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Integration of a LOHC storage into a heat-controlled CHP system

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ABSTRACT

In order to enhance efficiency of thermal energy supply in residential buildings, combined heat and power (short: CHP) systems are more and more replacing conventional heating systems. However, heat-controlled CHP systems either generate an excess of electrical energy, which is commonly fed into the power grid, or suffer from a lack of electrical energy, which has to be covered from the grid. In order to increase self-sufficiency and self-consumption, electrical energy storage should be integrated into a heat-controlled CHP system. Therefore, an electrical storage based on a Liquid Organic Hydrogen Carrier (LOHC) is investigated in this work. For this purpose a heat-controlled CHP system coupled with an LOHC system is modelled and simulated. The CHP system and the LOHC system were evaluated concerning key figures like self-sufficiency, self-consumption rate and primary energy demand. Moreover, a comparison between an LOHC system and a battery system was done. Both systems showed that with an additional electrical energy storage system the primary energy demand can be significantly decreased and the self-sufficiency and the self-consumption rate can be improved. Best results concerning electrical self-sufficiency could be achieved using a battery.

Both systems are able to reduce the primary energy equally, however with the LOHC technology slightly more primary energy can be saved.

1. Introduction

The market share of combined heat and power (short: CHP) systems has increased greatly in recent year. This increase is mainly caused by the necessity to reduce CO_2 emissions and save primary energy [1]. A CHP system provides electrical and thermal energy simultaneously, which both can be used e.g. in residential buildings. Therefore, a high overall efficiency can be achieved and CO_2 emissions and respectively the primary energy demand can be reduced [2–5].

CHP systems can be differentiated into current-controlled and heat-controlled systems. Current-controlled systems adapt their energy supply to the electrical energy demand of the consumer. In contrast to current-controlled systems, the focus of heat-controlled systems is on the supply of thermal energy. CHP systems that are used in domestic applications, for example to replace conventional heating systems, usually are heat-controlled systems.

The thermal energy is used to charge the thermal energy storage, which supplies the thermal energy demand of the consumer. In a heat-controlled CHP system the engine only supplies thermal (and thus electrical) energy if the thermal energy storage is fully discharged. As soon as the thermal energy storage is fully charged, the engine will be shut down. During charging of the thermal energy storage the electrical energy can be either used directly or, if electrical energy production exceeds demand, excess electrical energy is fed into the power grid. During engine downtime, the thermal energy supply is maintained by discharging the thermal energy storage and in state of the art CHP systems the electrical energy demand has to be covered by the power grid [4,6]. Such an operation can be economically reasonable e.g. under the conditions of the German CHP law. In other situations, measures should be taken to increase self-sufficiency and self-consumption.

To optimize the supply of electrical and thermal energy by a CHP system and to reduce unused excess electrical energy, a common approach is to determine a specific thermal energy storage capacity that enables both a heat- and an electrical-controlled CHP system [7]. This means that with a tailored thermal energy storage capacity the CHP system is able to fit its electrical energy supply to the electrical energy demand more properly without neglecting the thermal energy demand [8].

Another approach to reduce the excess electrical energy is to convert electrical energy into thermal energy. By using this method

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the electrical energy demand can be adapted to the electrical energy supply of the CHP engine. For this method electric heat pumps or electric chillers for air conditioning can be used, like it is described in Ref. [9]. If excess thermal or electrical energy is used for cooling purposes, these systems are called trigeneration systems. Chicco et al. reported [10], that with the use of excess energy from the CHP system the overall primary energy demand can be significantly reduced.

An alternative approach for excess energy reduction was examined by Barbieri et al. However, instead of using additional systems to convert electrical energy into thermal energy different CHP engine technologies were used. In their study different CHP engines, with different ratios between thermal and electrical power (i.e. different efficiencies) were examined to determine which engine is the most suitable option for a single family dwelling in order to avoid excess electrical energy [11].

