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PAPER

Energy storage in residential and commercial buildings *via* Liquid Organic Hydrogen Carriers (LOHC)

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This contribution proposes the usage of Liquid Organic Hydrogen Carriers (LOHC) for the establishment of a decentralised energy storage network. Due to the continually increasing amount of renewable energy within the power grid, in particular in countries of the European Union, a huge demand for storage capacities develops that can hardly be met by large-scale systems alone. Because of their high storage density and good manageability LOHC substances permit the local storage of excess energy in residential and commercial buildings. Following the approach of a CHP system ('combined heat and power' or more precisely a 'combined heat and storage' system), thermal losses from the storage processes can be used for heating (and cooling) purposes in order to increase the overall efficiency. An evaluation of the economic feasibility identifies possible approaches to generate income from storage operation. The usage of exhaust heat for heating proves to significantly support the business case by providing a considerable financial contribution that is usually not exploitable for centralised storage units.

1. Introduction

Between the years 2000 and 2010 the generating capacity of renewable energies that exists worldwide has more than quadrupled from around 65 GW to 310 GW (excluding hydropower whose capacity slightly increased to approx. 1000 GW).[1] Altogether 22% of electricity is currently produced by renewable energies while many countries in the world strive for much higher shares in the upcoming decades. The European Union has announced the target share for renewable energy in electricity production to be 30–40% in 2020;[2] Germany tries to achieve a 50% share until 2030.[3]

A shared characteristic of energy production from renewable sources like wind or solar is their highly intermittent character which depends mainly on meteorological factors and can hardly be influenced or controlled. The so-called capacity factor of renewable electricity generation is very low in comparison to fossil-fuelled or nuclear plants. Therefore the on-going installation of massive capacities will cause energy overproduction in times of high loads from renewable energies and *vice versa* energy shortages under unfavourable weather conditions.

As a consequence more and more energy has to be stored in order to compensate for the fluctuating energy output. An estimation of the total storage capacity, which is necessary, is very

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Broader context

Worldwide efforts to raise the share of renewable energies necessitate the installation of massive storage capacities to compensate for their fluctuating energy output in the future. The mentioned storage demand cannot be satisfied by conventional technologies for electricity storage like pumped hydroelectric storage or batteries alone. Only chemical energy carriers provide sufficiently high storage density. Liquid Organic Hydrogen Carriers (LOHC) are liquid energy carriers that can be handled in the existing infrastructure for liquid fossil fuels and enable safe and efficient storage of energy. A contribution to the prospective overall storage demand could come from decentralised units like domestic or commercial buildings which participate in the trading of surplus energy. The thermodynamic and economic feasibility of these decentralised storage units can be significantly improved by the usage of the waste heat of the storage processes for house climatisation.

sophisticated and is strongly interrelated with the future expansion of electrical networks. While storage demand is still manageable for low shares of renewable energy, massive surpluses are expected beginning at renewable energy shares of around 40%.[4] Total storage demand in Germany in 2020 might account for up to 40 TW h [5] while in a 100% renewable energy system up to 170 TW h could be necessary by 2050.[6] All existing pumped hydroelectric storage facilities in Germany are limited to approx. 40 GW h due to the low storage density which is obtained by the technology where energy is stored solely mechanically.

While high power storage systems like flywheels, supercaps or batteries typically have storage cycle times of seconds or minutes only, many experts consider chemical energy storage technologies as most promising for the long-term storage of renewable energy.[7]

In this context the usage of reversible energy carriers could be a promising option. In contrast to common energy carriers (like coal, natural gas, *etc.*) reversible energy carriers can be easily recycled as the loading/unloading processes are reverse reactions. Energy can be stored *via* transition between an energy-lean and an energy-rich state. Different systems have been proposed and studied in the past decades, *e.g.* toluene–methylcyclohexane or metal hydrides. In the German language the term "Energie tragende Stoffe" (energy carrying substance) or ETS has been phrased for such reversible energy carriers that provide good manageability both in the energy-lean and energy-rich state and can therefore be easily handled.[8,9]

In regard to the efficient storage of hydrogen, "Liquid Organic Hydrogen Carriers" (LOHC) have been widely discussed and evaluated. Major activities have been located in Northern America,[10] Europe[11,12] and Japan. LOHCs are reversible energy carriers whereat the transitions between the energy-lean and the energy-rich states are carried out *via* hydrogenation/dehydrogenation of a liquid, easily manageable substance. The hydrogen carrying liquid – the carrier – is not consumed and can be used in many hydrogenation/dehydrogenation cycles. LOHCs and related concepts have been described in a variety of publications.[13–15]

In the following study heterocyclic aromatic hydrocarbons, like *N*-ethylcarbazole (NEC), are considered as carrier materials. These compounds have first been suggested by the company Air Products and Chemicals.[16,17] With regard to its thermophysical properties the corresponding perhydrocarbazole (H12-NEC) can be handled very similar to diesel fuel. As a consequence the complexity of handling, transporting and storing gaseous hydrogen is basically reduced to the handling of a liquid substance. It is expected that the existing infrastructure for mineral-oil-based fuels can be easily modified to such an extent that it can also be used for the distribution of LOHC.

As fully dehydrogenated *N*-ethylcarbazole is a solid at ambient temperature the dehydrogenation process is limited to a 90% discharge. Hence 5.3 wt% materials energy density can be achieved (theoretical limit is 5.8%). This results in a gravimetric storage density of approx. 1.75 kW h kg^{-1} (system storage density including the complete tank system is consequently lower).

The fundamentals of the hydrogenation and dehydrogenation reactions of *N*-ethylcarbazole are illustrated in Fig. 1. Extensive studies on this matter have been performed and published, amongst others by F. Sotoodeh *et al.*[18–21] Detailed studies about the lifetime and reusability of catalysts do not exist yet. For dehydrogenation Ahluwalia *et al.* assume a catalyst productivity of 500 000 kg LOHC per one kg of catalyst and catalyst costs of 150 Euro per kg.[22]

LOHC substances could play an important role in several parts of our energy system. Besides the storage of electrical energy as mentioned, the use of LOHC substances as clean fuel for mobile applications like for cars, trucks or ships is also envisaged for the future.

The focus of this publication lies on the implementation of an energy storage system for residential and commercial buildings or groups of buildings based on LOHC. The transition of the mainly fossil-fuelled energy system towards regenerative sources (in Germany called 'Energiewende' – 'energy sea change') has already shifted the role of buildings from mere energy consumers to energy producers (*e.g. via* rooftop photovoltaics). In a future energy system buildings could in addition support the integration of intermittent renewable energies by acting as decentralized energy storage facilities. As prices for electric energy are expected to fluctuate heavily in a largely regenerative energy system (due to drastically changing supply/demand scenarios as a function of weather conditions), a systematic buying and selling of electric power by 'energy-trading' buildings could support the business case for energy storage in buildings.

