsules. Moreover, salt hydrates are non-flammable and possess a higher enthalpy of fusion than paraffin. For this reason, research in this field of science is of high interest. Both of these classes of PCMs demonstrate that, futuristically, the costs of material need to be lowered, while the effective energy density must simultaneously be increased. The development of PCMs for high-temperature applications is still chiefly in the experimental and testing stage. On account of the planned extension and upgrading of solar thermal power plants, these new technologies may have a bright future after continued innovative optimization and development steps. Furthermore, the storage of decentralized waste heat from industry or condensation power stations may be another promising area of future application (Institut für Regenerative Energietechnik, 2009).

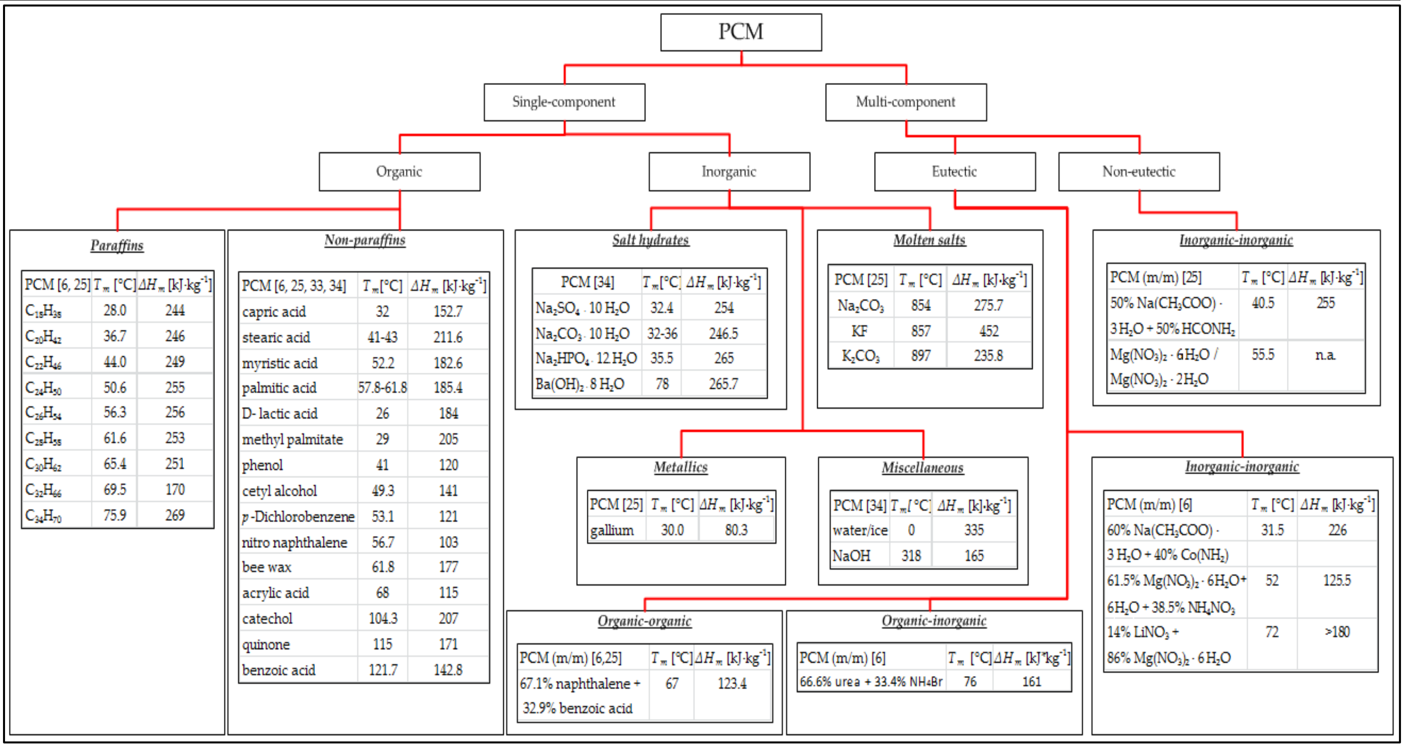

Figure 3. Classification and examples of PCMs.

3. Electricity market analysis

This section describes the results of power market analysis with reference to the previously described investigation of the surplus wind energy potential for commercial heat storage. In Germany today, life without a secure energy supply is hardly imaginable. Along with that, the current energy system is inconceivable without the integration of renewable energy sources. There is a general trend of an increasing adoption of renewable energy sources across Europe, partly due to the European Union`s energy policy based on its 20-20-20 commitments, leading toward renewable energy contributing 20% of energy use by 2020 (Arteconi et al. 2013). However, it has been the objective of the Federal Government of Germany to achieve a percentage of at least 30% renewable energy by the year 2020 (Deutsche Energie-Agentur GmbH, 2010). Astonishingly, statistics published by the German Federal Environment Ministry in 2009 (German Federal Environment Ministry, 2009) already calculated a percentage of 35% by 2020. As the Fourth Revolution, the trend towards automation and data exchange in manufacturing technologies and processes, as stated multiple times, the restructuring of the energy system brings with it challenges that must be solved. The input of regenerative energy sources, such as wind power or solar power, that are dependent on meteorological conditions and are characterized by rapid and heavy fluctuations (volatility), as well as underlying forecast inaccuracies, provides a huge challenge to present-day network operators. The power network is not equipped with substantial storage capacities, and the modern electricity supply is directly reconciled with the demand.

Electricity networks in Europe are predominantly geared towards the national electrical supply networks of individual countries. The established European Network of Transmission System Operators for Electricity (ENTSO-E) is a group of national power supply system operators from individual nations, and secures a pan-European, synchronous network operating with a line frequency of 50 Hz. This network also enables bypassing of shortages resulting from unscheduled blackouts of large-scale power plants, since additional performance can be summoned up from other regions of the continent. Compensation of volatile surplus generation and deficits also takes place on the scale of a few percentage points of the national demand of the linked countries (European Transmission System Operators, 2013).

3.1 Method of market analysis

In order to gain information, data, and energy statistics, a detailed literature review was conducted. This included contacting regional and national network operators, transmission system operators, energy networks such as BWE, Dena or ENTSO-E, as well as numerous energy-oriented organizations, such as the Federal Bureau of Statistics of Germany and several Federal Ministries of Germany. In general, the response was very restrained in the case of commercial operators, who, as expected, refused any access to records and did not provide information already openly available on the internet or studies supplied by the ministries or energy networks; most network operators and transmission system operators did not bother to answer the requests. This might be connected with investigating the potential of merely purchasing the surplus energy. However, openly available data and scientific studies did draw inferences regarding this potential, presented in the following.

3.2 Electricity demand in Germany and Europe

Similar to power generation from wind and sun, the demand for electricity cannot be precisely predicted. However, past statistics offer the ability to describe the historical course of electricity demand. **Table 1** shows electricity consumption data of some relevant ENTSO-E European countries from 2008. Based on this data, the annual average of consumed electrical performance was determined. Germany apparently is the European country with the highest electricity consumption (557.2 TWh), as well as demand, thus accounting for 16.21% of the total end power consumption in the ENTSO-E.

Table 1. Electricity consumption data of selected ENTSO-E-affiliated European countries from 2008.

(based on the ENTSO-E database statistics)

Country	Total electricity consumption 2008 [TWh]	Annual average of consumed electrical performance 2008 [MW]
Austria	68.4	7809
Belgium	89.5	10,216
Switzerland	64.4	7351
Cyprus	4.9	559
Germany	**557.2**	**63,608**
Denmark	36.1	4123
Spain	274.1	31,294
France	494.5	56,451
Greece	56.3	6422
Hungary	38.9	4441

Italy	337.6	38,538
The Netherlands	120.3	13,733
Norway	128.9	24,717
Poland	142.9	16,313
Sweden	144.1	16,451
Great Britain	399.6	45,619
ENTSO-E	3437.9	392,467

According to the most recent relevant statistics available, concerning the net power consumption in Germany in 2011, published by Dena and the Federal Ministry for Economy and Technology of Germany, the net consumption at that time amounted to a total of 541 TWh. Industry demanded the highest quantity of power with 251 TWh in 2011, followed by 40 million households accounting for a consumption of 140 TWh. Trade and commerce consumed 133 TWh, while the transport sector used up 17 TWh. Germany exported 56 TWh of electricity to neighboring countries and imported 50 TWh, thereby having a positive balance of 6 TWh net excess export (German Federal Ministry of Economy and Technology, 2011). **Figure 4** shows the detailed percentages of consumption within the households, revealing that end energy consumption of space heating is often underestimated.

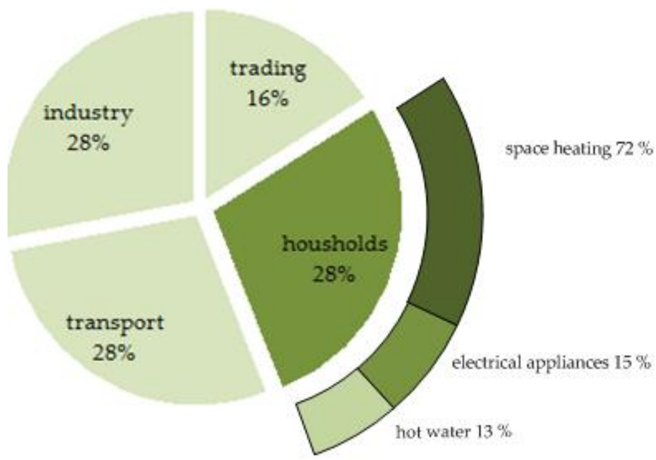

Figure 4. Use of electrical end energy (German Energy Agency, 2012).

Germany`s total gross energy generation in 2011 amounted to 612.1 TWh, of which renewable energies account for 123.2 TWh (20% of the total gross energy generation 2011), and wind power in particular provided 48.8 TWh (8% of the total gross energy generation 2011) (German Federal Ministry of Economy and Technology, 2013).

Figure 5 shows the system balance of the grid regulation network over a specific period of time (24 December 20124–January 2013). On the basis of this diagram, it is obvious that, in general, there is actually an excess supply of electricity to the grid due to regulations and power supply security measures. For example, on December 24, 2012, there was a massive excess feed-in to the grid regulation network, with a peak load of approximately 8.1 GW. Section 3.3.2. links this phenomenon of extraordinary excess feed-in to surplus wind.

Direct space heating by electricity is currently less common in Germany, unlike in France where electric panel converters are installed on a large scale (installed stock of electric convectors in 2008: 56.8 million). Only 4.8 million dynamic electrical storage heaters are installed in the German market, where the most common means of heating is instead by the combustion of gas or fuel oil. District heating is regarded as the most promising development trend (DNV KEMA Energy & Sustainability, 2013).

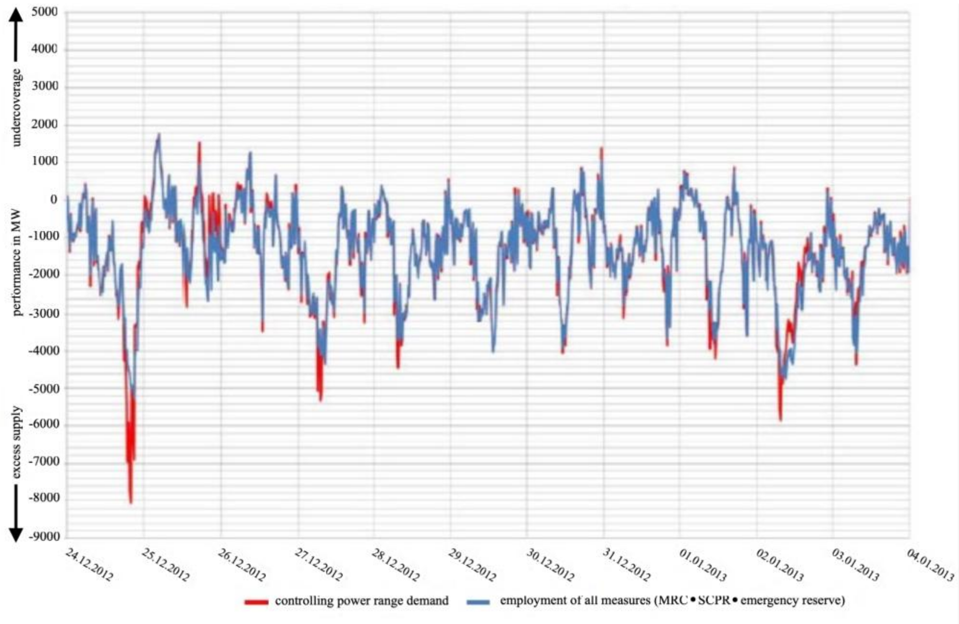

Figure 5. System balance of the grid regulation network from 24 December 2012 to 4 January 2013 (data and diagram received from transmission system operators).

3.3 Wind energy in Germany

The use of wind energy is increasingly developing as a mainstay of future European energy supply. Wind energy is converted into electricity at the lowest costs compared to other renewable energy sources, and is therefore the most cost-efficient generation technique. Furthermore, wind energy is available in every country, and it supplies, with regard to seasonal variation, the highest quantity of electricity when electricity demand is highest.

The availability of electricity generated from wind power differs fundamentally from that of conventional generation using fossil resources. For its integration into the existing power supply system, two aspects are of particular significance:

(1) In-fed electricity fluctuates depending on the availability of wind, thus wind energy;

(2) In-fed electricity is generated on a decentralized basis across a wide area using large numbers of wind turbines (Institut für Solare Energieversorgungstechnik, 2008).

Feed-in of wind power from individual plants is accompanied by heavy fluctuation, as observed in local variation in wind strength, ranging from 0% to 100% of the performance that can theoretically be achieved using a wind turbine. Balancing of this volatile feed-in behavior is achieved through the simultaneous operation of tens of thousands of plants covering the entire country (Deutsche WindGuard GmbH, 2012;

Popp, 2010; Paatero and Lund, 2005). However, the inducted wind power is far apart from a consistent or demand-oriented unfolding of performance.

The University of Kassel`s Institute for Solar Energy Supply Technology e.V. (ISET) published records of hourly actual wind power feed-in from 2005, combined with the installed wind power plant performance in Germany. This data is shown in **Figure 6** and shows how the provided performance related to the installed performance was inducted into the electricity grid during 2005. Additionally, the average performance and, in comparison to that, the monthly average electricity demand is indicated on the diagram. Hence, wind power feed-in is never disrupted in Germany.