In this work the effect of an additional electrical storage system (short EES) for storing excess electrical energy during the charging process of the thermal energy storage is studied. This energy is afterwards used to maintain the electrical energy demand during the engine downtimes. Electrical storage systems for CHP in form of a battery have already been investigated in the work of Motevasel et al. [12] and Bianchi et al. [13]. It was proven, that the integration of an additional EES in a CHP system can significantly improve the degree of utilization of the electrical energy. Moreover, these works show that excess electrical energy, which has to be fed into the power grid, can be reduced. For the EES in both works a battery was assumed as storage system. With respect to cycle stability as well as power and energy density conventional lead-acid, Ni-Cd, Ni-Metal hydride, Lithium Ion, and ZEBRA batteries were suggested for the use in residential buildings.

Despite of the common approach to use batteries for EES in residential buildings [14,15,16], in this research a hydrogen storage technology is investigated. Although, hydrogen storage technologies, unlike batteries do not store electrical energy directly, the use of hydrogen technology is also suitable for electrical energy storage in residential buildings, as it was shown by Santarelli et al. [17]. In this work a storage system, that consists of an electrolyzer, a fuel cell and a storage tank for compressed hydrogen was considered as a standalone energy system for residential buildings in remote regions.

In this work Liquid Organic Hydrogen Carriers (LOHC) have been examined for their suitability for integration into a CHP systems. The LOHC technology is based on the reversible hydrogenation of an organic liquid. Teichmann et al. [18] reported on LOHC storage and its benefits compared to conventional hydrogen storage. Thereby they demonstrated that with the usage of electrical and thermal energy from the LOHC storage system, this storage system can be an interesting alternative for electrical storage purposes in residential buildings.

An LOHC material that has come into the focus of recent research is dibenzyltoluene (short: H0-DBT) [19]. Using the H0/18-DBT system a gravimetric storage density of 6.2 wt% can be achieved. Its dehydrogenated form is an industrially well-established heat-transfer oil and therefore available at a relatively low prize. The reaction scheme of hydrogenation and dehydrogenation of DBT is depicted in Fig. 1.

The hydrogenation process is an exothermic process, which takes place at about 150 °C and 30 bar. The conditions for the endothermic dehydrogenation process are 300 °C and 1 bar [19]. The enthalpy of formation of the hydrogenation reaction is -68.1 kJ mol_{H2}^{-1} [20]. What makes LOHC especially interesting in the context of heat-controlled CHP is the fact of the exothermicity of the hydrogenation reaction. Hydrogenation is performed in times of surplus electrical energy, which occurs in times of high heating demand. Hence, the heat of the hydrogenation process can be used to cover parts of the heating demand. This reduces the fuel demand of the CHP engine and also the capacity required for storage of electrical energy.

The aim of this work is to investigate the interplay of a heat-controlled CHP system and an LOHC storage system within residential buildings. For this purpose a detailed model was established, which was simulated over a whole year using standardized load profiles for residential buildings, with a resolution of 1 min. Two options for the provision of the dehydrogenation heat are examined. Furthermore, two versions for the conversion of chemical bounded energy of hydrogen to electrical energy were examined. Additionally, the LOHC storage system is compared to battery storage. The entire system is evaluated in terms of self-consumption rate, self-sufficiency and primary energy consumption.

2. Organization and operating of an LOHC system with a CHP system

A schematic of a coupled CHP and LOHC system can be seen in Fig. 2.

If electrical energy supply exceeds the electrical demand, the excess is stored into the LOHC system. At a first step water is split with help of an electrolyzer for the generation of hydrogen. During the hydrogenation step the hydrogen is stored chemically on the LOHC. Subsequently the hydrogenated LOHC is stored in a storage tank. The hydrogenation reaction is exothermic.

Hence, the thermal energy released by this process can be used for heating purposes.

Depending on the temperature difference between the heat source and the heat sink, more or less heat can be recovered. However, perfect recovery of all heat does not seem to be realistic. To take this behavior into account a utilization degree of thermal energy from heat sources is introduced in the presented model.

By utilization the heat of the hydrogenation reaction the overall efficiency of the CHP system can be from improved. This is to the fact that the heat from the hydrogenation unit, in case of a heat controlled CHP system, is released at times when heating is needed. Thus, less exhaust heat from the engine is needed and therefore the fuel demand decreases. The electrical storage efficiency of the investigated LOHC system, including the efficiency of the electrolyzer and the fuel cell, is 18%. However, if waste heat from the storage process is used the overall storage efficiency can be increased to 52%.