2. Description of the concept

The fundamental concept of decentralised energy storage in commercial and residential buildings is visualized in Fig. 2. Energy streams are depicted as red arrows, mass flows as blue arrows. In times of energy surpluses the mentioned decentralised storage system purchases electrical energy from the public power grid and produces hydrogen *via* electrolysis. The hydrogen is immediately used to hydrogenate an unloaded (that means dehydrogenated) LOHC system. No extensive buffer storage is used for gaseous hydrogen in order to minimize respective safety concerns.

Energy-trading buildings consume power from the power grid at times of low prices and overproduction. The stored energy can later be released when the load exceeds production and prices are accordingly high. The hydrogenated LOHC is then dehydrogenated and the hydrogen is used in a fuel cell or combustion engine to produce electrical energy. This electric power is either used to cover the energy demand of the building or it is 'sold' and fed back to the power grid. Depending on legal regulations

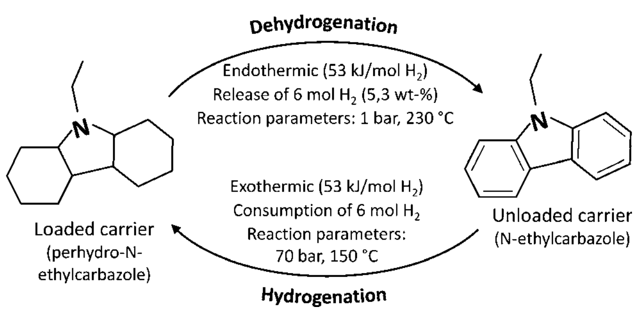

Fig. 1 Energy storage *via* hydrogenation and dehydrogenation of *N*-ethylcarbazole.

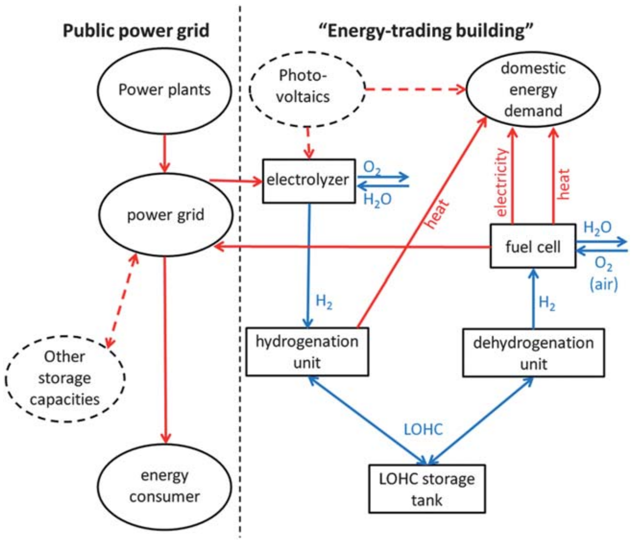

Fig. 2 Concept of decentralized CHP energy storage with fuel cells.

concerning energy storage it can in some cases even be reasonable to completely sell the electricity produced and to consequently cover the energy demand of the building by energy bought from the public power grid.

The mentioned concept asks for an electrolyser, a fuel cell, hydrogenation and dehydrogenation units, a tank for the LOHC system and a heat storage system. As another possibility the fuel cells could be replaced by alternative power generation units such as a gas engine. In principal, it should also be possible to integrate a PEM-fuel cell and a PEM-electrolyser in one single unit. The size and cost of the system could be decreased in this case.

The LOHC substance exists in different energy states: hydrogenated/loaded, dehydrogenated/unloaded as well as partially loaded intermediates. In a closed LOHC cycle, such as in a building, a second tank is not necessarily needed, because the different forms can be mixed. During hydrogenation the composition of the mixture changes towards a higher degree of hydrogenated products, similar to the charging condition of a storage battery. Many houses which use crude-oil based heating already possess a storage tank for oil-like substances. This tank could also be used for LOHC storage which would accordingly lower the investment costs.

Instead of purchasing electric energy from the grid, the storage system can alternatively use the energy coming from a roof-top photovoltaic system to load the LOHC. As an option, water produced from the fuel cell could be recycled for further usage in the electrolyser. In this case an additional water tank for processing water would be necessary. Storage of oxygen that is produced in the electrolysis is not recommended since an additional tank would be required, safety concerns would arise and the sale or further usage of rather small amounts of oxygen does not seem reasonable. Therefore the oxygen produced during electrolysis can be released into the atmosphere.

One advantage of the concept is the possibility to use exhaust heat generated by exothermic operations of the LOHC storage system for heating purposes – according to the concept of CHP (combined heat and power; in this case combined heat and storage).[23–25] As will be shown in Chapter 3 this increases the total efficiency significantly. The following heat sources are available:

- The hydrogenation of LOHC is highly exothermic and is carried out at temperatures of about 150 °C.
- Waste heat from the electrolyser (PEM, 80 °C).
- Waste heat from the fuel cell (either PEM at 80 °C, or SOFC at 600 °C).

The storage efficiency for LOHCs (electricity-to-electricity) is usually around 30–40%.[8] Hence, up to 70% of the energy is lost for electricity and converted to heat. The use of buildings for energy storage allows using this thermal energy for heating purposes. In summer – when no heating is needed – we propose to use the waste heat (in combination with an absorption refrigeration system) for cooling the building. The overall energetic efficiency can therefore be increased significantly. Otherwise, a water cooling system is required to remove the waste heat from the system during the warm season.

3. Energy balance and thermodynamic evaluation

The overall energetic efficiency of the proposed building storage system was evaluated by means of a process simulation. The required processes were modelled using Aspen Plus Version 7.3.

According to common usage efficiencies for electrolysis and fuel cells are based on the lower heating value (LHV) of hydrogen unless stated otherwise.

In this simulation a proton exchange membrane (PEM) electrolysis cell was used because it is considered as a promising technology to produce hydrogen with energy derived from renewable energy sources. Although hydrogen productivity is lower in comparison to alkaline electrolysis, the big advantage of PEM-electrolysis is the possibility to run it at partial loads and also at short-time overloads. The fast dynamic behaviour allows for a quick start-up to reach the operation temperature (80 °C). The same advantages are also valid for PEM fuel cells (FC) for electricity production. Therefore, this technology was considered as one option in this simulation. In addition to the PEMFC a solid oxide fuel cell (SOFC) was modelled. The big advantage of the SOFC is that it produces heat at a high temperature level (650–1000 °C). Hence this heat can be applied to fully drive the endothermic dehydrogenation reaction.

Energy either produced by solar cells on the top of the building or provided by the power grid when the price for electricity is low is used to run the electrolysis. An energy input of 15 kW is suitable for a demonstration project.

At state-of-the-art the PEM electrolysis is able to use 0.263 kW per cell with an electrical efficiency of 71% based on the lower heating value (LHV) of hydrogen. In this simulation a stack consisting of 57 single electrolysis units is used to attain a power input of 15 kW. It is assumed that both PEMFC and SOFC have electrical efficiencies of 55% (LHV).[26–28]

In Table 1 the side conditions of the simulation are summarized.