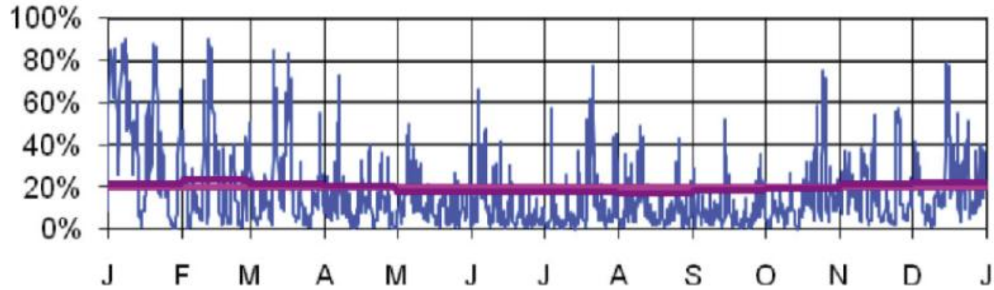

Figure 6. Actual feed-in of wind power in Germany in 2005 in terms of the installed performance (blue). Average provided performance (red). 100% corresponds to at that particular moment installed nominal capacity of wind power plants. Comparative to the average performance, the course of monthly electricity demand is provided (purple). (Popp, 2010; Institut für Solare Energieversorgungstechnik, 2008).

3.3.1. Stock of wind power generation capacity

As illustrated in **Figure 6**, the installed wind power performance of the total wind energy plants deployed in Germany in 2005 delivered an annual average proportion of 20% of their performance capacity to the power network. Further data from the years 2006 to 2008, also published by the ISET, confirm this indication of circa 20% average performance that was inducted to the power network as a proportion of the total installed performance. This value is specified as the degree of utilization or utilization rate (Popp, 2010):

$$degree\ of\ utilization\ = \frac{average\ power}{effective\ power} \tag{7}$$

$$= \frac{amount\ of\ full\ load\ hours}{annual\ number\ of\ hours\ of\ an\ energy\ conversion\ plant} \tag{8}$$

Up to 27 March 2013, the total installed generation capacity (installed net performance$_{el}$) connected to the German power network amounted to 175.3 GW (exclusive of ultimately shutdown plants) according to the official power plant catalog of the Federal Network Agency of Germany (BNetzA). On 31 December 2011, this value was documented at 164.0 GW. Renewable energy accounts for a total of 75.5 GW (31 December 2011: 65.3 GW), therefore, the continued upgrading of this sector is evident. Overall, 71.5 GW (31 December 2011: 61.0 GW) has been reward-enabled in accordance with the Renewable Energies Act (EEG). Furthermore, a total of 30.285 GW of installed net performance$_{el}$ is derived from wind power plants, both offshore and on-shore (German Federal Network Agency, 2013a), thus constituting an increase of wind generation capacity of 1.685 GW referred of 31 December 2011. **Table 2** presents data for relevant regions that are considered for the possible implementation of this project. More than half of the installed wind power performance in Germany (56.65%) originates from plants within the relevant region.

Table 2. Net performance$_{(electrical)}$ in MW per relevant federal state (German Federal Network Agency, 2013a).

	Brandenburg	**Mecklenburg-Vorpommern**	**Niedersachsen**	**Schleswig-Holstein**	**Total**
Wind power (off-shore plants)		48	220		268
Wind power (on-shore plants)	4664	1768	7210	3246	16,889
Total	4664	1816	7430	3246	17,157

3.3.2. Total surplus wind power in Germany

In order to identify surplus generation of wind power that could not be supplied to the power network, e.g., because of grid bottlenecks or overstrained regulation control of power plants, the "failure work" needs to be determined. Failed work is wind power that has been denied access to the power network due to Feed-In Management (FIMan), known in Germany as Einspeisemanagement (EinsMan). Pursuant to § 11 of the German Renewable Energy Act, FIMan describes the temporary reduction of feed-in performance from renewable energy plants. In certain cases, network operators are hereby authorized to regulate renewable energy power plants with a performance of above 100 kW, regardless of their duty to pursue § 9 of the Renewable Energy Act. Hence, failure work is one of two sources of low-cost wind energy, next to temporarily cheaper electricity from the regular power network (discussed in Section 3.3.3), that could charge the storage unit. **Figure 7** provides an overview of how to calculate the failure work within the region intended for the potential electricity supply of the thermal TES.

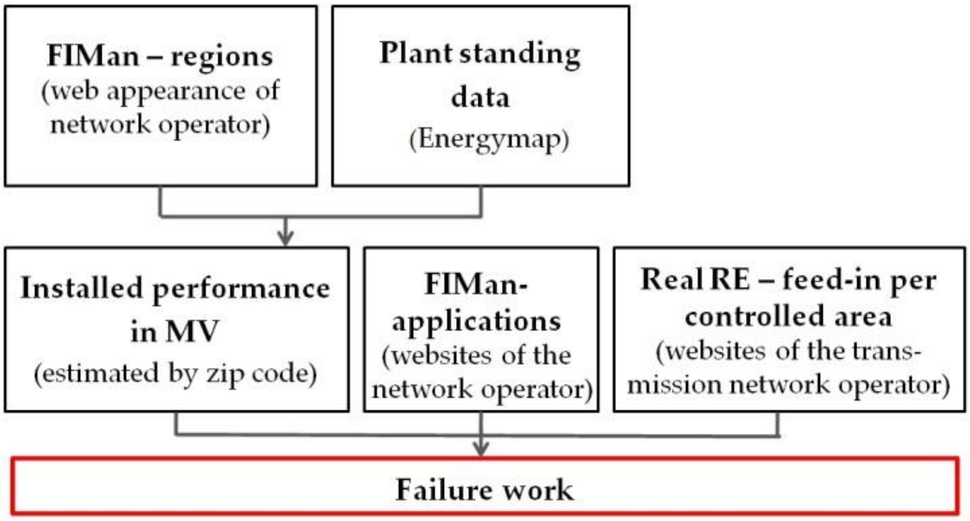

Figure 7. Method for calculating the potential of failure work within a certain region.

According to the German Federal Network Agency, nearly 74 GWh was lost due to FIMan in 2010. Individual wind power plant operators north of Schleswig-Holstein (the northernmost German federal state) even had to offload a quarter of their total generation. In total, in pursuance of § 12 of the German Renewable Energies Act, about six million euros in loss compensation was paid in 2010 (German Federal Association of Wind Energy, 2012a; German Federal Association of Wind Energy, 2012b).

Figure 8 shows regions affected by FIMan in Northern and Eastern Germany, as these are the relevant regions concerning the location of the TES and beyond that, it is mainly the network operators in these regions that are fortunately, with regard to the objectives of this project, affected by FIMan. Altogether, in Germany in 2011, 9 of 257 network operators were executing FIMan. In 2011, at least 4.3 GW of installed wind performance, meaning at least 24% of the installed wind performance within the designated area of 9 relevant network operators, was affected by FIMan. This amounts to 15.04% of the total wind performance in Germany at that time, equating to approximately 295 to 529 GWh, depending on the method of calculation. That is an approximate average value of 0.9% of Germany`s total generated wind power which could not be inducted, indicating another, yet enormous, boost in rates of failure work (up to 200–350%), considering that wind energy failure work already increased from roughly 10 GWh to 150 GWh between 2004 and 2010 (German Federal Association of Wind Energy, 2012a; German Federal Association of Wind Energy, 2011; German Federal Association of Wind Energy, 2012b).

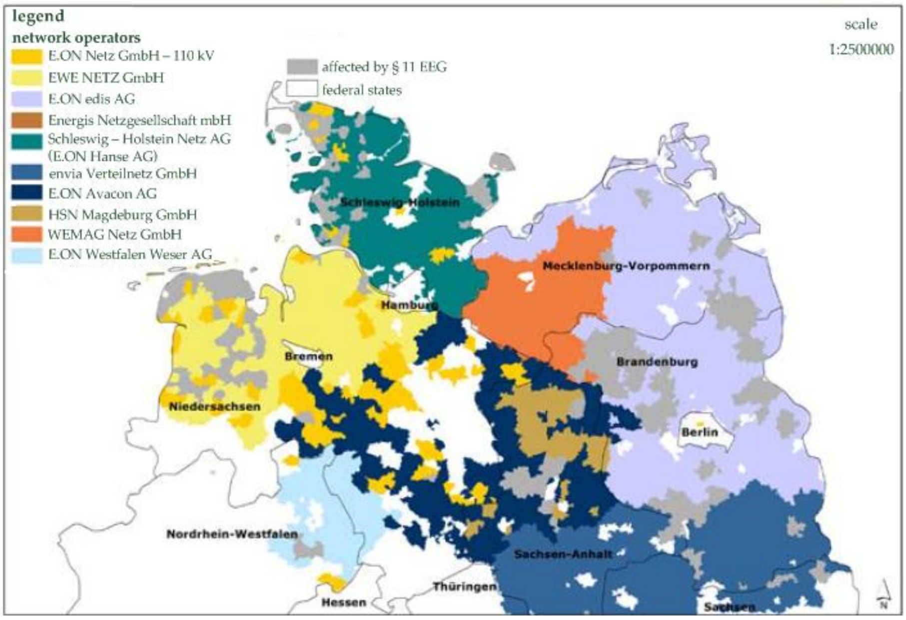

Figure 8. Regions affected by FIMan in Northern and Eastern Germany in 2011 (German Federal Association of Wind Energy, 2012a).

Due to the location of current research (Neubrandenburg, Germany), in the federal state of Mecklenburg-Vorpommern, the network operator E.ON edis AG, is of particular interest. **Figure 9** shows the total installed wind performance within the region and the wind performance that was affected by FIMan in Northern and Eastern Germany at the end of 2011. This data was collected half a year later than the data shown in the previous passage, documenting that 1.2 GW of the total wind performance in the region was affected by FIMan (E.ON edis AG). The amount of failure work at E.ON edis AG in relation to the total quantity of failure work in 2011 is 32–38%. In theory, surplus wind power is obviously available in order to feed the planned TES.

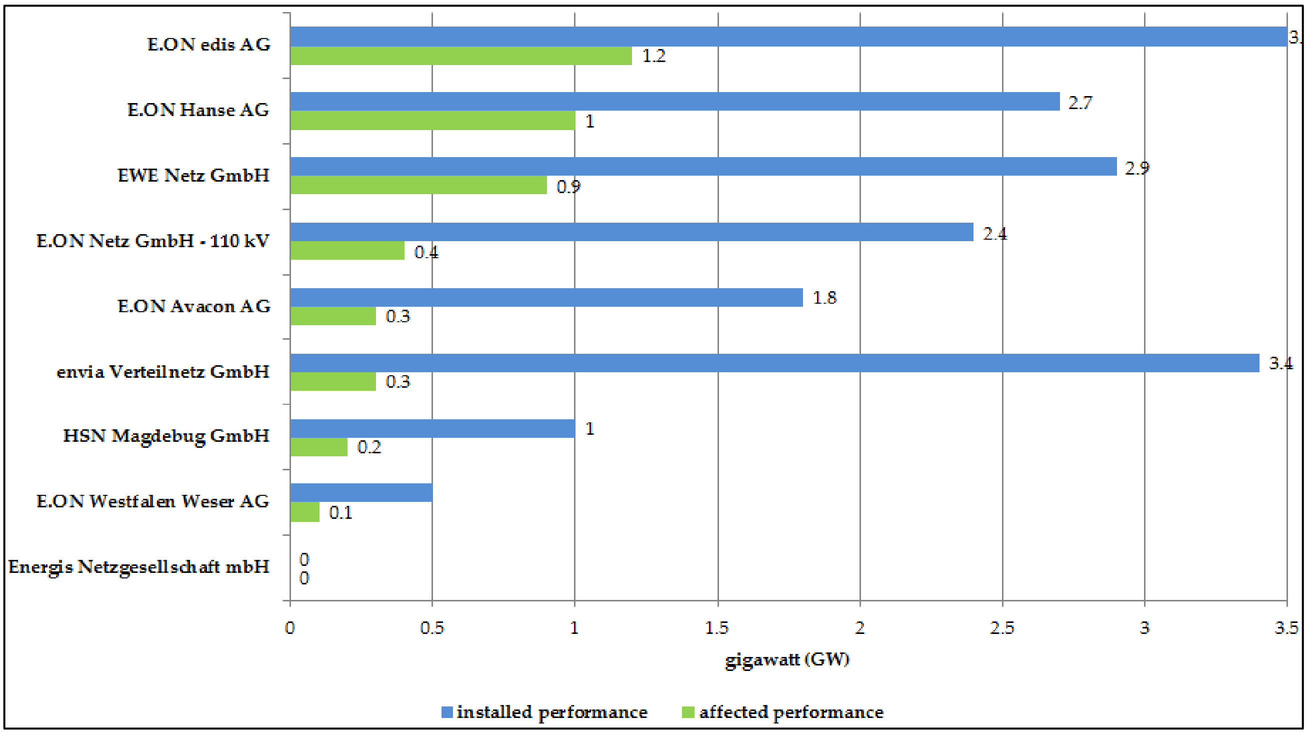

Figure 9. Installed wind performance and wind performance affected by FIMan of particular network operators in Northern and Eastern Germany in 2011 (data obtained from: German Federal Association of Wind Energy, 2012a).

Figure 10 illustrates the number of FIMan operations in 2011. With 6,653 operations for a total of 217 days in Germany, every one or two days, FIMan took place, which is seven times more operations than in 2010 (1085 operations at 107 days; database 2010 (German Federal Association of Wind Energy, 2011)). With regard to the region and E.ON edis, 444 operations took place. The reasons for failure were mainly capacity overloads in the 110 kV high-voltage network and at high-voltage and medium-voltage transformation substations.

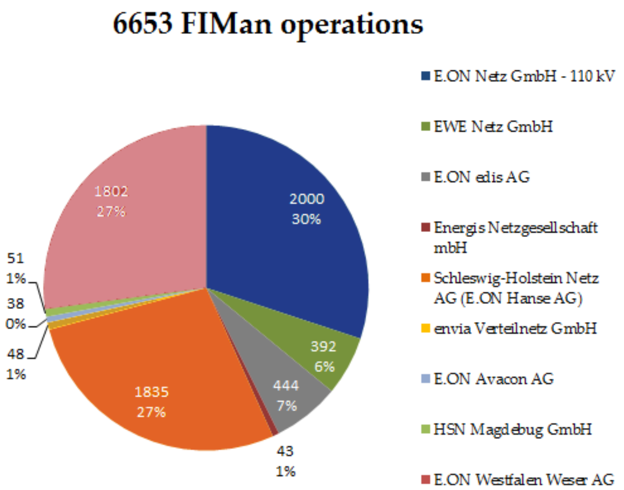

Figure 10. Quantity of FIMan operations pursuant to §11 EEG for network operators in 2011 (data obtained from: German Federal Association of Wind Energy, 2012a).