The discharging process is subdivided into two major steps. First, LOHC is pumped form the storage tank into the dehydrogenation reactor. The dehydrogenation reactor operates at a temperature level of 300 °C and 1 bar [19].

Since it is an endothermic reaction, thermal energy has to be supplied. Therefore, two different options for endothermic heat supply were investigated in this work. Both systems were compared to each other, and it is evaluated which one is more suitable for the thermal energy supply of the endothermic dehydrogenation process in respect to save primary energy and achieve a high self-self-sufficiency.

The first possibility for thermal energy supply at the required temperature level is the combustion of a certain share of the released hydrogen in a hydrogen burner (compare Fig. 2a).

The second opportunity is the usage of a natural gas burner for thermal heat supply, since a supply of natural gas for the CHP engine already exists.

After the release, hydrogen has to be converted into electrical energy in a subsequent step. For this purpose it can either be utilized in a fuel cell, as shown in Fig. 2a and b or the CHP engine can

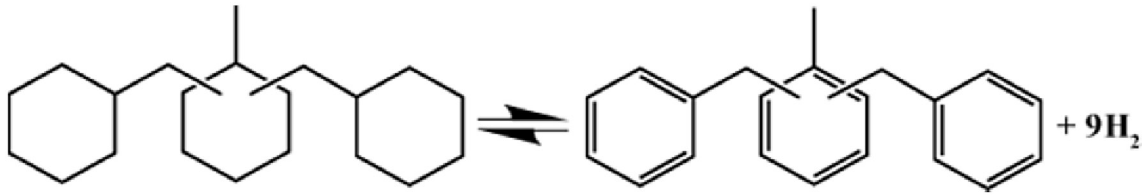

Fig. 1. The hydrogenated (H18-DBT) and dehydrogenated (H0-DBT) form of dibenzyltoluene [19].