Table 1 Side conditions of the Aspen simulation[26,27]

Efficiency electrolysis (LHV)	71%
Efficiency fuel cell (LHV)	55%
Input electrolysis	15 kW

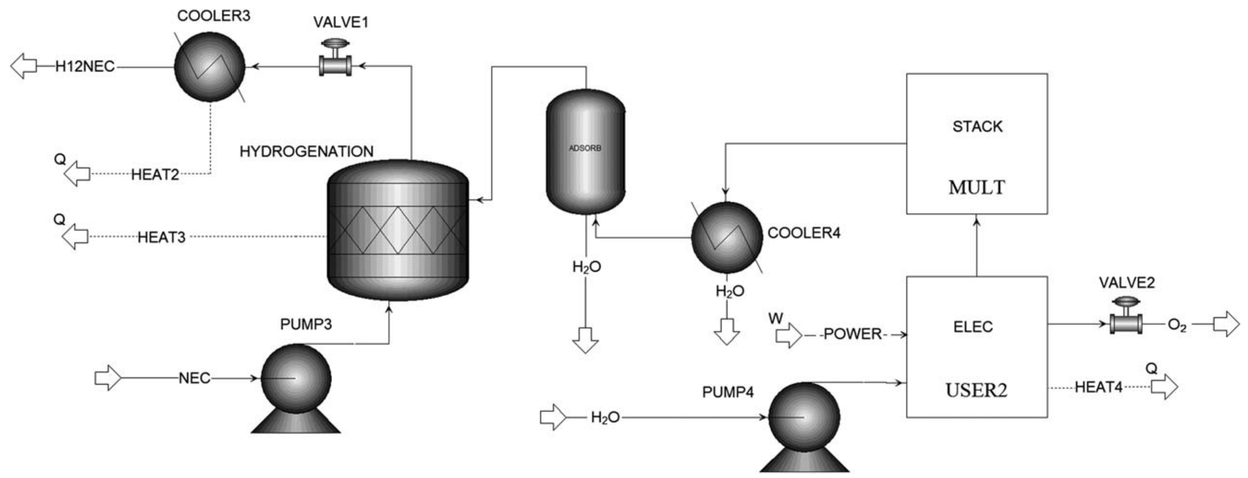

Fig. 3 ASPEN Plus flow sheet of the electrolysis and hydrogenation process.

The two sub-processes, energy production and consumption, are temporally separated (they never occur at the same time as either energy is stored or energy is released). Hence the simulation can be separated into two parts:

- Electrolysis and hydrogenation.
- Dehydrogenation and fuel cells.

Fig. 3 and 4 show the flow sheets of the Aspen simulations.

As high pressures (70 bar) are required for the hydrogenation of LOHC the electrolysis should work on a high pressure level (80 bar) in order to make an additional hydrogen compression redundant.

To attain that pressure in the electrolyser, the inlet water stream has to be pumped to a pressure level of 80 bar. It is assumed that the water stream reaches the operation temperature of 80 °C in the electrolysis without previous heating.

Before entering the hydrogenation reactor the remaining water is separated by condensation and adsorption. Therefore the hydrogen stream is cooled to 25 °C and pumped through the adsorption fixed bed reactor.

In the hydrogenation reactor NEC is completely converted to H12-NEC at 150 °C and 70 bar in the presence of a catalyst. As the hydrogenation is strongly exothermic the generated heat is removed by water cooling. The hydrogenated H12-NEC which leaves the reactor is finally expanded to 1 bar, cooled and delivered into the storage tank.

When electricity is needed either in the building itself or in the power grid (see Fig. 4), H12-NEC (or mixtures with partially loaded intermediates) is pumped from the storage tank into the dehydrogenation reactor where hydrogen is released in the presence of a catalyst at 230 °C and slightly above ambient pressure. The reaction is strongly endothermic with a heat demand of 53.18 kJ mol^{-1} H_2.[29]

At a temperature of 230 °C a certain amount of NEC/H12-NEC is in the vapour phase. To avoid bigger amounts of LOHC reaching the fuel cell, the stream leaving the dehydrogenation reactor is partially condensed in a vapour–liquid separation unit. The liquid uncharged NEC stream leaving the reactor is used to preheat the H12-NEC coming from the storage tank before entering the reactor. The purified hydrogen leaving the condenser is applied in a fuel cell to generate electricity. For this purpose air has to be compressed and fed to the fuel cell in a stoichiometric ratio. The fuel cell's operating pressure is slightly above ambient pressure. Because the reaction is exothermic, the fuel cell must be cooled.

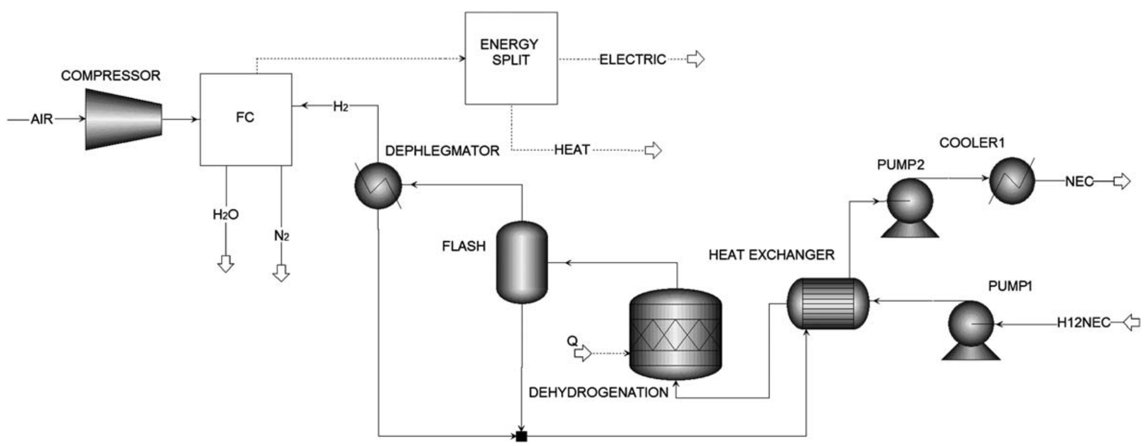

Fig. 4 ASPEN Plus flow sheet of the dehydrogenation and fuel cell process.

Table 2 Evaluation of the storage process

	Case 1	Case 2	Case 3
Electricity input electrolysis [kW]	15	15	15
Electricity demand process [kW]	0.1	0.1	0.1
Electricity output [kW]	5.7	3.0	4.2
Storage efficiency electrical [%]	38	20	28

Table 3 Temperature levels and heat fluxes from the heat sources (−) and to the heat sinks (+). Energy input electrolysis = 15 kW

Main heat sources	Temperature level [°C]	Heat flux [kW]
SOFC (case 1)	800	−6.8
PEMFC (case 2)	80	−6.8
PEMFC (case 3)	80	−5.5
Electrolysis	80	−2.5
Hydrogenation	150	−2.2
Dehydrogenation	230	+2.8

For an energetic evaluation of the process the electrical storage efficiencies were calculated. The electrical storage efficiency is defined as the ratio between the electrical energy output and the electrical energy input of the whole LOHC storage process:

$$\eta_{\text{Storage,electrical}} = \frac{P_{\text{el,output}}}{P_{\text{el,input}}}$$

An energy balance of the whole process was performed. Three different cases were defined with respect to the technology applied for producing power from hydrogen:

- SOFC: no additional heat for dehydrogenation is required (case 1).