Figure 11 shows the network operators' and the monthly quantity of and days with FIMan operations in 2011. Vertical bars indicate FIMan operations per month, shown on the left axis. The strokes depict the number of days with FIMan operations for each month on the right axis. This diagram indicates when excess wind power could be available with regard to a future implementation of the investigated concept.

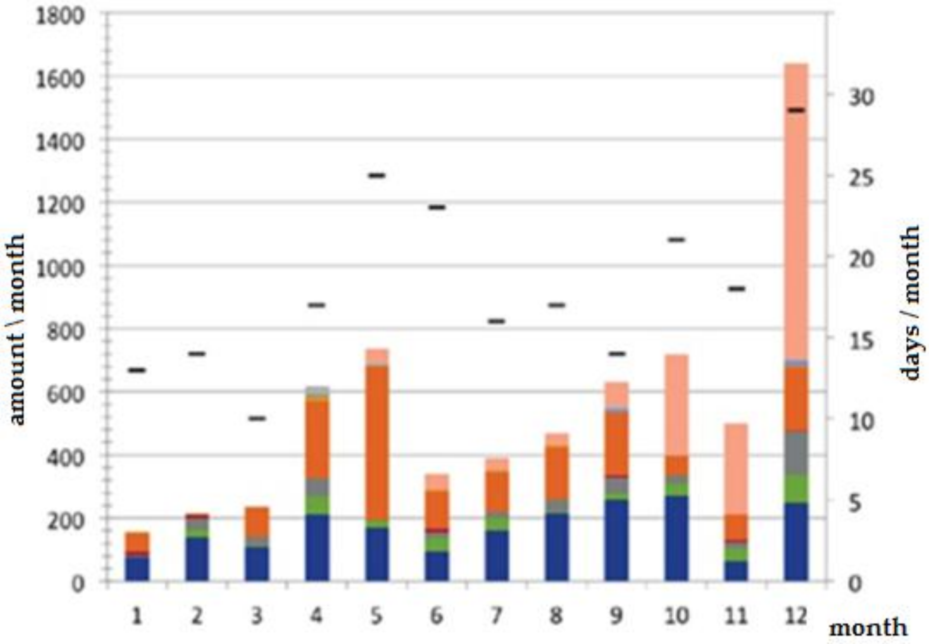

Figure 11. Network operators' and monthly quantity of and days with FIMan operations pursuant to § 11 EEG in 2011 (data obtained from: German Federal Association of Wind Energy, 2012a).

Present cases of surplus wind energy can be examined from more recent data, published by the BNetzA. The following analysis of surplus wind energy focuses on more generalized statistics for the whole area of Germany. These statistics describe events related to the transmission system operators (rather than the network operators). **Figure 5**, shown in Section 3.2, presented proof that, for example, on 24 December 2012, there was an oversupply of wind power to the grid. This excess feed-in temporarily coincided with an abrupt occurrence of wind, raising power generation, derived from the concerned wind power plants, from approximately 4 GW to more than 19 GW. This is shown in **Figure 12**.

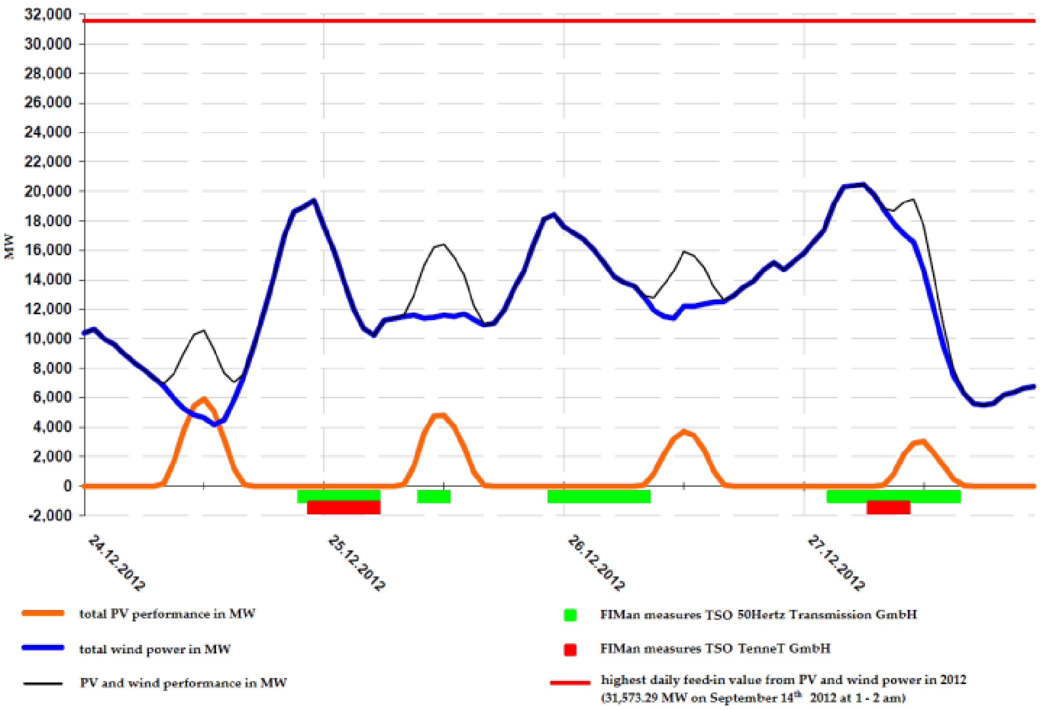

Figure 12. Germany-wide feed-in of wind power and photovoltaic plants from 24 December to 27 December of 2012 (German Federal Network Agency , 2013b).

Excess feed-in of fluctuating solar and wind power induced four FIMan operations, operated by 50Hertz Transmission GmbH, and two FIM (German federal information management) operations, executed by TenneT TSO GmbH. These operations were observed shortly after the emergence of the high peak. Whether errors in forecasting or other reasons are responsible for this oversupply is still the subject of investigations by the Federal Network Agency of Germany. **Figure 12** also shows the highest hourly feed-in value in 2012, contributing a total inducted performance of 31.57329 GW on 14 September 2012, at 1–2 p.m.

During the winter season 2012/2013, due to high feed-in of renewable energies, the German transmission system operators, 50Hertz and TenneT, were forced to carry out regulation measures for 42 days pursuant to § 13 section 2 in relation to § 11 EEG (FIMan operations), as seen in **Table 3**. Heavily affected by this, in particular, were the federal states of Brandenburg (35 days), Niedersachsen (26 days), and Schleswig-Holstein (21 days), as in previous years. In Mecklenburg-Vorpommern (control area: 50Hertz), 3 operations took place at the level of the transmission network. In total, the quantity of days where FIMan operations executed by these transmission system operators took place strongly decreased compared to the winter season 2011/2012 (66 days in total; 50Hertz: 55 days, TenneT: 36 days). Unlike in 2011/2012, in winter season 2012/2013, no emergency measures carried out by transmission system operators pursuant to § 13 section 2 EnWG (Energy Economy Law of Germany) were reported (German Federal Network Agency, 2013b).

Table 3. Quantity of days with feed-in reduction due to FIMan operations (German Federal Network Agency , 2013b; data requested at the transmission system operators pursuant to § 13 Section 5 (bottleneck evaluation)).

Federal state	**Control area**	**Oct 12**	**Nov 12**	**Dec 12**	**Jan 13**	**Feb 13**	**Mar 13**	**Total (Oct 12–Mar 13)**	**Control area observation**
Brandenburg		5	5	8	7	4	12	41	
Mecklenburg-Vorpommern		1	0	1	0	0	1	3	
Sachsen	**50Hertz**	0	0	0	0	0	1	1	41
Sachsen-Anhalt		2	1	0	0	0	1	2	
Thüringen		0	0	0	0	0	1	1	
Niedersachsen		0	2	3	6	3	3	17	
Schleswig-Holstein	**TenneT**	1	2	3	1	3	8	18	24
Germany-wide									42

Overall, during the winter season 2012/2013, renewable energy plants have been regulated for a total of 724 hours due to FIMan operations, therefore producing failure work. In 86.5% of the events, the reason for regulation was high re-feed-in from the subordinate distribution network. This re-induction of surplus power can lead to overload of utilities, such as transformers or bus bars, in distribution stations (German Federal Network Agency, 2013b). **Table 4** displays the federal states that were particularly affected by FIMan, including Brandenburg (381 hours), Niedersachsen (143 hours), and Schleswig-Holstein (133 hours). Comparison to the winter season 2011/2012 also confirms a strong decrease of regulated hours because of FIMan originating in the transmission network. The value of the winter season 2011/2012 amounts to 1,632 hours in total.

Table 4. Number of hours with regulation in the transmission network per federal state due to FIMan (German Federal Network Agency , 2013b; data requested at the transmission system operators pursuant to § 13 section 5 (bottleneck evaluation)).

Federal state	**Time duration [hours]**
Brandenburg	381:40
Mecklenburg-Vorpommern	11:45
Sachsen	6:15
Sachsen-Anhalt	34:00
Thüringen	14:00
Niedersachsen	143:28
Schleswig-holstein	133:36

As is evident, transmission system operator, 50Hertz, was struck much more frequently by FIMan measures (447 hours) than TenneT (277 hours).

The reason for this sharp fall in FIMan operations in winter season 2012/2013 compared to winter season 2011/2012 was presumably the less fierce weather conditions that drove fewer bottlenecks within the transmission network in fewer situations than in the previous year. This is also supported by regarding the in-fed quantities of solar and wind power. Compared to winter season 2011/2012, far fewer feed-in peaks occurred, which, in consequence, are the cause of feed-in reductions (German Federal Network Agency , 2013b).

3.4. Electricity rates

In order to understand the potential of purchasing cheap electricity at the electricity stock exchange, the mechanism of price generation needs to be outlined:

In 2002, the electricity stock exchange in Leipzig (European Energy Exchange; abbreviated: EEX) was established as the marketplace for electricity trade. Electricity rates generated at the EEX have a fundamental impact on forward contracts that are not traded at the exchange; therefore, the EEX is price-setting in a broader context. Ideally, demand and supply should be counterbalanced at any second in order to secure a stable network. Whether a power plant can sell its electricity depends on its marginal costs, e.g., primarily, cheap power plants have higher demand (so-called merit-order). Price generation relies on the marginal costs of the most expensive required power plant, known as the "marginal power plant," which sets the price for power generation from all other electricity-inducing power plants. Marginal costs are basically determined by the fuel costs of the most expensive necessary power plant and its costs for CO_2 certificates. If the resource costs of fossil power plants rise, this will be reflected in higher electricity rates because generation is more expensive. This effect was observed in 2008, in the case of an oil-fueled marginal power plant, when there were record prices for crude oil. It should be recognized that a European merit order has already been in existence for a long time, as a result of the so-called "market coupling" . Due to market coupling, price differences between stock exchanges can be minimized. Next to Germany, France, and the Benelux countries, Norway, Sweden, and Denmark are participants as well in this market coupling exchange. High electricity rates might also be interpreted as a signal of shortage; if power plants with high generation costs supply electricity to the network, only a few available power plants remain in the merit order to start electricity generation at increasing demand. Low electricity rates are consequently a sign of an unstressed situation.

Elementary laws of price generation are increasingly influenced by renewable energy, as seen in **Figure 13** (Deutsche Industrie- und Handelskammer [DIHK], 2012; Fraunhofer Institute for Solar Energy Systems, 2012). Owing to the legally established feed-in priority to the network, renewable energy sources are the highest priority for sale. Even the abolishment of the feed-in priority would barely have repercussions concerning wind and solar energy because neither possesses fuel costs. The reward for renewable energies is fixed by law and paid outside of the stock exchange, and due to the responsibility of primary feed-in for renewable energy sources at the EEX, the most expensive conventional power plants are driven out of the market. The established electricity price is oriented toward the marginal costs of inexpensively generating power plants. Due to this merit order effect, it can be assumed that as renewable energy sources increase in quantity, the electricity stock exchange rates will further decrease (Deutsche Industrie- und Handelskammer, 2012; Fraunhofer Institute for Solar Energy Systems, 2012) . In 2011, renewable energies already accounted for a decrease of 0.87 cent·kWh^{-1} on the spot market, according to the Federal Environment Ministry of Germany (German Federal Environment Ministry, 2012). In the coming years, this effect will continue to increase. This will be especially distinct at midday, traditionally the time of day with the highest demand for electricity and consequently also the highest electricity rates. It confirms and corroborates the commercial strategy of this project of buying electricity at off-peak times only. However, despite this high demand, the midday electricity price is sinking to the lowest level of the day with increased regularity, due to the upgrading of solar and wind energy plants, e.g., in the case of strong solar radiation. An example is 14 September 2012, when heavy winds and strong solar radiation coincided in Germany at midday. Altogether, sun and wind provided about 32 GW, which was almost half the total amount of consumed electricity. Correspondingly, electricity prices fell to a minimum; therefore, purchase of electricity at the spot market was possible at 14.44 €·MWh^{-1}. On normal days, the range of prices lay between 30 and 60 €·MWh^{-1} during the first half of 2012 (Deutsche Industrie- und Handelskammer, 2012; Fraunhofer Institute for Solar Energy Systems, 2012).

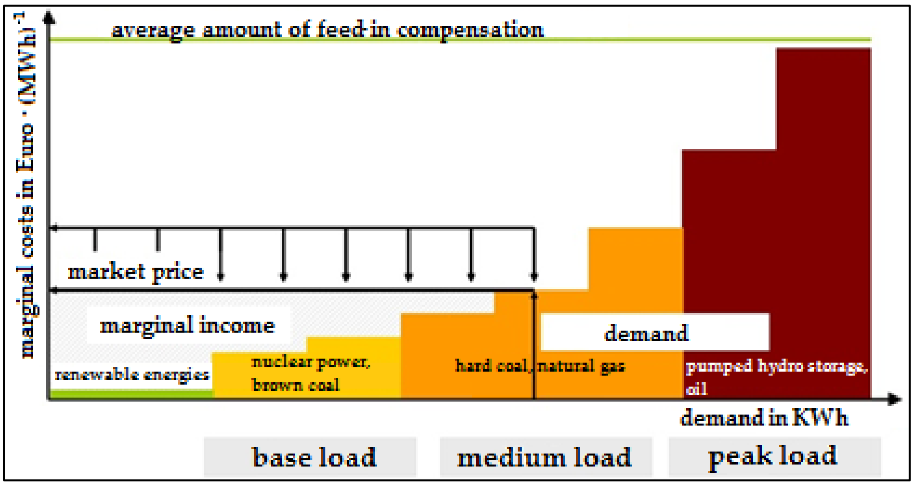

Figure 13. Electricity price formation at the European Energy Exchange (EEX), illustrating market clearing through the intersection of supply and demand curves and the influence of variable renewable generation. on price fluctuations (Deutsche Industrie- und Handelskammer, 2012).