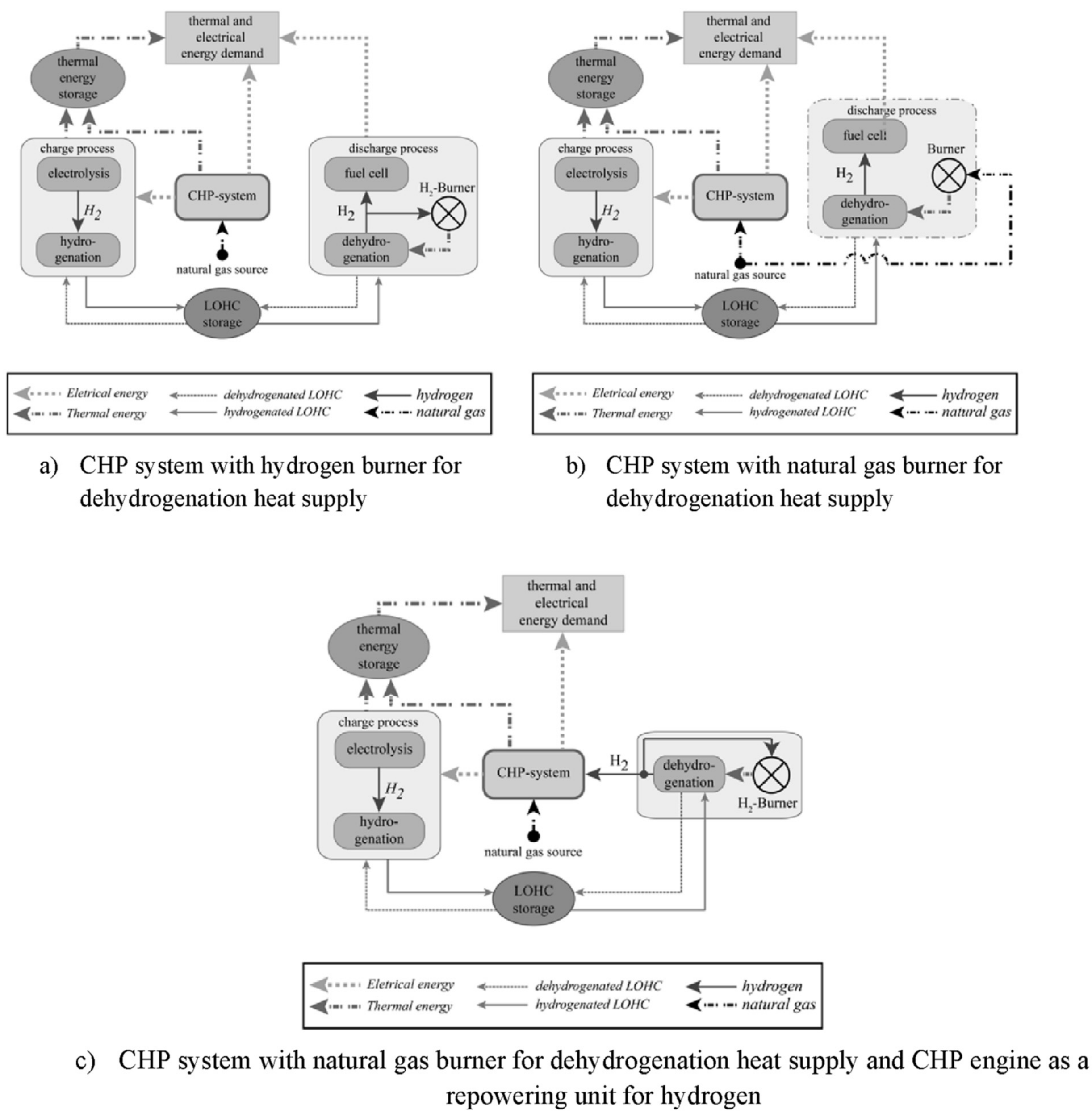

Fig. 2. CHP system coupled with an additional electrical energy storage system and its different variations.

be used for repowering (Fig. 2c).

This second method has the advantage, that no extra system is required for conversion of hydrogen to electrical energy, which results in lower system complexity and furthermore in lower investment costs. In this work both options were examined with regard to their ability to reduce the overall energy demand and possibility to increase self-sufficiency and self-consumption rate.

3. Model and simulation configuration of the LOHC/CHP system

MATLAB® Simulink was used for the dynamic simulation. The simulations were done with a time resolution of 1 min and a Runge-Kutta fixed step solver was used. The simulation time period was one year. The simulation consist of a CHP engine model, which delivers simultaneously electrical and thermal energy and calculates with help of a given efficiency the primary energy demand of the CHP system. In model applied in this work the CHP engine only operates at constant load and does not provide partial load behavior. Hence, if the thermal energy demand is satisfied, the CHP engine model is shut off. The model of the thermal energy storage is used to calculate the loading condition, which is used to determine whether the CHP engine has to be switched on or off. For the storage of electrical energy an LOHC system model was used, that calculates the amount of hydrogen which has to be stored in LOHC, depending on the electrical load or charge. For a detailed description of the model blocks, see the electronic Supporting information. Since the LOHC technology system is currently still under development, an experimental validation of the models were not performed.

4. Key figures

For the evaluation of simulation results different key figures were used. The self-consumption rate s describes the relation between the electrical energy which is used and the electrical energy which is supplied by the CHP system $E_{el,P}$ (Equation (1)). The used electrical energy can be further subdivided in electrical energy which is used directly by the consumer $E_{el,DU}$ and electrical energy which is used for charging $E_{el,Charge}$.

$$s = \frac{E_{el,DU} + E_{el,Charge}}{E_{el,P}} \tag{1}$$

As can be seen in Equation (1) the self-consumption rate describes which share of the own produced electrical energy is used within the respective residential building.

The self-sufficiency d (Equation (2)) describes the share of the electrical energy that can be covered by the CHP/LOHC system.

$$d = \frac{E_{el,DU} + E_{el,Disharge}}{E_{el,D}} \tag{2}$$

Again the equation consists of electrical energy which is used directly $E_{el,DU}$. However, this time the electrical energy, which is discharged from the storage system $E_{el,Discharge}$ is used. Moreover, the sum of both is now divided by the electrical energy demand $E_{el,D}$.