- PEMFC: dehydrogenation is heated electrically with power generated from the process (case 2).

- PEMFC: dehydrogenation is heated by hydrogen generated from the process with a porous burner (case 3).

The results of the three scenarios are summarized in Table 2.

The electrical efficiency depends on the way the heat is provided for the dehydrogenation step. Case 1 implies that the heat produced by the SOFC is sufficient for the heating of the dehydrogenation process and that consequently no further heating is required. Thus electrical efficiencies of 38% can be reached. Electrical heating (case 2) is the most inefficient method to heat the dehydrogenation process. With electric efficiencies of only 20% this case is only reasonable in an early stage of process development. In future buildings the electrical heating could also be substituted by a porous hydrogen burner (case 3) which increases the efficiency to 28%.

The power consumption of auxiliary and supporting systems (like pumps) is comparatively low. An energy demand of 0.1 kW is assumed.

During the whole process heat is constantly being produced. There are a lot of different heat sources which are usable in an integrative heating system and therefore an extended storage efficiency evaluation must be performed. The produced heat allows heating in winter time and cooling in summer time using absorption refrigeration. Huge challenges for the heat integration lie within the different temperature levels of the heat sources and the temporal separation of the sub-processes. The PEMFC and the electrolyser are working at a temperature level of 80 °C while the hydrogenation is at 150 °C (lower temperatures are possible but come with a lower reaction rate). Using a SOFC the temperature difference would be considerably higher.

Table 3 summarizes the temperature levels and the heat fluxes from the main heat sources and to the main heat sinks. There is less usable hydrogen in the fuel cell in case 3 because a certain amount of hydrogen is consumed in the porous burner in order to heat the dehydrogenation step.

Fig. 5 shows all energy fluxes for case (1) – usage of an SOFC – in a Sankey diagram. The width of the arrows corresponds to the amount of energy of the corresponding flux. For hydrogen flows

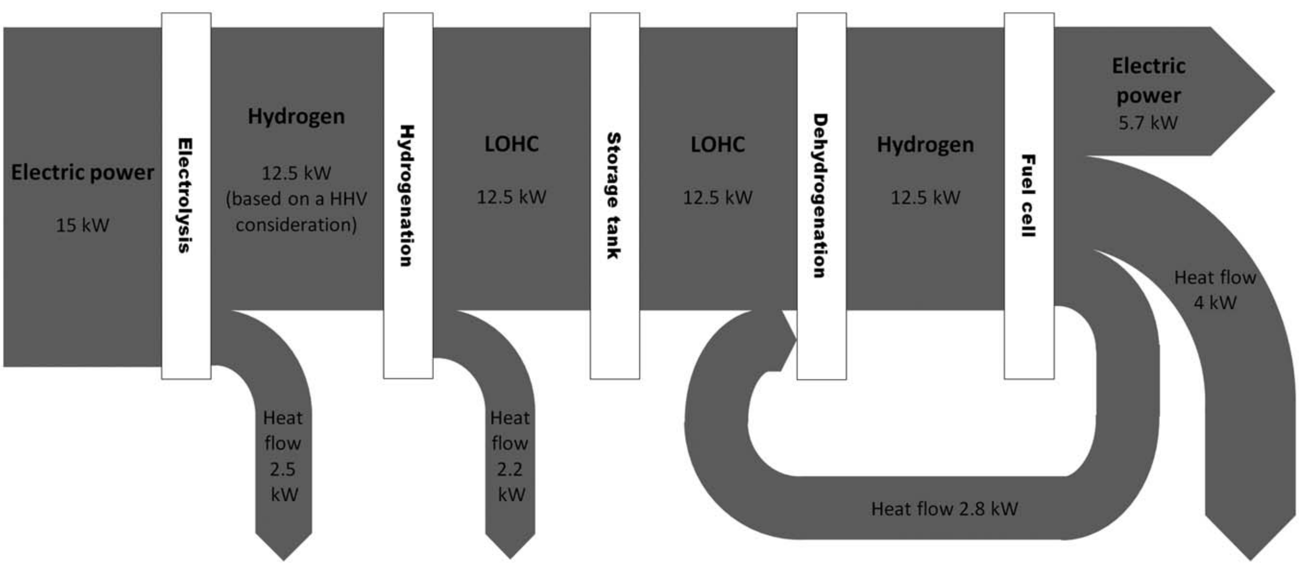

Fig. 5 Sankey diagram of energy fluxes of the complete process, case (1).

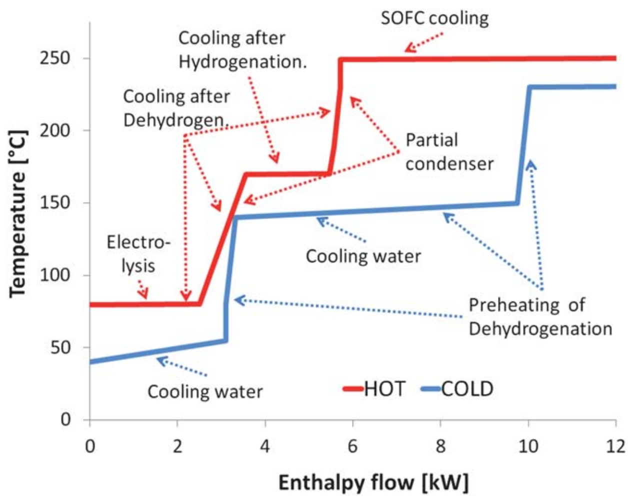

Fig. 6 Pinch analysis for heat integration.

the higher heating value (HHV) is used – otherwise output streams would not add up to the input stream.

Most of the heat that is produced in this process has a low temperature level of 80 °C. Nevertheless this temperature level is fully usable for the heating and cooling of buildings, a fact that makes the decentralised application of the LOHC energy storage technology in buildings particularly appealing. Today's heating installations use comparably low water supply temperatures in order to save energy. If a large heating surface area is used *e.g.* in floor heating installations, the temperature level that is required is below 50 °C.

Considering a combined heating and power generation process, maximum overall efficiencies of up to 95% could be reached. The total efficiency that is achieved as an annual average is expected to be lower than this value as in times with low heating demand (*e.g.* in spring), only some parts of the waste heat can be used.