Table 5 shows the most recent, available statistics (winter 2012/2013) concerning the average electricity price on the spot market in different European countries. Consequently, the reduction of electricity prices, due to upgrades in the renewable energy sector, remains ongoing. What lowers the stock exchange rates indeed raises the EEG-reallocation charge for the quantity of power generated from wind and sun, which is provided with a fixed feed-in reward. On the other hand, because of the low stock exchange price, the difference between the fixed feed-in reward and income is increased. This difference forms the basis of the EEG-reallocation charge. However, the economy and consumers only benefit from this effect of decrease by the EEG, both limited and with a time delay. Those who directly purchase solely at the spot market can take advantage of this benefit. Companies, and even the energy-intensive industry, practically never purchase on the spot market because the risk is too great. Generally, these enterprises buy mostly at the forward market, where price-decreasing effects appear only with a delay (Deutsche Industrie- und Handelskammer, 2012; Fraunhofer Institute for Solar Energy Systems, 2012).

Concerning the TES project, this suggests an immense potential for cheap and economic purchase of energy on the spot market, since it can be fed irregularly and within two days of purchase without long-term planning (forward market). If the store is empty, it might be a solution to offer conventional energy for district heating.

Table 5. Average day-ahead electricity price in Germany and the connected markets in winter 2012/2013.

Country	Average spot market electricity price [€·MWh^{-1}]
Denmark East	39.28
Denmark West	38.40
France	50.21
Germany	41.82
Sweden	39.83
Switzerland	52.64
The Netherlands	53.22

[sources: EEX, CASC, EMCC]

Occasionally, electricity rates at the EEX can even be characterized as negative prices, e.g., electricity consumers get paid for purchasing electrical energy because from time-to-time Germany's wind power plants generate more power than demanded by the consumers. **Figure 14** shows some negative spot market prices that occurred from 1 September 2009 to 1 March 2010. The record for negative electricity rates at the EEX was achieved on 4 October 2009, with 1499 €·MWh^{-1}. On Christmas Eve in 2009, electricity buyers received more than 14 million euros for the purchase of electricity (Deutsche Industrie- und Handelskammer, 2012; Fraunhofer Institute for Solar Energy Systems, 2012).

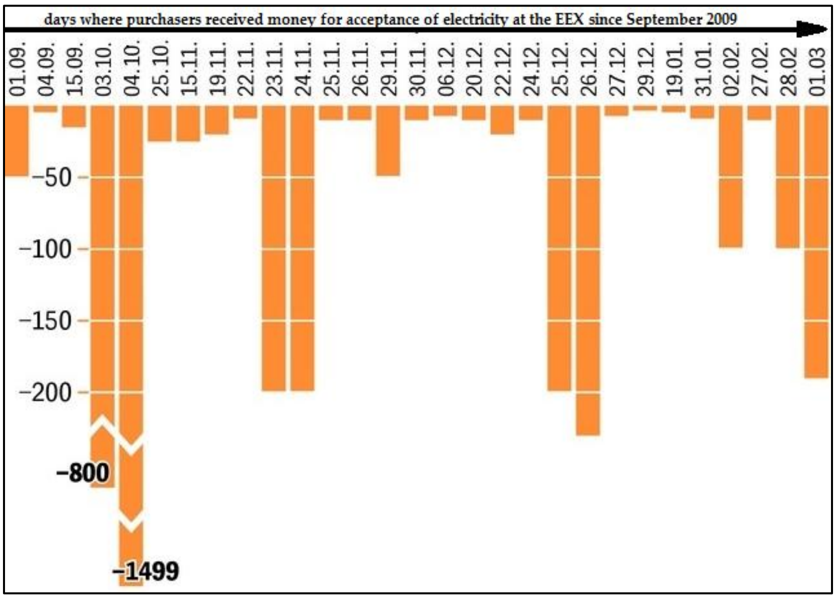

Figure 14. Negative electricity rates–daily budget prices in euro per MWh (Der Spiegel-Verlag, 2010).

Since 2010, the Federal Network Agency of Germany has decided to set a limit of 150–350 €·MWh-1 for negative electricity prices on the spot market (German Federal Network Agency, 2013b). This limit should be considered within calculations and before the construction of the TES. Negative electricity rates will not be eliminated by the Federal Network Agency due to its appeal for the construction of energy stores.

The Phelix Day Base is defined by the EEX (European Energy Exchange, 2012) as "the average price of the hours 1 to 24 for electricity traded on the spot market. It is calculated for all calendar days of the year as the simple average of the auction prices for the hours 1 to 24 in the market area Germany/Austria, disregarding power transmission bottlenecks". **Figure 15** displays the price development of the Phelix Day Base in winter 2011/2012 and 2012/2013. In winter 2012/2013, the average power price at the EEX Day-Ahead spot market was situated below that of winter 2011/2012 (47.52 €·MWh^{-1}), amounting to 41.82 €·MWh^{-1}. This is a difference of 5.70 €·MWh^{-1}; however, the trend is restricted to the winter months as development generally points toward lower electricity prices at the spot market. During October to the end of November 2012, the electricity price was nearly always lower than in October and November 2011, with a few exceptions.

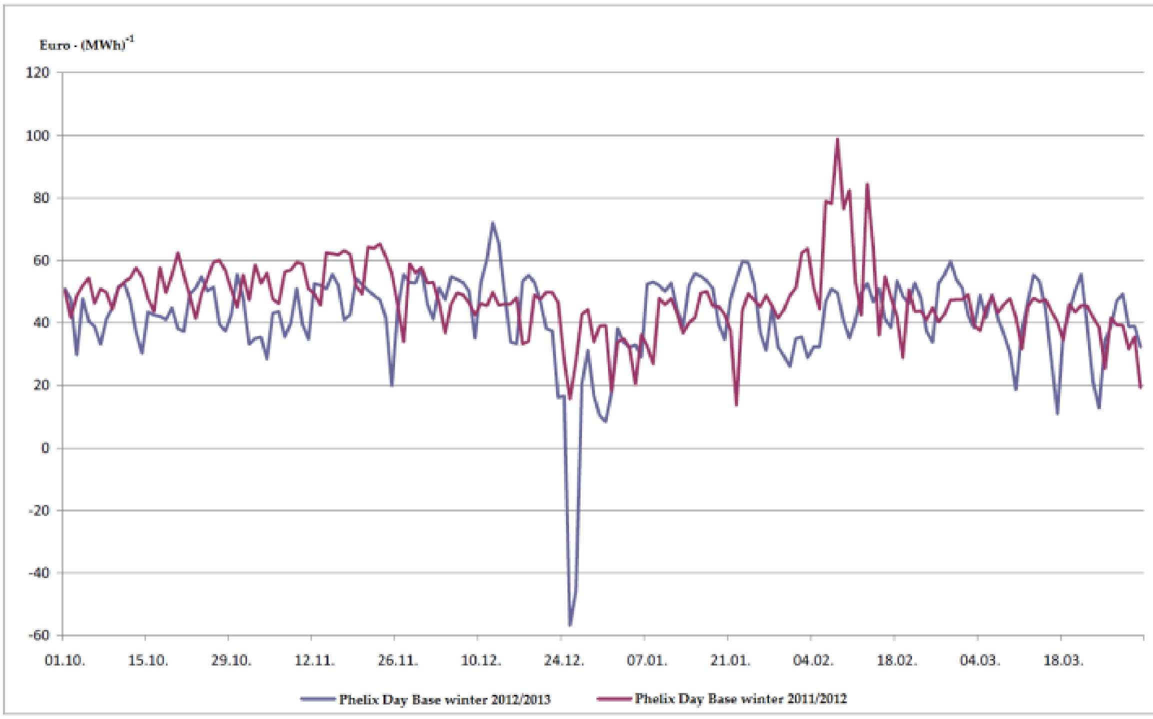

Figure 15. Price development of the Phelix Day Base in winter 2011/2012 and 2012/2013 (source: EEX spot market, 2013).

A clear deviation was observed between midnight and 8 a.m. on 25 and 26 December 2012. With reference to the previous example (24 December 2012, FIMan operations; Section 3.3.2), apart from the excess feed-in, there were also negative electricity rates on the electricity stock exchange in Leipzig at that day. Consequently, these events are connected. **Figure 16** shows the spot market prices for electricity on the 25, 26, and 31 December 2012. On the night of 25 December 2012, negative electricity prices accounted for -221.99 €·MWh^{-1}, while having a peak feed-in of wind energy of 19.360 GW (12 a.m. – 7 a.m.). The same incident happened on the night of

26 December 2012. The peak of predicted electricity from wind energy was 20.312 GW, inducing a decrease in prices down to -188.91 €·MWh^{-1}. Electricity rates did not turn positive again until the predicted demand increased (8 a.m.) (German Federal Network Agency, 2013b).

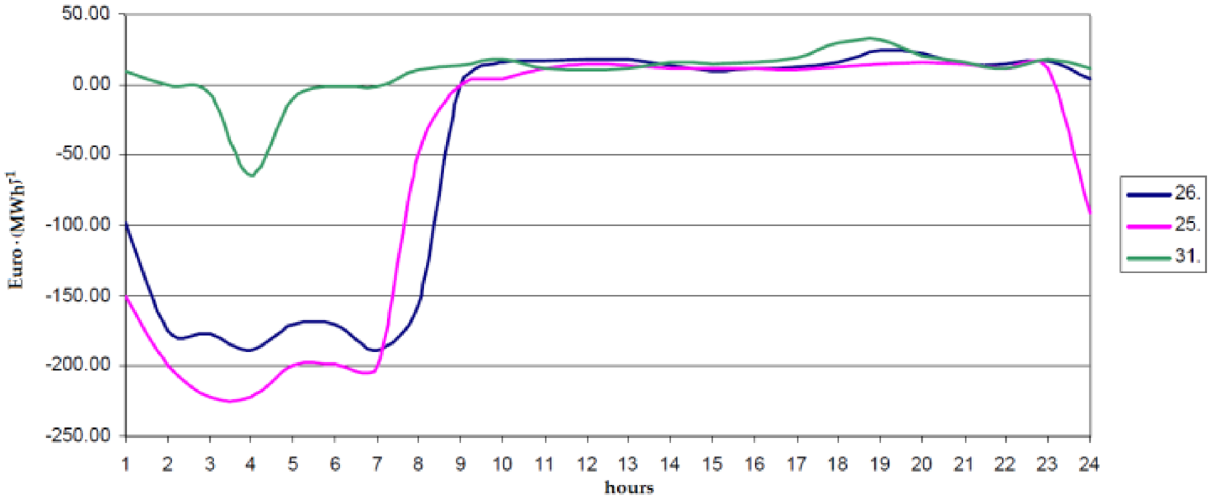

Figure 16. Spot market prices for electricity at 25, 26, and 31 December 2012 (source: EEX spot market, 2013).

In spite of the fact that, on 31 December 2012, there were similar wind conditions during Christmas 2012, prices developed which were clearly located in the less negative zones. An investigation by the BNetzA determined that there was no reason for the difference in spot prices because the quantity of fluctuations and wind power feed-in were at a comparative level on all three days. Furthermore, the load within the German network, as well as the net export balance, were also similar on these three days. Thus, the observed price differences cannot be explained by the raw data, but might have origin in an optimized demand and supply behavior on the part of the market participants, especially in the sector of marketing of conventional electricity generation capacity (German Federal Network Agency, 2013b).

3.5. Further calculations and conclusion in terms of market potential

In Section 3.2, Germany was identified as the country occupying the highest consumption rate of electrical energy within the ENTSOE, therefore, the correct foundation for this project is already laid. The northern and north-eastern region of Germany can be seen as ideal for the intended purposes, since 56.65% of the total installed wind energy performance were identified as being located in this part of Germany (Section 3.3.1).

After calculating with and extrapolating of the statistical values that were presented in Section 3.3.2, the theoretical annual availability of failure work within the region (E.ON edis AG) of at least 94.5 GWh (minimum) and at the utmost of 201.0 GWh can be stated (based on the data from 2011). Moreover, considering all relevant and present data, an annual arithmetic mean of 144.2 GWh was determined. Theoretically, between 0.259 and 0.551 GWh (arithmetic value based on calculations with the previous arithmetic value: 0.395 GWh) of failure work occurs daily in the area covered by E.ON edis AG. Of course, this is only the theoretical quantity of occurring failure work and it does not actually happen on a daily basis. In addition, there are annual heavy fluctuations and the continuing upgrade of network and plant capacity which hinder a reliable prediction. However, further calculations involving the days with operations (arithmetic value approximation based on **Figure 10** and **Figure 11**: 218 $d \cdot a^{-1}$ and 18 $d \cdot mo^{-1}$ nationwide, 32-38% of the total FIMan operations; therefore, approx. 69.8…76.3…82.8 $d \cdot a^{-1}$ and 5.8…6.3…6.8 $d \cdot mo^{-1}$) result in slightly more (1.295…1.975…2.755 GWh) failure work being inducted to the planned TES on every fifth day under ideal conditions (not including energy loss due to transmission and conversion). This is an average performance of 53.38…82.29…114.79 MW, being available within the region every fifth day. However, these values are only theoretical average values for estimation of the potential, based on the year 2011.

Although more recent data from transmission system operators show that FIMan operations, and therefore surplus wind power, tend to decrease, there is still a strong potential due to heavy fluctuations.

A possible way of accessing and purchasing failed work for the future implementation of this project would be negotiating a contract directly with the owner of a wind farm. In this manner, an electrical line leading directly from the power plant to the TES would be a possible solution, with benefits for both parties since the owner will receive money for the TES-in-fed wind power, which would otherwise be lost. Ideally, a contract would include a minimum daily load for a fixed (low) price that can be claimed by the storage owner in the case of insufficient feed-in of surplus wind power over a certain time (pre-calculations to be made). In doing so, one daily load is the energy that is transferred in long-term average per day through the special power line, constantly supplying the TES.