Additionally in this work the primary energy demand (Equation (3)) was examined.

$$PE = PE_{CHP} + f \cdot E_{el,powergrid} \tag{3}$$

This key figure PE describes the total amount of primary energy, which is needed to satisfy the energy demand of the residential building. The value PE_{CHP} is calculated from the combustion performance of the CHP engine and its runtime. In cases where the CHP system and if necessary the electrical storage system are not able to satisfy the electrical energy demand of the consumer, additional electrical energy from the power grid is required, which is described with the figure $E_{el,powergrid}$. Therefore, the overall energy balance has to take the primary energy for the CHP system PE_{CHP} and the primary energy demand for generation of electrical energy from the power grid into account. To combine these different energy forms a primary energy factor f is used. This factor describes how much primary energy on average is used to generate 1 kWh of electrical energy from the power grid. Based on a study of the German Federal Ministry for Economic Affairs and Energy the value of the primary energy factor f is stet to be 2.4 [21]. The primary energy factor varies between different countries, depending on which technologies are mainly used to supply electrical energy. Therefore, a sensitivity analysis is performed to analyze the influence of different primary energy factors.

5. Scenario

The following investigations of the CHP system and the LOHC storage system are based on the scenario of a single family house. The dwelling room size of the examined single family house was set to be 150 m^2. The typical specific annual space heating demand is 170 kWh m^{-2} a^{-1}. The annual energy demand of a three person household based on the German standard VDI 4655 [22] is given in Table 1.

The simulation of a heat-controlled CHP system with a battery storage showed, that with a thermal energy storage capacity of 30 kWh_{th} and an electrical storage capacity of 14 kWh_{el} best values for self-sufficiency, self-consumption rate and the service life of the battery and moreover for the CHP engine can be achieved. Therefore, all simulations were done with a thermal energy storage capacity of 30 kWh_{th} and an electrical storage capacity of 14 kWh_{el}.

6. Sensitivity analysis

For the most important key parameters a sensitivity analysis was performed to investigate the influence of these parameters to the key figures (see chapter 4). For this study the simulation model of the CHP system and an LOHC storage system with a hydrogen burner for supplying dehydrogenation heat was used. The sensitivity analysis concerning the battery efficiency and battery storage capacity was done with a CHP system and a Lead-Acid battery model (see Table 2).

The sensitivity analysis of the LOHC storage capacity shows, that a variation by ± 10% changes the self-sufficiency, the self-consumption rate and the primary energy demand less than 1%. The same behavior can be observed upon the variation of the battery storage capacity and the thermal energy storage capacity. Both key parameters were varied by ± 10%. However, only a change of the key figures below 1% can be observed. The utilization degree of the waste heat from the hydrogenation process was also varied between 0.40 and 0.95or respectively of about -50% and 19%. The simulation shows that in this chase the key figures change by maximal 1.5%.

The sensitivity analyses of the utilization degree of waste heat from the electrolyzer shows a stronger influence to the key parameters. However, in this case the utilization degree was increased by 80%, but even this change causes only a maximal change of 3.9% in primary energy demand.

The battery storage efficiency was also investigated and it shows that a small change of about 6% causes a change of about 3% in self-sufficiency and self-consumption rate but only 0.1% of the primary energy demand.

The primary energy factor, which is used to calculate the overall primary energy demand of the system, was also investigated. This factor only affects the primary energy demand. A change of ±25% of

Table 1
Annual energy demands for a single family house.

Annual energy demand	Single family house
Space heating demand	25,500 kWh
Domestic hot water	1500 kWh
Electrical energy demand	5200 kWh

Table 2
Sensitivity analysis for different key parameters.