To further evaluate the potential for heat integration within the described processes a pinch analysis was performed. The results are depicted in Fig. 6. The red curve describes hot flows which release energy while cold flows that require heat are in blue. The point of closest approach (in this case at 150 °C) is called the pinch point. The analysis shows that heat integration – where heat output from one part of the process can be used to cover the energy demand of another part of the process – is possible.

For simplification's sake the dynamics of the processes are neglected in this contribution. However, the usable amount of energy depends on the number of start-up and shut-down cycles. These factors influence the efficiency of the whole process and therefore have to be investigated in future dynamic experimental and modelling studies.

4. Economic evaluation

4.1 Possible business cases for energy storage applications

Although an increasing demand for energy storage clearly exists (see Introduction) this does not necessarily mean that there is also a profitable business case for potential operators of storage systems. The German feed-in-tarif law, for example, guarantees to the owners of renewable energy installation that the produced power can be delivered into the electric grid at all times.[30] Therefore, incentives for the storage of energy that intrinsically comes with additional costs and energy losses do not exist today.

Different energy storage applications have been analysed in regard to their economic feasibility.[31] Considering the characteristics of energy storage in residential and commercial buildings which are the focus of this contribution, possible business concepts are 'price arbitrage' and 'energy balancing'.

'Price arbitrage' describes leveraging the electricity price spread between periods of high and low electricity prices. Energy is being stored in times when electricity prices are low and discharged during high-price periods.

'Energy balancing' refers to the increasing need for shiftable generating capacities and consumers that can react within very short time intervals to balance any short-term discrepancies between energy production and load. Market mechanisms for the provision of balancing energy exist in many countries in the world; in Germany, the transmission network operators run a tender auction on a joint platform.[32] While the so-called primary and secondary reserves have to respond to any frequency deviations within very short time intervals (within milliseconds for primary and within 30 s for secondary reserves), minute reserves must be available within 15 minutes. The term 'positive' reserve refers to the provision of energy by generating capacities while 'negative' control power, on the other hand, implies that the operator of a storage unit or a controllable load agrees to act as a consumer of electrical energy when requested. Currently only units with more than 15 MW power can participate in the tender auctions for minute reserves in Germany. The concept of energy storage in buildings does not fulfil this criterion. Nevertheless, financial incomes by provision of negative control power are accounted for in the following calculations due to the following reasons: first, the demand for energy balancing is expected to increase significantly in the forthcoming years, consequently entry barriers might and should be lowered. More importantly, it is conceivable that within a "smart grid" that is currently being strived for in order to stabilize electrical networks, a multitude of smaller storage units could be pooled and could jointly provide control power.

As all storage operations come with inevitable thermal losses the usage of that energy for heating purposes enables additional income that is usually not accessible to large stand-alone systems.

The economic evaluation is performed under two basic conditions.

There are no assumptions made regarding public support, *e.g.* in the form of incentives for storage of energy. The economic evaluation is solely based on existing market mechanisms and prices.

A certain mix between control power provision and price arbitrage is proposed in the following in order to highlight different approaches to generate income from the storage operation. A detailed and elaborated operation strategy could also consist of only one type of revenue depending on actual market conditions.

4.2 Methodology and assumptions

Regarding the economic feasibility of energy storage *via* LOHC there exist only a few publications.[11,22,33]

The "Equivalent Annuity Method" is applied in this contribution to determine the financial impact of the capital investment and to evaluate its feasibility. In capital budgeting future cash flows are usually discounted to their 'Net Present Value (NPV)' to account for the differing points in time in which they occur. The initial investment for an asset locks up capital over a long time while future incomes must be discounted to their present values. The 'Equivalent Annuity Method' calculates the annualized cash flow of an investment by multiplying its net present value with the so-called annuity factor AF. An investment is economically feasible if the annuity is positive. An annuity of zero would mean that at least the invested capital plus interest is regained over the time span of the investment.

The annuity factor is defined as follows (i being the interest rate and n the number of years of usage):

$$\mathrm{AF}_{i,n} = \frac{(1+i)^n \times i}{(1+i)^n - 1}$$

Assuming an interest rate of 6% and a depreciation period of 20 years, the annuity factor equals 8.7%.

Revenues – provision of minute reserves. Prices for the provision of minute reserves are determined in a daily tender auction in Germany.[32] Storage operators can place bids for time slots of four consecutive hours. The prices of all accepted bids from the year 2011 have been analysed to determine the revenue that can be realized by the provision of control power. Table 4 shows the average prices for positive and negative minute reserves for every time slot in 2011. A 'capacity fee' is paid for the willingness to provide control power. If the minute reserve is called for delivery and energy is either consumed or produced (for negative or positive reserve respectively) by the storage facility, this is being paid in accordance with the 'energy price' as contracted.

The analysis shows that lucrative fees are only paid for the negative reserve during off-peak hours (8 pm to 8 am). In the following it is therefore assumed that the negative control power is provided in off-peak hours (87.3 EUR per MW per day which equals 31.9 EUR per kW per year). From the 2500 MW of negative control power that are regularly put out for tender, approx. 140 MW (5.6%) were actually accessed on average.[32] The capacity factor of control power provision is consequently assumed to be 5% (consequently the amount of energy that is stored during the 12 hours of control power provision per day is equivalent to the energy that would be consumed during 0.6 hours of full-load operation which equals 9 kW h per day).

Table 4 Results of 2011 tender auctions for minute reserves in Germany (own analysis based on published data[32])

	Positive reserve		Negative reserve	
Time slot	Capacity fee EUR/MW	Energy price EUR/MW h	Capacity fee EUR/MW	Energy price EUR/MW h
0–4 am	0.4	322	38.3	102
4–8 am	1.2	379	38.6	107
8–12 am	2.0	451	5.0	65
12–4 pm	1.8	431	6.0	65
4–8 pm	1.6	456	6.0	59
8–12 pm	1.2	407	10.4	71

For the mentioned energy trading building with an electric input of 15 kW, the provision of negative minute reserves in off-peak hours would consequently lead to annual revenues based on the capacity fee of 478 Euro and revenues through the kilowatt-hour based energy price of 306 Euro per year. It is assumed that the stored energy (reduced by the losses resulting from the 38% efficiency) can be sold at prices of 100 EUR per MW h which generates further revenues of 125 Euro. Total income from the provision of minute reserve adds up to 909 EUR per year.

Revenues – earnings through price arbitrage. As negative minute reserves are only provided during 12 hours per day the storage unit can be used for price arbitrage during the rest of the time (during peak hours).

The financial result of price arbitrage depends mainly on the price differential between input and output electricity and the energy losses occurring during storage. According to thermodynamic calculations in Chapter 3 the total efficiency of the process is limited to 38% (case 1), the building must purchase 2.63 kW h for 1 kW h of power output. In the following it is being assumed that power input occurs during times of excess energy production resulting in very low electricity prices of 3 Ct. per kW h. As future price developments are very difficult to predict there is no fixed sales price (and consequently price differential) assumed as input parameter for the evaluation of the economic feasibility in the following. The approach of this contribution is to – *vice versa* – determine under which conditions (regarding sales price and storage operating strategy) a profitable operation of the storage system is possible.