Given that there have been negative electricity rates, as well as excess feed-in of balance systems, e.g., on 24 December 2013 (see above), there has been a tremendous oversupply of generated electricity, which constitutes potential cheap electricity for charging the planned energy store. Additionally, as presented above, there were many other days with excess supply, offering immense opportunities for strategic and intelligent purchase of excess electricity. The potential for buying electricity at negative prices therefore is definitely given, but impossible to predict. While operating the TES, an ongoing market analysis will be essential in order to run the TES most economically. However, due to increasing availability of renewable energy, and because of the merit order, less expensive and consequently more economic purchase of electricity generally, but especially during off-peak and high wind energy feed-in-times, from today's viewpoint seems to be warranted within the next 15 years, indicating significant commercial potential. The core idea behind the most economic purchase strategy is indeed buying at times of FIMan operations and of cheap or even negative electricity prices, which have been shown to occur on numerous occasions in the past. Additionally, prices as high as 350 $€ \cdot MWh^{-1}$ are sometimes paid for the purchase of electricity at oversupply. Therefore, aligned to these purposes, a concept for a potential TES is presented in the next section.

4. Technology research

After investigation of the state-of-the-art in literature and this author's considerations concerning TES, the concept of an innovative underwater stratified sensible heat storage, combined with a latent TES, was developed.

Seasonal heat storage in large water reservoirs has been implemented in several practical applications. A prominent example is located in Neubrandenburg, Germany, where surplus heat generated during the summer months by the Neubrandenburg gas and steam turbine power plant is stored in a deep groundwater aquifer at a depth of approximately 1m200 m, without the use of additional thermal insulation. During the heating season, the stored thermal energy is recovered and utilized to supply district heating to the Rostocker Straße residential area and the Neubrandenburg University of Applied Sciences. The system was designed and constructed by a company called GTN.

In contrast, Phase Change Materials (PCMs) have so far remained limited to isolated or experimental applications. The company Saint-Gobain Weber previously marketed a plaster mortar containing microencapsulated paraffin-based PCMs, intended to moderate indoor temperature fluctuations and reduce the need for active air conditioning. This product has since been discontinued, as have Knauf's "Comfortboard 23" gypsum plasterboards, which were designed for a comparable purpose.

4.1. Underwater sensible heat storage combined with latent TES

The proposed potentially-economic TES is a stratified sensible heat storage located in a lake or sea, and stores heat at temperatures of up to 90 °C. **Figure 17** shows the construction schema:

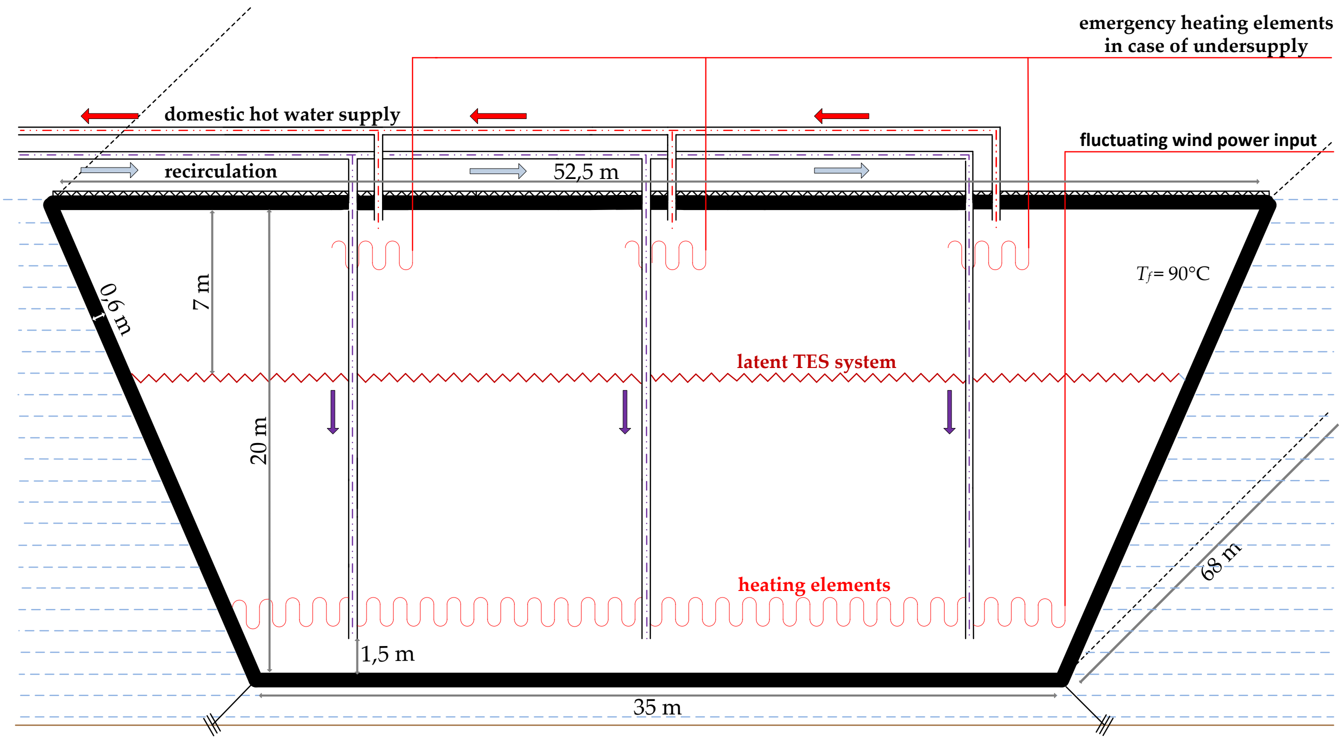

Figure 17. Construction sketch of the TES system.

One innovative idea is combining the underwater sensible heat storage with a latent TES by coiling tubes within the sensible heat storage, therefore incorporating the advantages of both sensible TES and latent TES. The TES system is to have the geometrical structure of a trapezoidal prism, reaching a water depth of 20 m. The construction is grounded by heavy weights or underwater concreting to the lake or sea floor. Thick layers of insulation are essential on the sides and bottom. The floating cover insulation layer, with contact surface to the atmosphere and to external circumstances, such as birds or maintenance work, therefore has to be more stable, e.g., covered by wooden planks. It also prevents sinking of the TES through buoyant construction material. The total visible surface at water level is 3570 m^2, arising from an upper width of 52.5 m and a length of 68 m. For a better understanding of the dimensions, these are the exact metrics of one half of a soccer field at the European championships or World Cup (FIFA norm) (International Federation of Association Football, 2007). The bottom width is 35 m, thus giving a total storage volume of 59,500 m^3 (calculation formula: (52.5 m+ 35 m)/2 · 20 m · 68 m).

Heat storage water tanks with stratification have already proven to be an efficiency-improving method of energy conservation. Water is widely known to be an effective medium for TES and thermal stratification, as briefly described in Section 2.1, emerges due to density variation caused by temperature variation; when water of different temperatures is stored in a tank system, warmer and colder water separate due to the gravitational effect (Shah and Furbo, 2003; Dincer and Rosen, 2002).

Figure 18 displays a sketch of the top view of the TES system, indicating hot water output pipes (red) and cold-water input pipes (blue).

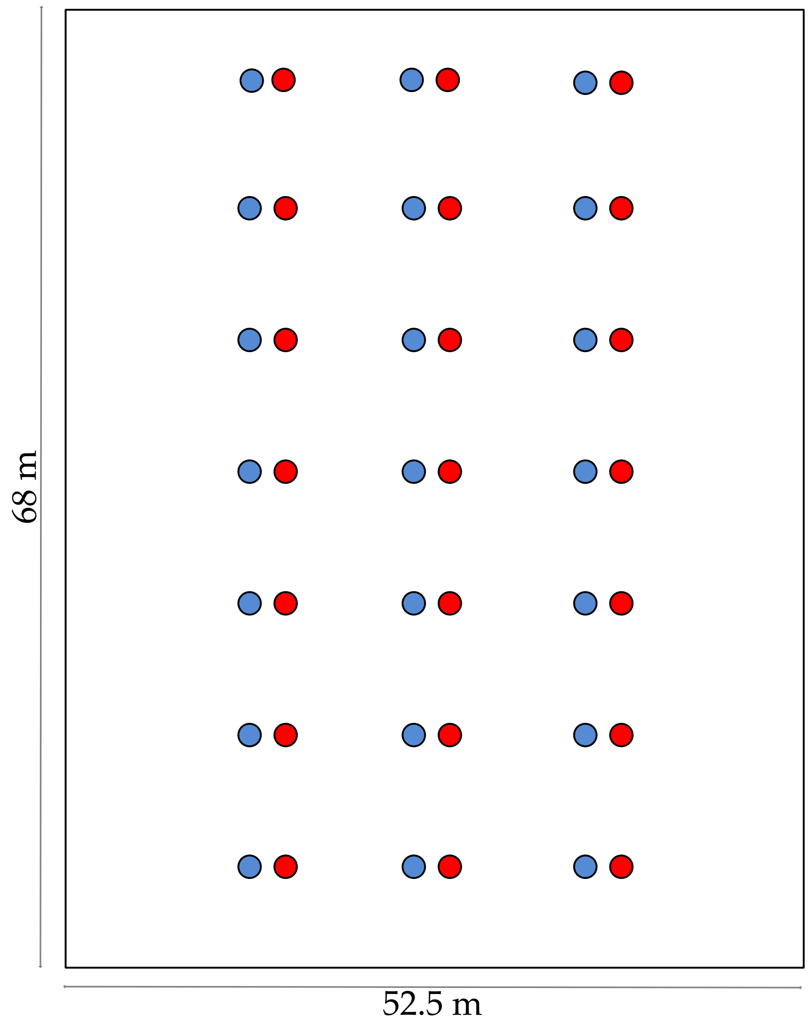

Figure 18. Top view sketch of the TES system.

At the top temperature layer of the store, multiple pipes, which are spread over the upper surface of the storage, are connected in order to pump hot water out of the storage for domestic hot water supply or space heating. Discharging from the top is essential, because here the procedure is accomplishable at the highest temperature. In the community, heat exchangers absorb the heat from the pumped-out hot water, and the warm water is transferred to the houses. Since the total storage medium mass inside the TES remains nearly constant, the water is recirculated back into the store through various pipes leading past the heating elements in the lower part of the store. During times of high electricity purchase, and thus input, the water will be directly reheated and, ideally, continuous charging and discharging will be maintained. As a consequence, the mass flow equilibrium between hot water output and cold-water input is required to be automatically modulated at all times. Due to the stratified configuration, in terms of temperatures, both charging and discharging procedures must be carefully managed with APT valves. Residual heat after passing the heat exchangers will not be lost (heat loss due to transport along the pipes surface neglected), but also recirculated with the water via these pipes back into the store. The system is supplied with inexpensive electricity, e.g., surplus wind power as analyzed in the previous section, by heating elements that convert electricity into sensible heat and, therefore, electrical energy into thermal energy. Conversion of energy and release of heat take place in the lower part of the storage. The heating elements cover a large surface of the bottom area to ensure maximum efficiency. Processes inside the store include natural thermal convection because of density differences, heat convection due to the flowing input water, and heat conduction.

Enhancement of storage performance will increase the effectiveness of the TES. This can be performed through the reduction of storage costs, reduction of heat losses, improved construction design, or increase of storage density. As a consequence of these considerations, the idea of integration of a latent TES to the sensible TES has arisen. This is integrated in the upper half of the storage, 7 meters below the top insulation layer. The installation will be realized through long, thin, spiral tubes, similar to some conventional heat exchangers, that will be spread throughout the entire storage level at 7 m depth and will offer a high ratio of surface area for heat transfer to PCM volume.

If only a PCM tank is used, instead of combining it with a sensible store, two or more PCMs with different melting temperatures are required to cover the same temperature distribution range as stratified water tanks. These types of systems are not in commercial use as sensible TES due to the low heat transfer rate during storage and the recovery process. During the phase transition of liquid-solid PCMs, the interface moves away from the convective heat transfer surface, leading to an increase in the thermal resistance of the growing layer of the solidified PCM, thereby resulting in a poor transfer rate. On the other hand, a sensible TES is the least efficient method for energy storage, due to a low heat storage capacity per unit volume of the storage medium (Rebhan, 2002; Sharma et al. 2009; Ataer, 2009; Babay et al. 2013). A combined sensible and latent TES eliminates the difficulties described to some extent and secures the advantages of both.

In the construction concept, liquid-solid phase change was chosen, for it is easiest to implement (volume change at phase transition), especially inside a sensible TES

(Zalba et al. 2003). Appropriate PCMs have been found that operate at temperatures between 75 and 84 °C (Section 4.1.1: Heat storage media of choice), which is the temperature range needed for this technological concept.

The system functions as follows: the latent TES is charged and in operation when the upper half of the sensible TES is close to being fully charged, reaching a nearly constant temperature of 90 °C in order to be able to supply a secure stream of heat on demand. The objective, in terms of delivery promise, is that the TES is operating in this state in the top layer for most of the time. A fully charged TES takes place when a lot of failed work or negative and low electricity rates are discovered. While discharging with no simultaneous charging of the sensible TES (e.g., when no cheap power is available), cold water flows back in and does not get reheated, reaching the latent TES at some point and triggering the release of previously stored latent heat at the surface of the latent TES tubes that directly becomes sensible heat, which is now available for direct hot water output by keeping the required temperature constant for some time (78–84 °C depending on the PCM). As such, integration of a latent TES acts as a safety element for regulation assistance. Furthermore, the idea increases the energy density in the upper half of the TES system and the performance capacity of the whole TES system. An increase in energy storage density means having the same volume of storage but an extended quantity of energy, which can be stored and extracted. Another advantage is that, due to release of latent heat, the period between requirement of purchase of fluctuating power – in an economic thinking: availability of cost-efficient purchase of power – and the state of having a discharged TES that can no longer provide the promised hot water of 75–90 °C at the top temperature layer, is being prolonged, without increase of storage volume.

Another setup of heating elements for emergency energy supply in case of insufficient temperature in the top layer is also installed. These additional emergency heating elements are only used when the top temperature layer is below 75 °C and when there is demand. This may occur when there has not been an input of excess inexpensive electricity for some time. Therefore, the top layer can be directly and quickly heated with available inexpensive electricity or, if no cheap electricity is able to be bought, with power purchased at conventional rates. Due to the design of this installation, the heat is not necessarily bound to rise up to the top layer by thermal conduction and gravitational effect elevation, but is immediately accessible in case of emergency. However, this situation shall be prevented by all means.