Key parameter ξ	ξ	$\Delta\xi$		$\frac{ds}{d\xi}$	$\frac{dd}{d\xi}$	$\frac{dPE}{d\xi}$
LOHC storage capacity	14 kWh	15.4 kWh	10%	0.34%	0.48%	−0.09%
		12.6 kWh	−10%	−0.40%	−0.58%	0.10%
Battery storage capacity	14 kWh	15.4 kWh	10%	0.41%	0.44%	−0.10%
		12.6 kWh	−10%	−0.42%	−0.45%	0.10%
Thermal energy storage capacity	30 kWh	33 kWh	10%	−0.38%	−0.71%	0.03%
		27 kWh	−10%	−0.05%	0.34%	−0.03%
Utilization degree hydrogenation	0.80	0.40	−50%	1.1%	−1.1%	1.5%
		0.95	19%	−0.3%	0.4%	−0.6%
Utilization degree electrolyzer	0.5	0.30	−40%	1.2%	−1.4%	2.0%
		0.90	80%	−1.9%	3.3%	3.9%
Battery efficiency	85%	80%	5.9%	−2.9%	−2.9%	−0.10%
		90%	−5.9%	2.9%	2.9%	0.10%
Primary energy factor	2.4	1.8	−25%	–	–	−3.7%
		3.0	25%	–	–	3.7%

this factor results in a change by ± 3.7% in the annual primary energy demand.

7. Results

In the following, the simulation results of a CHP system with EES are presented. The impact of the LOHC system to the self-sufficiency, the self-consumption rate and the primary energy demand are examined. Furthermore, a comparison between an LOHC system and a Lead-Acid battery was performed.

7.1. Comparison of CHP systems with and without LOHC storage

To examine the impact of the additional EES, the CHP system was simulated with and without the LOHC storage.

The considered LOHC system uses a hydrogen burner for thermal energy supply of the dehydrogenation process, as it is shown in Fig. 2a.

For discharging 1 kWh_{el} of electrical energy from the LOHC storage system, performance analysis shows that the storage system has to be charged with 5.5 kWh_{el} electrical energy. This means that 4.5 kWh_{el} have to be applied for the storage process itself and can be considered as storage losses. Hence, a part of the storage losses can be expressed as useful thermal energy. The storage losses can be reduced by using the waste heat of the storage process. As a result of this recommendation 1.9 kWh of useful thermal energy can be obtained from the hydrogenation process.

The simulation results of the CHP system with and without the LOHC storage are depicted in Fig. 3.

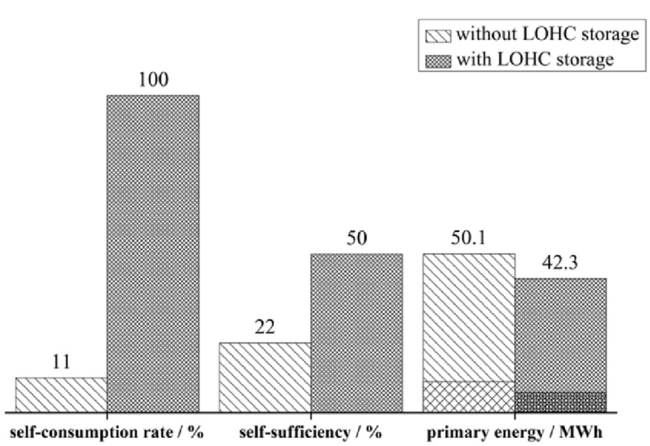

Fig. 3. Comparison between a CHP system with and without an LOHC storage system.

Without electrical storage only 11% of the electrical energy generated by the CHP system can be used by the consumer. This means that 89% have to be fed into the power grid. Compared to the CHP system with an LOHC storage system, the complete electrical energy which is supplied by the CHP system is used within the system and no overshoot of electrical energy has to be fed to the power grid.

Considering the self-consumption rate it should be taken into account, that the high consumption of electrical energy from the CHP engine can be caused due to a low storage efficiency.

With help of the LOHC storage the self-sufficiency of the system can be increased from 22% to 50%. The fact that the total electrical energy demand cannot be covered is due to two reasons. First, the ratio of heat to electric energy generated by the CHP engine is higher than the ratio in terms of demand. Second, the conversion of parts of the electrical energy into usable heat in the storage further shifts this ratio towards heat production.

The primary energy demand can be reduced by 7.8 MWh per year by integrating the LOHC storage. This is a reduction by 16% in comparison to a CHP system without an electrical storage system. This can be explained by the reduced electrical energy demand from the power grid and the usage of waste heat from the storage system. The share of primary energy from the power grid is highlighted with a cross pattern in Fig. 3. Furthermore, less fuel is needed for the CHP engine for producing heat, since the hydrogenation step also provides a certain share of the thermal energy demand.