Revenues – heating. The heating of buildings is one of the main consumers of primary energy. In 2008 domestic and commercial buildings accounted for one third of total final energy consumption. More than 75% of that energy is being used for heating purposes (the rest is electricity).[2]

In the proposed concept exhaust heat that is generated during the storage process can be used for heating in winter and cooling in summer. The required amount of energy strongly depends on the quality of thermal insulation. While newly built low-energy houses potentially reduce energy consumption to as low as 40 or even 15 kW h m^{-2} a^{-1} for the so-called passive houses, an average German building requires 170 kW h m^{-2} a^{-1}. Old buildings without modern thermal insulation usually consume more than 350 kW h m^{-2} a^{-1}.[34]

The building in consideration has 150 m^2 of living area and consumes 170 kW h of heat per square meter per year. According to common prices for community heating or natural gas the value of the heat is assumed to be 10 Ct. per kW h.[35]

Costs – depreciation of capital investment for LOHC equipment. Based on a mass-production of the main components the total investment for the described equipment is assumed to be 40 000 Euro. Considering that a conventional gas- or oil-fired heater is not necessary anymore, the additional investment is approx. 30 000 Euro. To achieve comparability to annual cash flows the annuity is used that expresses the cost per year for owning and operating this asset. Based on an annuity factor of 8.7% the annual depreciation equals 2616 Euro.

Costs – operation and maintenance costs. For various other costs an annual amount of 250 Euro is assumed.

4.3 Presentation of results

Based on the described assumptions the annualized net present value of the investment is calculated depending on important parameters of operation.

Fig. 7 shows the annuity of operating an energy trading building depending on the electricity price spread between purchase and sales price (*x*-axis) and the capacity factor (*y*-axis). The latter describes the share of total annual time that the storage is in full-load operation regarding energy input. As the storage unit is used for provision of control energy half of the time and the stored energy (less the energy losses) needs to be fed back to the grid, 36% is the maximum capacity factor possible (50% control power, 36% energy input and 14% energy output).

The grey and orange-shaded areas on the left show operating conditions which lead to a negative annuity; the installation and operation of the described storage system would not be profitable under economic aspects in this region. The other areas show operating points where a positive result is achieved.

For comparison market data of the European Energy Exchange (EEX spot market auction) has been analysed in order to determine the amplitude and occurrence of price spreads during peak hours (8 am to 8 pm).[36] The curves in Fig. 7 show the average price spreads that could have been realized by buying electricity during the hours with the lowest possible prices and selling it (less losses from the storage process) at the highest possible prices. With increasing capacity factor, marginal and consequently average price spreads decrease.

For a more detailed understanding the composition of revenues and costs is shown in Fig. 8 for three different scenarios regarding price spread and capacity factor. The scenarios under consideration are shown in Table 5. Scenarios A and B describe combinations of price spread and capacity factor which correspond to the 2009 situation at the EEX and are therefore scenarios reflecting the current situation.

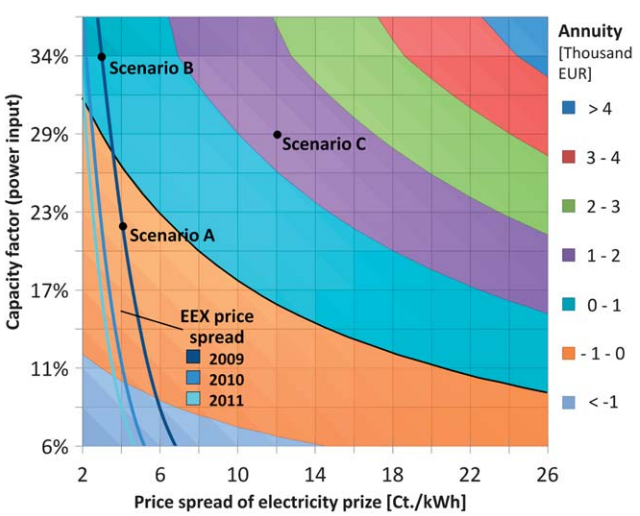

Fig. 7 Calculation of economic feasibility.

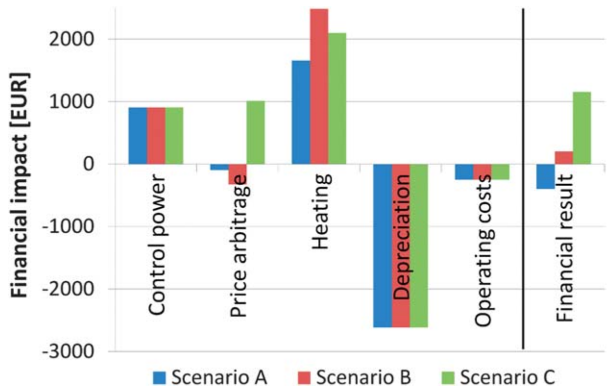

Fig. 8 Composition of annuity for different scenarios.

4.4 Discussion and evaluation of sensitivity

Evaluation of the economic feasibility of the proposed energy storage concept shows that positive business cases are possible but are strongly dependent on the assumed technical and economical parameters that will be discussed in the following.

Provision of negative control power. As mentioned earlier small storage units operating at sub-MW-power levels can currently not participate in the market for control power in Germany. It would therefore be necessary to develop both the technology and the legal basis to enable a multitude of small storage units to jointly provide control power. Regarding the high number of buildings that could be used for this kind of energy storage, the possible contribution of this decentralized energy storage would be very interesting. In the German state of Bavaria alone, there exist approx. 1.8 million households that are nowadays equipped with heating-oil fired heating systems and thus with potential LOHC tank capacities. Assuming that all of them would be switched to LOHC technology in the future, they could provide up to 27 GW of negative control power. Capacity fees for the provision of control power are likely to increase in the future.

Arbitrage based on electricity price spread. The financial assessment clearly showed that the price difference between purchasing and sales price is a crucial parameter regarding economic feasibility.

Price fluctuations which exist today at wholesale electricity markets (*e.g.* EEX) are currently not passed through to the end consumers of electric energy which is necessary for a reasonable business case.

The analysis presented in Section 4.3 shows that the prices for electricity in the year 2008 at the EEX could already enable a (slightly) positive business case when high capacity factors (with consequently lower price spreads) are applied (scenario B).

Table 5 Price scenarios for the economic feasibility study presented in Fig. 8

Scenario	Price spread	Capacity factor
Scenario A	4 Ct. per kW h	22%
Scenario B	3 Ct. per kW h	34%
Scenario C	12 Ct. per kW h	29%

It is very difficult to forecast future price developments. Nevertheless, it is very likely that the end consumers will deal with more heavily fluctuating electricity prices in the future due to the steadily increasing share of renewable energies and the planned introduction of 'smart grid'-technologies. This could lead to a significantly better financial performance (scenario C).