4.1.1. Heat storage media of choice

Considering the performance of the TES, an effective store depends largely on the storage material, whereas certain requirements should be met, such as having a long service life, being non-toxic and non-flammable, and possessing a high heat storage capacity. In addition, a high thermal diffusivity α (formula: $\alpha = \frac{\lambda}{\rho \cdot c_p}$; unit: e.g., $m^2 \cdot s^{-1}$) and a high thermal effusivity e (formula: $e = \sqrt{\lambda \cdot \rho \cdot c_p}$; unit: $J \cdot m^{-2} K^{-1} s^{-1/2}$) are desirable. A high thermal diffusivity of the heat storage medium enables a rapid response to temperature differences, e.g., quick charging and discharging. A high thermal effusivity results in a high amount of heat being stored. Capability to withstand charging/discharging cycles without loss in storage capacity, change in structure, or loss in performance, as well as low costs and wide availability, are important properties of efficient storage media (Oladunjoye and Sanuade, 2012; Hahne, 2009).

In the case of the sensible heat store medium, water was chosen as a transport and storage medium at the same time. Other interesting sensible TES media, for example, oils or few eutectic mixtures of molten salts such as 54% KNO_2, 40% $NaNO_2$, 5% $NaNO_3$ (m/m), have been dismissed because of higher costs, the large overall size of the storage, undesired oxidation mechanisms, and safety problems (need for inert gas cover in case of oils). However, these media can provide high-performance operating temperature ranges of 100–300 °C (oils) and up to 300 °C and above (molten salts). A non-eutectic molten salt that was considered was sodium hydroxide, which is characterized by its melting point at 320 °C and range of usage up to 800 °C. One disadvantage of sodium hydroxide is its property of being highly corrosive, especially at high temperatures. Due to the location in the sea or lake, representing an ecosystem, and therefore having the potential to pose a significant environmental issue related to leakage, another reason for excluding molten salts and oils as large-scale sensible heat storage media was encountered (Ataer, 2009). Water, as the quantitatively dominant natural compound of the outer storage location, is additionally very inexpensive and widely available for effective use to store sensible heat, as well as to transport thermal energy to consumers. Water has significant advantages, as it is non-toxic, non-combustible, and easy to handle. Furthermore, water has a comparatively high specific heat capacity (4.1843 $KJ \cdot kg^{-1}K^{-1}$ at 20 °C and 101.325 kPa (Wagner and Pruß, 2002)), high density (998.3 $kg \cdot m^{-3}$ at 20 °C and 100 kPa (Stephan and Mayinger, 1998)) and relatively high thermal conductivity (0.5995 $W \cdot m^{-1}K^{-1}$ at 20 °C and 100 kPa (Kretzschmar and Kraft, 2009)). Another advantage is that heat exchangers can be avoided, because water is used as a heat carrier, as mentioned above, hence saving costs. When energy input is scarce, due to insufficient purchase of low-priced surplus wind power, natural convection flows can be utilized (stratified TES). Consequently, simultaneous charging and discharging of the storage is possible, for the output is at the top of the TES and the input at the bottom (**Figure 17**). In general, adjustment and control of a water system are flexible and variable (Ataer, 2009; VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen, 1997; Langeheinecke et al. 2001). The major disadvantage is that working temperatures are limited to less than 100 °C, unless the system is pressurized. Therefore, the maximum and optimal working temperature on the top temperature layer of the construction is 90 °C. Additionally, water is also corrosive, which must be considered in the architecture of the TES.

Considering the latent TES system within the sensible TES, a suitable PCM had to be found, possessing certain requirements that were needful. Next to the optimal temperature range concerning the melting point, a high specific heat of fusion, high density, high specific heat capacity, high thermal conductivity, congruent melting behavior, small change of volume at phase transition, low supercooling, chemical and physical stability, as well as reproductive phase transition, were desired. Moreover, the PCM should be non-flammable and non-explosive (Marx, 2010). Economic aspects such as costs and availability were also considered.

With regard to PCM, a very efficient option with remarkable characteristics was identified and selected for the latent TES system. The first choice, in terms of highest performance, is the octahydrate of barium hydroxide, an inorganic PCM (salt hydrate). **Figure 19** shows the structural formula of barium hydroxide octahydrate (chemical formula: $Ba(OH)_2 \cdot 8\ H_2O$ (Schultz, 2013), M = 315.46 g·mol^{-1} (Schultz, 2013), $\rho_{solid,24\ °C}$ = 2070 kg·m^{-3} (Dincer and Rosen, 2002; Lane, 1980), $\rho_{liquid,84\ °C}$ = 1937 kg·m^{-3} (Dincer and Rosen, 2002; Lane, 1980; Heckenkamp and Baumann, 1997), CAS: 12230-71-6 (Jing et al. 2007)).

Barium hydroxide octahydrate has a melting point T_m of 78 °C (Dincer and Rosen, 2002; Lane, 1980; Abhat, 1983; Neumann and Emons, 1989; Lindner, 1996), and thus melts within the required temperature range. Its heat of fusion Δh_m was determined to be 280 kJ·kg^{-1} barium hydroxide octahydrate (Lindner, 1996), which is relatively high compared to other PCMs within the temperature range, hence offering an excellent storage density. The specific heat capacity c_p of barium hydroxide octahydrate is stated at 1.26 kJ·kg^{-1}K^{-1} at 20 °C and 100 kPa (Oberpaul, 2002). Thermal conductivity of barium hydroxide octahydrate accounts for $\lambda_{solid,23\ °C}$ = 1.255 W·m^{-1}K^{-1} (Dincer and Rosen, 2002; Lane, 1980) and $\lambda_{liquid,85.7\ °C}$ = 0.653 W·m^{-1}K^{-1} (Dincer and Rosen, 2002; Lane, 1980). Experiments by Jing et al. (2007) show that barium hydroxide octahydrate still did not exhibit any undesired supercooling and phase segregation after more than 500 thermal cycles, the point to which experiments were conducted. Furthermore, no obvious changes in the melting temperatures and fusion heat of barium hydroxide octahydrate were observed with increasing number of thermal cycles. Therefore, this PCM holds significant promise in the context of this project. Even if the compound were to undergo some serious changes after thousands of thermal cycles, the construction is designed to enable replacement of PCM material at temperatures above 80 °C (liquefied), simply by rinsing out and refilling the latent TES tubes using connecting valves on the outside of the TES system. It is also important to note that the compound is non-flammable and non-explosive (Merck KGaA, 2013).

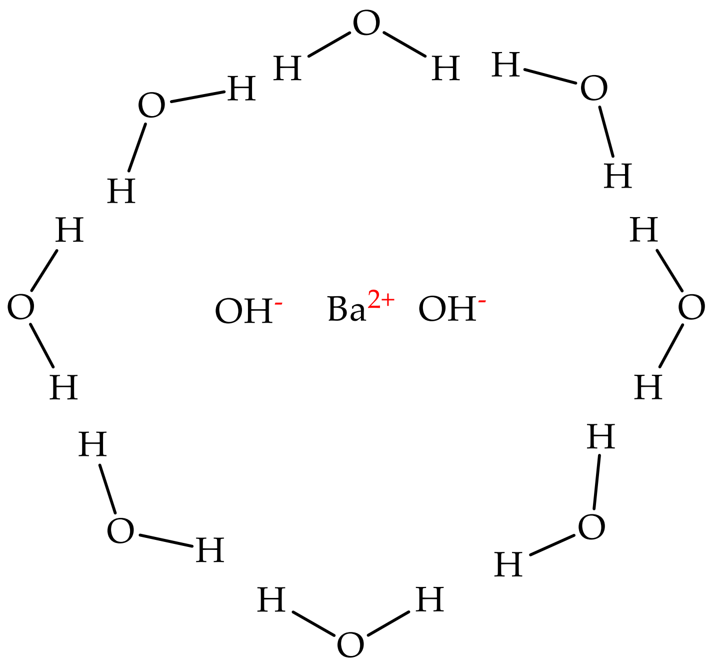

Figure 19. Chemical structure of barium hydroxide octahydrate.

However, there are also some disadvantages. Barium hydroxide octahydrate is harmful to humans by inhalation and in contact with skin (Carl Roth GmbH, 2012), and it is classified as slightly hazardous to water in Germany (Merck KGaA, 2013), just like ethanol, acetic acid, or sodium hydroxide solution (German Federal Ministry for Environment, Nature Conservation and Nuclear Safety, 2013). Security measures, such as safety valves and measurement tools, provide additional safety, and barium hydroxide octahydrate is separated from the environment outside the TES system by three barriers: the tube walls, the storage water, and the insulation walls. In case of leakage, the environmental consequences would be minor and non-threatening to the ecosystem, especially in the sea.

Incongruent melting behavior and subsequent multi-step solidification occurred in some experiments (Hörmansdörfer, 1990). The extraordinary caloric values of barium hydroxide octahydrate exist because of optimal formation of hydrogen bridge bonds within the molecule, integrating eight water molecules, and of the ratio of proportion. Nevertheless, liquefaction during heating through heat absorption and re-solidification through heat release cannot be seen as melting or solidifying in a classic sense, as it is mainly based on phase transformation, whereas hydration water is partially or completely released under heat intake and reintegrated under heat release. However, the expression melting is incorrectly, but, in practice, commonly used in context with PCMs on a hydrate basis for latent TES (Hörmansdörfer, 1990; Hörmansdörfer, 1996). Before construction of the TES, it is crucial to investigate whether a separation in different phases is happening over a certain quantity of thermal cycles. This process could be explained due to the possibility that hydroxide free of water of crystallization, and hydroxide with less water of crystallization, are insoluble in split-off water of crystallization. Because of the fact that the separated phases possess different densities, there might be a tendency for decomposition, whereas the phase with higher density, primarily the hydroxide, sinks to the bottom, while lighter phases (mostly the split-off water of crystallization) accumulate above. During recrystallization, water of crystallization might not be reintegrated at requisite velocity, narrowing heat release during reverse reaction. However, due to the low diameter of the latent circular coiling TES tubes (3 cm), this effect is minimized. In order to investigate whether mechanical support for reblending is necessary, further experiments in the laboratory are sufficient. In the case of occurring problems of segregation during experimentation, a solution could easily be achieved by pumping over and recirculation of the barium hydroxide octahydrate when liquefied.

Another option might be the addition of certain chlorides to the PCM, thus becoming a eutectic PCM. By doing this, a totally different melting behavior is induced that can be described as dry melting. Split-off of crystallization water and the absorption by the chlorides takes place simultaneously and completely, resulting in a relatively solid mass, even after trespassing of the melting point, which volume only slightly differs from the volume of the hydroxide-hydrate (Hörmansdörfer, 1990; Hörmansdörfer, 1996) .

When it comes to further construction research, the occurring change of volume at phase transition must be investigated as well. Generally, the latent TES tubes cannot consist of light metals since barium hydroxide octahydrate reacts turbulently with aluminum and its alloys under heat development and synthesis of decomposition gases, whereas constructional elements of light metals are destroyed in a minimum of time (Oberpaul, 2002; Hörmansdörfer, 1996). Inevitably, the construction components of the latent TES tubes have to consist of heavier materials, such as steel or copper. This is also important for other constructional elements of the entire TES, such as the heating elements referred to the case of leakage.

It has also been considered that barium hydroxide octahydrate is more expensive than other PCMs, such as organic fatty acids, but on the other hand, are more durable. Although research on the field of barium hydroxide as PCM in latent TES is still not advanced, and in spite of the above-mentioned disadvantages, it has been selected as best suitable PCM for this project due to its immense high energy capacity properties and potential for optimization. Therefore, in combination with sensible heat storage, it can be seen as innovation.

In case of possibly occurring problems during experimentation with barium hydroxide octahydrate, a surrogate PCM was selected as second choice: a eutectic mixture of two salt hydrates, namely magnesium nitrate hexahydrate and lithium nitrate (chemical formula: $Mg(NO_3)_2 \cdot 6\ H_2O$ / $LiNO_3$). **Figure 20** shows the chemical structure of both components. The ratio of mixture is 86% (m/m) $Mg(NO_3)_2 \cdot 6\ H_2O$ and 14% (m/m) $LiNO_3$. The melting temperature T_m is 72 °C which is relatively low, but still practicable for the purposes of concept modification. The heat of fusion Δh_m is 182 $kJ \cdot kg^{-1}$ and the specific heat capacity c_p was measured at 1.40 $kJ \cdot kg^{-1} K^{-1}$ at 20 °C and 100 kPa (Heckenkamp and Baumann, 1997). Thus, storage capacity and performance are much lower than in the case of the first choice, barium hydroxide octahydrate. However, there are advantages that make magnesium nitrate hexahydrate / lithium nitrate a plausible substitute, in the case of impracticality of project implementation with barium hydroxide octahydrate. One advantage of having a mixture at the eutectic point is achievement of a congruent melting behavior. Furthermore, this PCM crystallizes out after low supercooling and possesses a high stability of cycles that was tested after 10,000 cycles. Change of density is only minimal (ρ_{solid} = 1610 $kg \cdot m^{-3}$, $\rho_{liquid,84\ °C}$ = 1590 $kg \cdot m^{-3}$ (Heckenkamp and Baumann, 1997; Oberpaul, 2002)), circumventing the risk of damaging the latent TES tubes during phase transition. On the other hand, the density is lower than the density of barium hydroxide octahydrate, which further reduces the energy storage capacity of the entire TES system. However, due to the low reactivity of magnesium nitrate hexahydrate / lithium nitrate, the light metal aluminum is able to be used as construction material. In addition, magnesium nitrate hexahydrate / lithium nitrate can be regarded as toxicologically harmless and as non-hazardous to water. It is even used therapeutically (Dincer and Rosen, 2002; Heckenkamp and Baumann, 1997).

The following calculations predict the performance potential of the TES based upon integration of the first choice: barium hydroxide octahydrate.