To summarize the simulation results, it can be said, that the use of LOHC storage can significantly improve the behavior of the CHP system considering the use of electrical energy and the primary energy demand. These results are also consistent with the results of Motevasel et al. [12] and Bianchi et al. [13], since the reported that with an additional electrical storage system besides the improvement of the self-sufficiency, also the primary energy demand can be significantly decreased. Although, Motevasel et al. reported that a self-sufficiency of 100% can be achieved, results are comparable, since it must be considered that their system includes an additional energy source in form of a photovoltaic system.

7.2. LOHC storage system with a natural gas burner

As an alternative process option a natural gas burner was examined as thermal energy source for the dehydrogenation process, as it is depicted in Fig. 2b.

An advantage of this approach is, that the complete hydrogen can be used for the electrical energy supply and therefore the electrical storage efficiency can be increased by 12% points compared to the LOHC system with hydrogen burner.

The performance analyses showed that with this configuration 3.3 kWh of electrical energy and 0.81 kWh of primary energy have to be applied to the storage system, to discharge 1 kWh_{el} form this LOHC afterwards.

As could be expected the electrical storage efficiency increases from 18% of 30% by using an external energy source for the thermal energy supply of the dehydrogenation process.

The simulation results for the two different heating options are compared in Fig. 4. Due to the higher efficiency of the LOHC system with a natural gas burner the self-consumption rate of 91% is lower compared to the 100% self-consumption rate of the LOHC system with a hydrogen burner. However, in this comparison the lower self-consumption is positive, since it has to be attributed to lower storage losses.

In contrast to the self-consumption rate an increase of self-sufficiency can be observed if natural gas is combusted for dehydrogenation. The system with the natural gas burner reaches a self-sufficiency of 65%, whereas the system with the hydrogen burner only reaches 50%. This can also be explained by the higher storage efficiency of the system using natural gas combustion for dehydrogenation. This means that at same storage capacities, more electrical energy can be provided by the LOHC system that uses the natural gas burner for dehydrogenation heat supply.

The primary energy demand on the other hand is increased if an LOHC system with the natural gas burner is used. The additional need of primary energy which is needed for the natural gas burner is marked with gray color in Fig. 4. Since additional primary energy in form of natural gas is needed for the dehydrogenation process, the system with the natural gas burner has a slightly higher primary energy demand of about 500 kWh per year. Compared to the LOHC system with a hydrogen burner the primary energy demand increases by 1.2%, but is still 7.3% lower than without any electrical storage.

7.3. Fuel cell vs. combustion engine

For this comparison the fuel cell from the base case LOHC storage system was replaced by the CHP engine, as can be seen from Fig. 2c. With this modification system complexity and investment costs were reduced.

Using this system, it has to be considered, that at the beginning of the discharging process, the thermal energy storage is already fully charged and additional thermal energy produced by the engine cannot be stored anymore. Therefore, to avoid overcharging of the thermal energy storage, the filling level of the thermal energy storage must fall to 75% before the discharging process of the LOHC system begins.

A performance analysis showed that if 10 kWh_{el} of electrical energy are used for charging this system, 1 kWh_{el} of electrical energy can be discharged. Hence, the electrical storage efficiency is 10%, but by using the combustion engine of the CHP system more useful thermal energy can be supplied, compared to the LOHC system, which uses a fuel cell for the reconversion of hydrogen to electrical energy. This is due to the fact that the combustion engine has a higher operation temperature level than the fuel cell. Therefore, an energy analysis taking the utilization degrees into account shows, that about 59% of the electrical energy of the storage process is converted into thermal energy.

Considering this, it can be explain why the LOHC storage system with the combustion engine and the generator has the lowest annual primary energy demand (Fig. 5). Since in this system the largest amount of electrical energy, which is stored on the LOHC, is converted into useful thermal energy, the heat-controlled CHP system does not need that much of primary energy, as it is needed to cover the thermal energy demand by its own. Thus, compared to the LOHC and with the fuel cell about 1.4% of primary energy and compared to the CHP system without EES about 17% of primary energy can be saved. Again the share of the primary energy from the power grid is highlighted with a cross pattern. It can be seen, that the highest amount of primary energy from the power grid is used within the CHP system without an ESS.