Usage of thermal losses for heating. The considerations show that waste heat from the storage process can be used for house heating. As the substitution of fuel oil or natural gas based heating renders the provision of these expensive energy carriers unnecessary the financial impact is rather high. In comparison to centralized energy storage facilities where it is hard to find reasonable applications for exhaust heat, the business case of 'Energy trading buildings' is significantly supported by the economic value of the produced heat. With the expected rise in the costs for oil in the future, this part may become more and more relevant (different scenarios have been considered in the sensitivity analysis, see Table 7).

The above calculations take into account that at low capacity factors only part of the total energy demand for heating can be satisfied by the exhaust heat of the storage processes. Table 6 shows the amount of heat that is generated depending on the capacity factor.

For old buildings (which consequently have high energy consumption) an increase of the installed storage power must be taken into consideration. To achieve 100% coverage of heat demand at a capacity factor of 30% the input power into the storage unit would have to be 20 kW (assuming a heat demand of 200 kW h m^{-2} a^{-1}) or 31 kW (for 300 kW h m^{-2} a^{-1}), respectively.

Depreciation of initial investment costs. The costs that are mentioned are realistic for a future mass production of the main components like the electrolysis/fuel cell system and the hydrogenation and dehydrogenation units. Especially in the early stages of development actual prices would be certainly higher.

The sensitivity of the profitability of the concept on the investment costs is rather high. As the annuity factor is 8.7%, an increase in investment cost by 1000 Euro reduces the annual profit of storage operation by 87 Euro.

Efficiency of power-to-power storage. An efficiency of 0.38 is realistic if a high temperature fuel cell is being used for which the exhaust heat can be used for the endothermic dehydrogenation process (as shown above). Electrical heating or burning of hydrogen in a porous burner respectively lowers the efficiency of the process. Lower efficiencies have a negative impact on the earnings based on price arbitrage. The profit per kW h input is

$$\text{Profit} = \eta p_{\text{out}} - p_{\text{in}}$$

where η is the efficiency and p is the electricity price for purchased (in) and sold (out) power. p_{out} can also be expressed over the price differential to input power: $p_{\text{out}} = p_{\text{in}} + \Delta p$

The minimum price spread that is necessary to achieve a positive profit from price arbitrage is:

$$\Delta p = p_{\text{in}}\left(\frac{1}{\eta} - 1\right)$$

For the mentioned parameters (efficiency 38%, $p_{\text{in}} = 3$ Ct. per kW h), this value is 4.8 Ct. per kW h. It must be considered that the usage of smaller price differences (resulting in a negative contribution from price arbitrage) might overall still be reasonable if it enables higher capacity factors with additional heat generation (this is the case in scenarios A and B).

Sensitivity analysis. Table 7 shows the results of a sensitivity analysis for the mentioned and further input parameters. The influence of investment cost, efficiency and heating price on the annuity of storage operation is particularly significant. For example the usage of a PEM fuel cell in combination with a porous hydrogen burner (case 3 from Chapter 3) instead of a SOFC would lower the annuity by 563 Euro (to 505 Euro) compared to the referenced scenario C with a SOFC fuel cell and higher efficiency.

Table 6 Amount of heat generated by energy storage processes

Capacity factor	Heat generation [kW h]	In % of total heat demand
10%	8441	33%
20%	15 208	60%
30%	21 975	86%
36%	26 035	102%

Table 7 Sensitivity analysis of important input parameters (based on scenario C)

Input parameter	Original value	Alternative value	Impact on annuity [EUR]
Investment cost	30 000 €	40 000	−870
		25 000	+435
Efficiency	0.38 (case 1)	0.2 (case 2)	−1013
		0.28 (case 3)	−563
Power reserve earnings	87 € per MW per day	120	+179
		170	+452
Capacity factor minute reserve	5%	1%	−481
		10%	+600
Heating energy demand	170 kW h m^{-2} a^{-1}	80	−901
		300	+0
Heating price	10 Ct. per kW h	12.5	+525
		25	+1050

5. Conclusion

As the demand for the storage of electric energy steadily increases a decentralised concept like the one proposed in this contribution offers a chance to realize high storage capacities. Buildings or group of buildings that are currently equipped with crude oil-based heating systems are especially suited for the installation of LOHC storage systems for two reasons. First, heating oil is nowadays most often used when domestic heating or natural gas based heating is not available. This is often the case in regions – for example outside of the big cities and in more rural areas – where also the installed capacity of intermittent producing renewable energies is comparably high. Secondly, there is enough space for the necessary equipment available in the boiler room while for example the existing oil tanks can also be used for LOHC.

These oil tanks usually have capacities of around 2000 liters and could therefore store the same amount of LOHC liquid which – fully loaded – carries around 3.2 MW h of energy. As mentioned above there exist approx. 1.8 million oil-fired households in Bavaria that – assuming a complete substitution by LOHC systems – could jointly store 5.8 TW h of energy with a possible negative control power of 27 GW. Extrapolated on Germany or even Europe this kind of decentralised storage capacity could provide a huge contribution to the total storage demand.

The efficiency of hydrogen-based electricity-to-electricity storage concepts is usually limited to 30–40%. As shown in Chapter 3 the total efficiency can be significantly improved if the waste heat from the processes is used for heating purposes. Buildings are particularly suitable for such a combined system as the temperature level of exhaust heat from the LOHC storage system is at least 80 °C, a level that is very useful to heat and cool buildings.

The described energy storage concept could be a promising option also for old buildings with bad thermal insulation that cannot be refurbished easily. They could cover their high energy demand with the exhaust heat of the proposed storage concept.

The economic evaluation has shown that the usage of thermal losses of the storage processes for house heating generates very valuable income (in terms of saving costs for conventional fuels). This opportunity does usually not exist for large stand-alone storage units where sufficient demand for exhaust heat does not exist. The analysis is based on today's energy prices and additional financial incentives have not been assumed. Increasing costs for heating as well as possible legislative measures to support energy storage would therefore further improve the business case.

5.1 Community storage systems

As an alternative to individual storage systems the installation of larger systems seems feasible. Such 'community'-storage systems could provide both electricity and heat for a larger group of buildings, *e.g.* for a small village or an urban district. Some of the mentioned aspects of energy storage (provision of control power, balance of heat and electricity demand, maintenance, investment cost, *etc.*) can be easily managed in larger units. These storage facilities would very likely not be operated by individual home owners but by companies, *e.g.* by the local network operators.

5.2 Possible link to mobile applications

As LOHCs are liquid substances which can be handled similarly to conventional liquid fossil fuels, the use of LOHC as a clean fuel in cars is also envisaged for the future.[37] Because of their high storage density, as compared to battery electric vehicles, LOHC could enable the realisation of long travelling distances in a zero-emission concept. The LOHC that was loaded in peak hours with cheap prices could be used to exchange the spent fuel of a LOHC car. The proposed concept therefore offers the potential to link the challenge of storing large amounts of renewable energy overproduction with the vision of a sustainable hydrogen-based mobility.