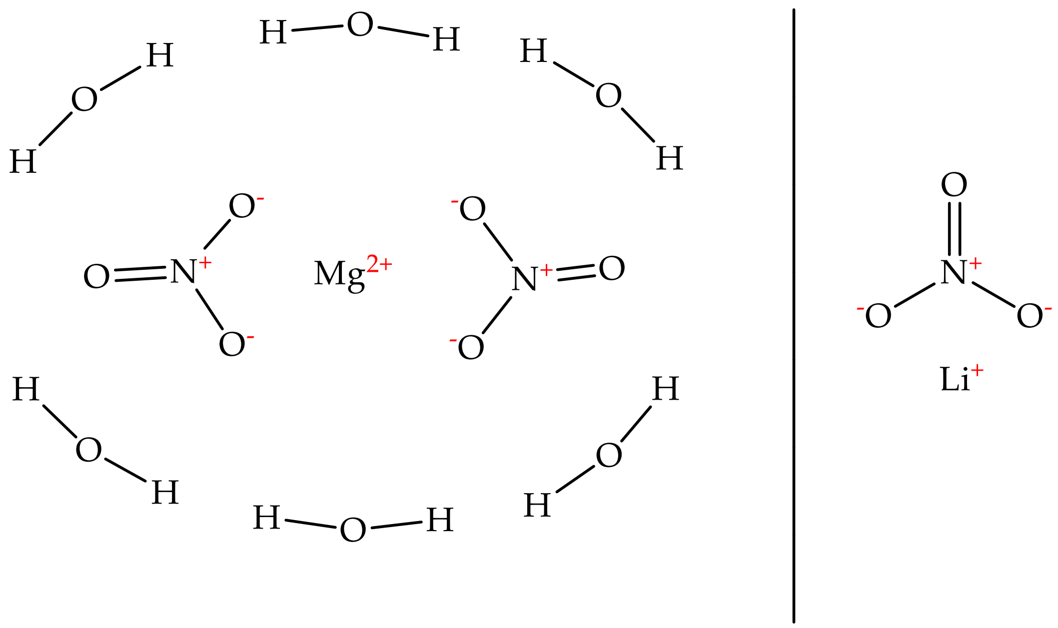

Figure 20. Chemical structure of magnesium nitrate hexahydrate (**left**) and lithium nitrate (**right**).

4.1.2. Calculations

This subsection presents results and explanations of rough calculations, which were carried out in order to assess the potential economic feasibility of the project, to determine the daily required amount of economically-priced electricity for input, and to estimate the potential of the TES.

Firstly, the total capacity for stored energy within the TES, when being fully charged, was determined based upon the calculation formulas (4) and (6) (Sections 2.1 and 2.2). Starting from the premise that the entire TES needs to be fed with a lot of energy, once at the beginning of operation for the purposes of first reaching the working temperature of 60–90 °C, the approximate overall initial energy input for fully charging (up to 90 °C) was estimated. It was assumed that the initial temperature of the water, which will be funneled into the newly-built TES, will be 10 °C.

To achieve this, the volume of the section of the latent TES had to be first figured out to gain information about the required mass of PCM (barium hydroxide octahydrate). In these calculations, changes of density and specific heat capacity of water and barium hydroxide octahydrate were neglected for simplification and because, in the case of barium hydroxide octahydrate, no data is yet available for calculation with the average specific heat capacities over the temperature ranges of 10–78 °C and 78–90 °C. The values for density and specific heat capacity stated above (Section 4.1.1) were used in calculations. Volume subtractions due to internal fittings, such as the heating elements, input pipes, and the coiled tubes of the latent TES, were neglected as well in this first estimate. Starting with a total TES volume of 59,500 m^3, the intertwining layer of small tubes (3 mm diameter) within the sensible TES at 7 m depth, containing the PCM for the latent TES part of the storage, was calculated to require a total of 81.6 m^3 of pure barium hydroxide octahydrate. Consequently, water amounts to a volume of 59,418.4 m^3, which equates to 59,418,400 l or 59,317.39

metric tons (59,317,388.70 kg). Taking into account the density, about 168,912 kg of barium hydroxide octahydrate are integrated into the TES.

Results of calculations show that by itself, the sensible TES with water as a storage medium stores 19,856.14 GJ (19,856,139,970 kJ). The latent TES (latent and sensible heat uptake by the PCM included) is able to store 64.32 GJ (64,321,689.6 kJ). Altogether, when fully charged, the TES contains 19,920.46 GJ (19,920,461,660 KJ) in storage capacity (based on an initial temperature of 10 °C). Converted into watt-hours, 5.53 GWh (5,533,461.573 kWh) are stored in the TES when completely charged. These values are merely theoretical results and are based on the assumption that an evenly distributed water temperature of 90 °C can be achieved (ideally through thermal convection and conduction with eventual loss of stratification).

Concerning the amount of input, the conversion of electrical energy into thermal energy (heat) takes place at a conversion rate of nearly 100% (Rummich, 2009; Rebhan, 2002). For calculations, the efficiency factor of energy conversion was set at η_{he} = 0.99. Energy losses due to transmission, via cables and distribution stations in the network, can be disregarded since this is the concern of the electricity retailer. Because intermittent power supply for the TES is part of the business concept, the heating elements must be designed to receive and convert an intermittent and significant quantity of energy in a short amount of time. This challenge can be accepted because of the large heating surface at the bottom of the TES (**Figure 17**), which distributes wattage from the heating elements over an area of about 2,000 m². Following from a maximum performance value of 114.79 MW of failure work arriving at the TES within the region (calculated in Section 3.5), the heating elements are required to provide 57.4 kW·m^{-2} for optimal exploitation of inexpensive surplus wind power. Because the heating elements are sinusoidal, with adequate space for water flow between the heating tubes (at least 70% of the volume of the heating layer), the heating elements must provide a maximum performance of 191.33 kW per heating element and 1 m^{-2} (with inclusion of space for water flow). It is certainly an engineering challenge to maintain sufficient water flow to ensure that the water temperature never reaches the boiling point along the heating element surfaces. These detailed calculations and designs of matters of engineering are part of future work and fall outside this concept presentation. Circulation of some kind is already possible due to the input pipes. Formulas (9) and (10) were used for approximate calculation of the time needed to fully charge the TES for the first time:

$$P = \frac{V_w \, \rho_w \, c_{cw}(T_2 - T_1) + m_{\,PCM}[c_{PCM}\,(T_m - T_i) + a_m \Delta h_m + c_{PCM}(T_f - T_m)]}{t_{heat} \cdot \eta} \quad (9)$$

$$t_{heat} = \frac{V_w \, \rho_w \, c_{cw}(T_2 - T_1) + m_{\,PCM}\left[c_{PCM}\,(T_m - T_i) + a_m \Delta h_m + c_{PCM}(T_f - T_m)\right]}{P \cdot \eta} \quad (10)$$

Thus:

$$t_{heat} = \frac{19{,}920{,}461{,}660 \; KJ}{114790 \; kJ{\cdot}s^{-1} \cdot 0.99}$$

According to this simplified calculation, the heating time for fully charging the TES at the beginning of operation will be around 2 days and 41.5 min.

The theoretical optimal operating temperature range is set from 60–90 °C (average temperature over the entire volume measured at the top, bottom, and middle of the TES). The quantity of energy within the range of 30 K (Δh_m of barium hydroxide octahydrate included) has been calculated and results in 7,499.73 GJ (7,499,732,723 kJ), 2.083 GWh, respectively. Next to the provided storage capacity, it is also of interest to consider how the storage is going to be used. Here, the time that goes by between charging and retrieval of a certain energy value offers revealing information. This means, when electricity is expensive and not available, energy released to customers is not supposed to be higher than 7,499.73 GJ within a certain period of time without the fresh purchase of electricity, and therefore without power input. This period of time was set to a maximum of five days due to the average calculations of electricity market analysis (Section 3.5). If there is a longer phase of wind lull, electricity at conventional rates is to be bought (less economically). However, results of market analysis showed that, for example, in the summer, when there is less wind, generally more fluctuating solar power will be available at economic prices.

$$t_{heat} = \frac{7{,}499{,}732{,}723 \text{ kJ}}{82{,}290 \text{ kJ}\cdot s^{-1} \cdot 0.99}$$

When failure work is available at an average performance of 82.29 MW (results from market analysis), complete recharge of the TES only takes 1 day and 2 h (loss of heat over the TES surface and simultaneous discharging not taken into consideration). At maximum power supply, where the overall heating reaches a performance of 114.79 MW at the heating elements, only 18.5 h of power supply are necessary to fully recharge. In addition, the emergency heating elements (installed at the upper part of the TES) can also be used to provide a higher storage heating performance during the temporary availability of a huge amount of inexpensive electricity. This further lowers the necessary heating time. In best best-case scenario, charging would usually take place daily for 3.7 h, depending on the availability of inexpensive electricity and economic electricity rates, e.g., during every night.

Formula (10) was also used for the approximation of the latent TES effect. Due to the phase change material, 11 min of scope of action for electricity purchase are added to the system. In future research, this time can be enhanced multiple times by increasing the installed mass of barium hydroxide octahydrate.

The ratio of energy recovered from the storage to the input energy, which is the energy efficiency of an energy storage system, can be used to describe the TES performance. The higher the volume of storage media and the lower the contact surface with the storage walls, the lower the rate of heat loss. Therefore, the relative heat losses decrease with increasing size and are proportionate to the perimeter area/volume or $V^{2/3}/V = V^{-1/3}$, thus as $V \rightarrow \infty$, the relative losses → 0. Hence, cylindrical or spherical 3D shapes of the TES would be the optimal construction shapes. However, calculations proved that design and practical implementation are far more inexpensive, practicable, and feasible when having a trapezoidal prism, especially when it comes to underwater setup and production assignments of large storage walls. Because of the large storage volume (59,500 m³), and due to modern technology insulation layers at the storage boundaries, heat loss within the storage will be reduced to a minimum. The total surface of insulation layers that need to be fabricated is 11,100 m³ (1 × 2380 m², 2 ×1700 m²,2 × 875 m²), plus the more solid, differently designed top insulation layer that accounts for 3570 m². The top insulation layer is required to be walkable for maintenance services. As insulation material for underwater use, multiple materials, as well as combinations of materials, were matters of consideration (e.g., polychloroprene (Neoprene), vacuum insulation panels (VIPs), aerogels or conventional materials).

After several phone conversations with manufacturers of neoprene, aerogels, and VIPs from Europe, China, India, and the United States, the potential materials proved unsuitable for construction of this project on grounds of either certain product properties (because of the TES specifications), production capacity (because of the huge surface of insulation layer), or purchase prices (due to expensive price). At last, a special, relatively inexpensive polypropylene insulation system was identified, which seems to be optimal under the exposed conditions (temperatures outside -20 °C and inside 90 °C, underwater location, and pressure up to approximately 3 bars) and the size of the storage. Certain polypropylene insulation foams were even already tested by Hansen et al. (2005) for underwater pipelines at depths of 2200 m, making the polypropylene foam definitely durable and stress-resistant at the planned water depths of 20 m. Additionally, the rate of compression does not affect the insulating properties significantly. The thermal and mechanical features of polymer foams generally vary as a function of foam density. Normally, higher density improves the mechanical properties, and reduced density means higher insulation capacity. For example, if combining of a branched homopolymer of polypropylene with a stiff linear copolymer of polypropylene, both of the benefits of high melt strength and high melt elongation are combined, resulting in excellent foam quality for the purpose. Such an insulation material is characterized by evenly distributed bubbles with a closed-cell bubble structure (Hansen and Jackson, 2005; Price et al. 2002).

The insulation material is required to consist of three layers. It is constituted of an inner layer (inside the TES) and an outer layer that is a solid polypropylene copolymer which offers mechanical protection against abrasion, resistance to UV rays, and aging stabilization. Both layers have a thickness of 0.10 m. The middle layer is the primary and thickest insulation layer with 40 cm of sensitive, but cheaper, polypropylene foam. For a rough calculation, a theoretical thermal conductivity λ of 0.12 $W \cdot m^{-1}K^{-1}$ for all layers was used (Hansen and Jackson, 2005; INEOS, 2010). Future calculations should go into greater detail, but this is not part of this work since this paper is only presenting the basic concept and the idea of a potential layout for a TES.

Heat flux through the insulation layers can be described with formula (11):

$$\dot{Q}_l = k \cdot A_{st} \cdot (T_{st} - T_a) \tag{11}$$

Heat losses depend on the total surface of the storage A_{st}, the difference in temperature between the store and the surrounding lake or sea, and the heat transfer coefficient k. The heat transfer coefficient, on the other hand, depends on the thickness of the insulation layers (l) and their heat conductivities λ:

$$k = \frac{\lambda}{l} \tag{12}$$

The heat transfer resistances at inner and outer surface are neglected because mostly the heat transfer coefficients are almost entirely determined by the insulation effect (Fisch et al. 2005). Coefficient k states the quantity of heat flux per m² and Kelvin through the heat insulation. The total outer storage surface (insulations layers included) is 11,789.36 m² (1 × 3716.04 m², 1 × 2505.04 m², 2 × 1813.04 m², 2 × 970.92 m²). As reference plane for the heat loss, the arithmetic mean of the inner and the outer storage surface was chosen for calculation. A temperature of 10 °C was set as the average ambient temperature at all outer TES surfaces. As storage media temperature, the maximum temperature of 90 °C was selected. The calculation is shown in the following:

$$\dot{Q}_l = 0.2\ W \cdot m^{-2} K^{-1} \cdot 11{,}444.68\ m^2 \cdot (90\ K - 10K)$$

The result constitutes 183.115 kW. Consequently, the overall heat loss per year is determined by multiplication with time duration:

$$\dot{Q}_l = 183{,}115\ W \cdot 8760\ h \cdot a^{-1}$$

The heat losses of the TES are 1.604 GWh·a^{-1} or 4.395 MWh·d^{-1}. These are 79.101 GJ · 5 d^{-1}.

Consequently, the efficiency factor of the TES is:

$$\eta_{st} = \frac{7{,}499.73\ GJ - 79.101\ GJ}{7{,}499.73\ GJ} = 0.99$$

Therefore, the performance of the TES only (without afflux pipes and discharge pipes) is, in theory, tremendously efficient, reaching a storage efficiency of nearly 100%. When multiplied by the efficiency factor of the heating elements (η_{he} = 0.99), the theoretical overall efficiency factor (output transport tubes neglected) is 0.98, which can be seen as a nearly ideal value.

Heat losses also occur at heat bridges and connected pipelines. Critical spots for insulation deficiencies are flanges and connections, especially pipes that lead out of the storage at the top of the system. Due to density differences between hot storage water and cold water, or water that chilled down within the pipelines at night, problematic circulating streams emerge within the pipes that transport the hot water into the pipelines and the therewith chilled-down water back into the TES. In order to prohibit this kind of temperature loss as much as possible, closing valves are installed within the TES. The pipelines leading toward the consumers are covered with a thinner, polypropylene foam insulation layer for reduction of heat losses. For further calculations, a heat loss of 10% from the TES to the domestic water supply site of consumption (consumer) was chosen. Therefore, the overall efficiency of the stretch of way of the energy from the arrival at the TES to the house of the consumer is 0.88209 (0.99 × 0.99 × 0.9).