Notes and references

1 U.S. Department of Energy, 2010 Renewable Energy Data Book, 2011, http://www.nrel.gov/analysis/pdfs/51680.pdf.
2 F. Birol, *World Energy Outlook 2010*, IEA (International Energy Agency), Paris, 2010, http://www.worldenergyoutlook.org/publications/weo-2010.
3 Bundesministerium für Wirtschaft und Technologie, Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung, 2010, http://www.bmwi.de/BMWi/Redaktion/PDF/Publikationen/energiekonzept-2010.pdf.
4 M. Sterner, *Presented at International Renewable Energy Storage Conference 2011*, Berlin, 2011.
5 C. Pieper and H. Rubel, *Report Electricity Storage—Making Large-scale Adoption of Wind and Solar Energies a Reality*, The Boston Consulting Group, 2010, http://www.abve.org.br/downloads/BCG_-_Electricity_Storage.pdf.
6 M. Sterner, M. Jentsch and U. Holzhammer, *Report Energiewirtschaftliche und ökologische Bewertung eines Windgas-Angebotes*, 2011, http://www.greenpeace-energy.de/fileadmin/docs/sonstiges/Greenpeace_Energy_Gutachten_Windgas_Fraunhofer_Sterner.pdf.
7 Verband der Elektrotechnik, Elektronik, Informationstechnik (VDE), VDE-Study: Energy Storage in Power Supply Systems with a High share of Renewable Energy Sources, Frankfurt, 2009, http://www.vde.com/de/InfoCenter/Seiten/Details.aspx?eslShopItemID=fba0f864-3ea2-4ce4-beff-ba71dadc8d8d.
8 B. Müller, K. Müller, D. Teichmann and W. Arlt, *Chem. Ing. Tech.*, 2011, **83**, 2002–2013.
9 B. Müller, W. Arlt and P. Wasserscheid, *Energy Environ. Sci.*, 2011, **4**, 4322–4331.
10 DoE project Hydrogen storage by Reversible Hydrogenation of Liquid-Phase Hydrogen Carriers, Contract number: DE-FC36-04GO14006, http://www.hydrogen.energy.gov/pdfs/progress08/iv_b_2_cooper.pdf.
11 G. Scherer, E. Newson and A. Wokaun, *Int. J. Hydrogen Energy*, 1999, **24**, 1157–1169.
12 D. Teichmann, W. Arlt, P. Wasserscheid and R. Freymann, *Energy Environ. Sci.*, 2011, **4**, 2767.
13 R. H. Crabtree, *Energy Environ. Sci.*, 2008, **1**, 134–138.
14 L. Schlapbach and A. Züttel, *Nature*, 2001, **414**, 353–358.
15 U. Eberle, M. Felderhoff and F. Schüth, *Angew. Chem.*, 2009, **121**, 6732–6757.
16 Pez *et al.*, *World Pat.*, WO 2005/000457A2, 2005.
17 A. C. Cooper, Final report Design and Development of New Carbon-based Sorbent Systems for an Effective Containment of Hydrogen, DOE Award No. DE-FC36-04GO14006, http://www.osti.gov/bridge/ servlets/purl/1039432/1039432.pdf.
18 F. Sotoodeh, B. J. M. Huber and K. J. Smith, *Int. J. Hydrogen Energy*, 2012, **37**, 2715–2722.
19 F. Sotoodeh and K. J. Smith, *Ind. Eng. Chem. Res.*, 2010, **49**, 1018–1026.
20 M. Sobota, I. Nikiforidis, M. Amende, B. Sanmartin Zanon, T. Staudt, O. Höfert, Y. Lykhach, C. Papp, W. Hieringer, M. Laurin, D. Assenbaum, P. Wasserscheid, H.-P. Steinrück, A. Görling and J. Libuda, *Chem.–Eur. J.*, 2011, **17**, 11542.
21 K. M. Eblagon, D. Rentsch, O. Friedrichs, A. Remhof, A. Züttel, A. J. Ramirez-Cuesta and S. C. Tsang, *Int. J. Hydrogen Energy*, 2010, **35**, 11609–11621.
22 R. K. Ahluwalia, T. Q. Hua, J.-K. Peng, M. Kromer, S. Lasher, K. McKenney, K. Law, J. Sinha, TIAX-Report Technical Assessment of Organic Liquid Carrier Hydrogen Storage Systems for Automotive Applications, 2011, http://www1.eere.energy.gov/hydrogenand fuelcells/pdfs/liquid_carrier_h2_storage.pdf.
23 M. Salvador and S. Grieu, *Energy Build.*, 2012, **47**, 659–673.
24 H. Tischer, G. Verbic, *Towards a Smart Home Energy Management System - A Dynamic Programming Approach*, Innovative Smart Grid Technologies Asia (ISGT), 2011 IEEE PES, Date of Conference: 13–16 Nov. 2011.
25 NEC Corporation, Development of Large-scale Energy Storage Systems and the Strategy of Global Deployment, http://www.nec.co.jp/techrep/en/journal/g12/n01/120110.html.
26 K. Ahmed and K. Foger, *Ind. Eng. Chem. Res.*, 2010, **49**, 7239–7256.
27 A. Heinzel, *Chem. Eng. Technol.*, 2009, **81**(5), 567–571.
28 C. Heinlein, Bachelor thesis, University Erlangen-Nuremberg, 2012.

29 S. P. Verevkin, V. N. Emel'yanenko, A. A. Pimerzin and E. E. Vishnevskaya, *J. Phys. Chem. A*, 2011, **115**, 1992–2004.
30 German Feed-In Tariff law, Gesetz für den Vorrang Erneuerbarer Energien, http://www.erneuerbare-energien.de/files/pdfs/allgemein/application/pdf/eeg_2012_bf.pdf.
31 C. Pieper and H. Rubel, *Report Revisiting energy storage – There is a business case*, The Boston Consulting Group, 2011, https://www.bcgperspectives.com/content/articles/energy_environment_revisiting_energy_storage/.
32 German Internet platform for tendering control reserve, www.regelleistung.net.
33 A. Shukla, S. Karmakar and R. B. Biniwale, *Int. J. Hydrogen Energy*, 2012, **37**(4), 3719–3726.
34 Bundesministerium für Verkehr, Bau und Stadtentwicklung. Energieausweis für Gebäude nach Energieeinsparverordnung (EnEV 2009), 2009, http://www.bmvbs.de/cae/servlet/contentblob/34854/publicationFile/1046/enev-2009-lesefassung-nicht-amtliche-fassung.pdf.
35 I.H.K. Schleswig-Holstein, Cost comparison for domestic heating, 2011, http://www.ihk-schleswig-holstein.de/innovation/energie/zahlen_daten_fakten/734186/VEA_Fernwaerme_Preisvergleich.html.
36 European Energy exchange (EEX), spot market auction. Analysis of data from 2009-2011, www.eex.de.
37 D. Teichmann, W. Arlt and P. Wasserscheid, *Automobiltech. Z.*, 2012, 430–434.