If the estimated 7499.73 GJ (2.083 GWh) reach the TES every fifth day, these are 1,499,946,545 kJ·d^{-1} or 416.652 MWh·d^{-1}, thus 0.5475 PJ·a^{-1} or 152.078 GWh·a^{-1}. After deduction of storage, conversion, and transport heat losses, the consumers are supplied with 1,323,087,848 kJ·d^{-1} or 367.524 MWh·d^{-1}, hence 0.4829 PJ·a^{-1} or 134.146 GWh·a^{-1}.

Regarding the current conditions of most consumers, electrical, electric-driven, or driven via natural gas or heating oil combustion, continuous-flow water heaters are installed. Electric-driven continuous-flow water heaters have an efficiency factor of

0.99 (Verein Deutscher Ingenieure eV, 2013), and gas-driven continuous-flow water heaters possess an efficiency factor of 0.84 (Verein Deutscher Ingenieure eV, 2013). Warm water generation using an electric-driven continuous-flow water heater statistically accounts for 330–990 $kWh \cdot a^{-1}$ and $capita^{-1}$ in Germany (Deutsche Auftragsagentur [DAA], 2013), while generation by a gas-driven continuous-flow water heater adds up to 380–1140 $kWh \cdot a^{-1}$ and $capita^{-1}$ (Deutsche Auftragsagentur, 2013). Heating oil-driven continuous-flow water heaters consume 550–900 $kWh \cdot a^{-1}$ and $person^{-1}$ (Offel, 2013). Therefore, an average value for energy consumption by means of warm water generation can be set at 730 $kWh \cdot a^{-1}$ and $capita^{-1}$.

Costs of warm water generation differ depending on the kind of fuel, as well as the efficiency factor of energy conversion and heat loss due to distribution within the house. Regarding the average costs of power (0.23 $euro \cdot kWh^{-1}$ / in 2011 [source: Federal Ministry of Economics and Technology of Germany]), natural gas (0.065 $euro \cdot kWh^{-1}$ / from January–July 2013 (Verivox GmbH, 2013)) and light heating oil (0.085 $euro \cdot kWh^{-1}$ / from June 2012-June 2013 (Statista GmbH, 2013)) for private consumers, an arithmetic mean of 0.13 $euro \cdot kWh^{-1}$ was calculated. The warm water from the TES system, which is to be sold via district heating to a community of private consumers, has to generate a benefit for both the TES operator and consumers; otherwise, it might not be lucrative enough for consumers or a municipality, and they would not begin signing contracts and ordering warm water from the TES operator. Therefore, the price per kWh of energy is set to be 20% less than the average price per kWh of the most cost-efficient method of private continuous-flow water heater supply from the viewpoint of the consumers (natural gas); thus, the TES operator may charge 0.052 $euro \cdot kWh^{-1}$. In the case of electrical or heating oil supply, this would even reduce the consumer's cost on average by 38.82% (heating oil) and 77.39% (electricity). In the case of heating oil and natural gas, costs are further reduced since there is no need for energy conversion, therefore no efficiency factor, such as, for example, 0.84 (natural gas). The appointed value for selling warm water results in an annual total revenue of:

$$134{,}146\ MWh \cdot a^{-1} \cdot 52.00\ euro \cdot MWh^{-1} = 6{,}975{,}592.00\ euro \cdot a^{-1}$$

This indicates a turnover of 19,111.21 $euro \cdot d^{-1}$. Based on the market analysis (Section 3), the average purchase of electricity at 20.00 $euro \cdot kWh^{-1}$ is absolutely realistic. When signing a contract for the failure work acceptance with a wind power plant operator at even lower price conditions (depending on the legal position of the EEG and its feed-in compensation), and at the purchase of negatively priced power, where a future increase of occurrence is to be expected, the average electricity purchase price might be decreased to 10.00 $euro \cdot kWh^{-1}$. Therefore, the costs of power purchase for input to TES storage can be calculated (overall efficiency factor of 0.88209 minded):

$$152{,}078\ MWh \cdot a^{-1} \cdot 20.00\ euro \cdot MWh^{-1} = 3{,}041{,}560.00\ euro \cdot a^{-1}$$

$$152{,}078\ MWh \cdot a^{-1} \cdot 10.00\ euro \cdot MWh^{-1} = 1{,}520{,}780.00\ euro \cdot a^{-1}$$

Thus, at the predicted value of average costs of 20.00 $euro \cdot MWh^{-1}$, average electricity purchase costs add up to 3,041,560.00 euros annually or 8333.04 euros daily. While calculating far more fictively, with potential average energy purchase costs of

10.00 euro·kWh^{-1}, average electricity purchase costs of merely 1,520,780.00 euro·a^{-1} and 4166.52 euro·d^{-1} were determined.

Calculations of the profit, initial costs, and costs of maintenance of the TES system are neglected since the determination of these costs is part of further research activities:

6,975,592.00 euro·a^{-1}	*6,975,592.00 euro·a^{-1}*
- *3,041,560.00 euro·a^{-1}*	- *1,520,780.00 euro·a^{-1}*
3,934,032.00 euro·a^{-1}	*5,454,812.00 euro·a^{-1}*

In the case of average costs of 20.00 euro·MWh^{-1}, the profit is 3,934,032.00 euro·a^{-1} or 10,778.17 euro·d^{-1}. In the event of average costs of 10.00 euro·MWh^{-1}, which is quite visionary up to today, the profit increases to 5,454,812.00 euro·a^{-1} or 14,944.69 euro·d^{-1}.

If natural gas, as currently most common and most cost-efficient fuel for domestic warm water generation in Germany, is taken into consideration again, the average consumption per person can be assumed as 760 kWh·a^{-1} (380–1140 kWh·a^{-1}). When multiplied by the above stated efficiency factor of natural gas combustion for warm water heating (0.84), an arithmetical mean of 638.4 kWh·a^{-1} and capita^{-1} are fed into the water pipes of the houses. Thus, the total number of consumers that are supplied by the TES can be estimated as followed:

$$\frac{134{,}146{,}000\ kWh \cdot a - 1}{638.4\ kWh \cdot a^{-1} and\ person^{-1}} = 210{,}129\ people$$

At maximum performance of the TES, an estimated average of 210,129 inhabitants, or 52,533 households (2 adults and 2 children), of a major city can be supplied with warm water.

In Germany, most space heating in private houses is done by natural gas combustion (51%). The average annual consumption of natural gas for space heating per m² is 101.5 kWh (77–126 kWh·m^{-2} and a^{-1} [76]). A 4-headed household occupies an average of 126 m² in Germany (Deutsches Statistisches Bundesamt, 2009), which is 31.5 m² per person.

Theoretically, omitting the seasonal intermittence of space heating consumption, the following calculation can be performed:

$$101.5\ kWh \cdot m^{-2}\ and\ a^{-1} \cdot 31.5\ m^2 = 3197.25\ kWh \cdot a^{-1}$$

If added to the total hot water consumption mean value, 3957.25 kWh· a^{-1} are consumed per person in Germany. After multiplication by the natural gas combustion efficiency factor (0.84), 3324.09 kWh per person are estimated to reach the space heating and hot water distribution pipes within buildings in Germany. Hence, the following estimation results:

$$\frac{134{,}146{,}000\ kWh \cdot a - 1}{3{,}324.09\ kWh \cdot a^{-1} and\ person^{-1}} = 40{,}356\ people$$

A total of 40,356 inhabitants, or 10,089 households (2 adults and 2 children), can be supplied by the TES with hot water and space heating (district heating). This is equivalent to a medium-sized German town.

One big precondition for success and realization of this economic concept is perpetual market analysis and market observation, as well as having extraordinary skills in deciding about purchase at the right time, since slight mistakes can lead to forced purchase at the wrong time in order to fulfill the needs of consumers, resulting in less economic and higher prices.

5. Conclusion

The market analysis uncovered the frequent occurrence of surplus wind energy at certain times that leads to a relatively high generation of failure work (loss of electricity) and low, sometimes even negative, electricity rates on the EEX. The results of market analysis prevent losing track of the actual long-term objective, namely reaching maturity pertaining to an innovative and successful patent application and taking commercial advantage of the energy situation in Germany. Indeed, the potential for purchase of surplus wind energy and economically supplying private households with heat based on the idea of a district heating distribution system is immense, as the rough calculations stated (Section 4.1.2). Thus, this project could benefit both the consuming recipient and the TES operator because of low electricity purchase prices, low heat loss, and high efficiency factors, which combine to result in 20.0–73.4% lower heat prices for consumers. On the other hand, the estimated profit (excluding initial costs and maintenance costs) is highly promising, and is predicted at approximately 4 million euros (rough estimation). Quite opportunistically, there is even potential for up to approximately 5.5 million euros of profit, if the electricity market continues to develop along the path described in Section 3.

Naturally, prior to the large-scale practical implementation of the TES system, it is inevitable that numerous problems must be resolved at the research and development stages. Therefore, it is strongly recommended to initiate a funded research project to further investigate these aspects. Consequently, more detailed and reliable calculations are required to facilitate the initiation of this project.

The economic feasibility of the process is always of highest significance when it comes to energy storage. This means that before the TES is implemented, initial costs and the maintenance costs of the storage, plus the quantity of input, purchase prices, overall efficiency, and profit, must be continuously observed, considered, and calculated in detail in the subsequent development phases.

Further consideration regarding the utilization of the TES surface, which reaches above water level, leads to two ideas:

(1) In order to make the TES system even more appealing for a medium-sized city, sand could be spread across the surface and a beach area, containing a beach volleyball court and soccer field, as well as a recreation park, could be provided for tourists in the summer;

(2) Alternatively, a photovoltaic park, which provides additional direct heating for the TES, might be an optimal solution for usage of the top surface of the TES.

Thermal energy storage (TES) systems also offer significant potential for demand-side management by enabling end users to shift energy consumption from peak to off-peak periods, thereby reducing operational costs. For instance, several municipal utilities in Germany, such as those in Berlin, have implemented large-scale hot-water storage systems that utilize surplus electricity to generate and store heat during periods of oversupply. Similarly, private consumers with photovoltaic systems increasingly use excess solar power to produce domestic hot water in summer months. While reconversion of stored heat in water to electricity remains economically impractical due to low efficiency, high-temperature storage materials such as fireclay or volcanic rock, exemplified by Siemens' large-scale pilot systems, demonstrate promising prospects for cost-effective load shifting and integration of variable renewable energy sources.

One limitation of our study is that it is based on analysis of market price-related data that was generated from 2005 to 2013. The study's predicted outcome likely remains consistent with post-2014 results, owing to rising material, electricity, and government subsidy costs. Therefore, this study is also aimed at inspiring other scientists to explore and compare TES systems of present-day Germany, Europe, and even other parts of the world to our data, as it would be interesting to have a more detailed physical explanation of the applicability of the developed TES system in 2025.

In general, the business concept outlined promises to be highly successful on the basis of this investigation. In addition, by aiming to utilizing excess wind power, the TES effectively reduces CO_2 emissions in comparison to conventional power generation, which in turn reduces the environmental impact of power systems. Still, some risks remain due to heavy fluctuations in annual wind occurrence and unpredictable changes in the electricity market, which render accurate forecasting a challenging undertaking. One limitation of this study is that it is based on analysis of market price-related data that was generated from 2005 to 2013. The study's predicted outcome likely remains consistent with post-2014 results, owing to rising material, electricity, and government subsidy costs. Therefore, this study is also aimed at inspiring other scientists to explore and compare TES systems of present-day Germany, Europe, and even other parts of the world with our data, as it would be interesting to have a more detailed physical explanation of the applicability of the developed TES system in 2025.

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Nomenclature

a_m fraction melted
a_r fraction reacted

A_{st}	surface of the storage (m²)
e	heat effusivity ($J \cdot m^{-2}K^{-1}s^{-1/2}$)
c_{ap}	average specific heat capacity between T_i and T_f ($kJ \cdot kg^{-1}K^{-1}$)
c_{lp}	average specific heat capacity between T_m and T_f ($kJ \cdot kg^{-1} K^{-1}$)
c_p	specific heat capacity ($kJ \cdot kg^{-1}K^{-1}$)
c_{sp}	average specific heat capacity between T_i and T_m ($kJ \cdot kg^{-1} K^{-1}$)
c_{pw}	specific heat capacity of water ($kJ \cdot kg^{-1}K^{-1}$)
Δh_m	heat of fusion per unit mass ($kJ \cdot kg^{-1}$)
Δh_r	endothermic heat of reaction (kJ)
k	heat transfer coefficient ($W \cdot m^{-2}K^{-1}$)
l	layer thickness (m)
m	mass of heat storage medium (kg)
M	molar mass ($g \cdot mol^{-1}$)
P	performance (W)
Q	quantity of heat stored (J)
$\dot{Q}_l$	heat flux of heat losses (kW)
T	temperature (°C)
T_a	ambient temperature (°C)
T_f	final temperature (°C)
t_{heat}	heating time (s)
T_i	initial temperature (°C)
T_m	melting temperature (°C)
T_u	upper (maximum) temperature (°C)
T_{st}	storage temperature (°C)
V_w	volume of water (m³)

Greek letters

α	thermal diffusivity ($m^2 \cdot s^{-1}$)
η	efficiency factor
η_{he}	efficiency factor of the heating elements
η_{st}	efficiency factor of the storage (in terms of heat loss)
λ	thermal conductivity ($W \cdot m^{-1}K^{-1}$)
ρ	density ($kg \cdot m^{-3}$)
ρ_w	density of water ($kg \cdot m^{-3}$)

Abbreviations

a	year
BNetzA	Federal Network Agency of Germany
CAES	compressed air energy storage
CASC	Capacity Allocating Service Company
d	day
EEG	Renewable Energies Act (Germany)
EES	electrical energy storage
EEX	European Energy Exchange (Leipzig, Germany)
EMCC	European Market Coupling Company
ENTSO-E	European Network of Transmission System Operators for Electricity
EnWG	Energy Economy Law of Germany
FIFA	International Federation of Association Football
FIMan	Feed-In Management
h	hour

mo	month
MRC	minute reserve capacity
PCM	phase change material
PHPS	pumped hydropower storage
PV	photovoltaic
RE	renewable energies
SCPR	secondary controlling power range
TES	thermal energy storage
TSO	transmission system operator
VIP	vacuum insulation panel

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