The self-consumption rate for both systems with LOHC storage is 100%. In terms of self-sufficiency a decrease of 16% points has to be observed, compared to the fuel cell scenario due to the lower storage efficiency. However, compared to a CHP system without EES the self-sufficiency is still 12% points higher.

Although, the self-sufficiency of the LOHC system with a combustion engine and a generator is worse than an LOHC system with a fuel cell, this system can be considered as a worthwhile alternative, since lowest primary energy demand is achieved and the system uses the combustion engine and generator of the CHP engine instead of requiring an additional reconversion unit, such as a fuel cell.

7.4. Comparison of LOHC and a lead-acid battery

In the following the LOHC storage system is compared to a

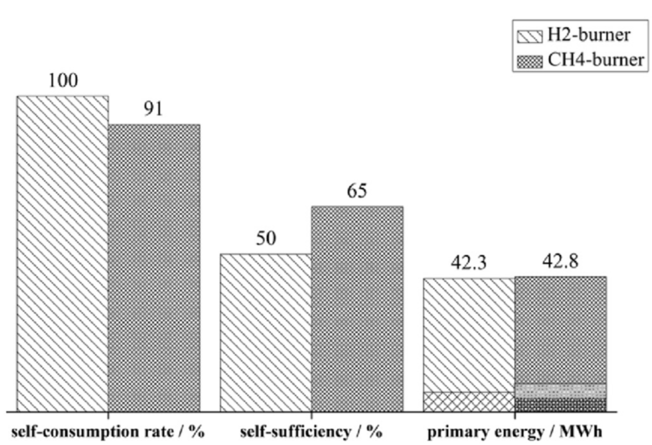

Fig. 4. Comparison between an LOHC storage system with a hydrogen burner and a natural gas burner.

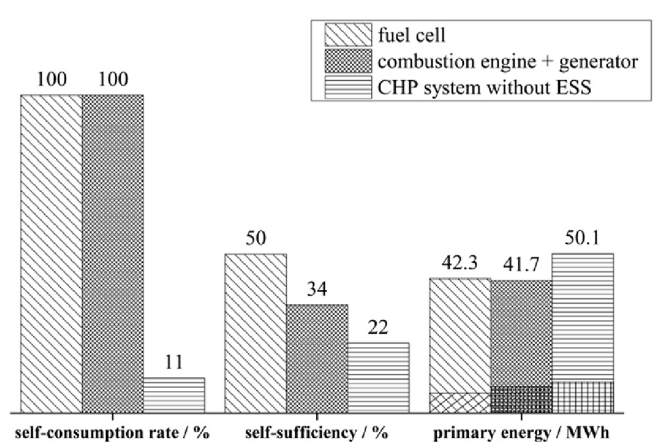

Fig. 5. Comparison between a CHP system with LOHC system with a fuel cell, with an LOHC system with a combustion engine + generator as a reconversion unit and without an electrical storage system (EES).

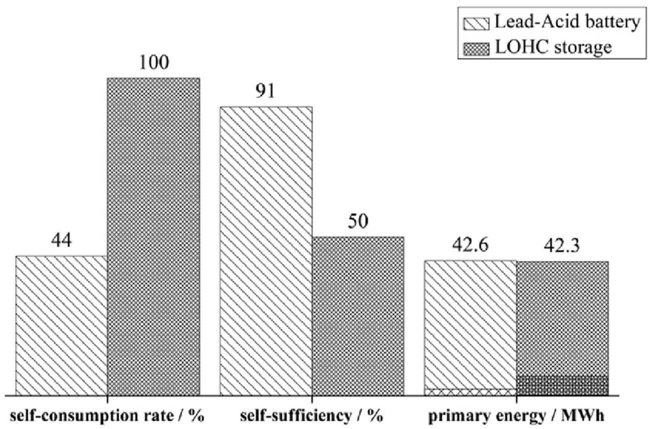

Fig. 6. Comparison between a CHP system with a Lead-Acid battery storage and an LOHC storage system.

battery storage system. Well established and commonly used battery storage types are lithium ion and lead acid batteries [23]. Compared to each other the lithium batteries have a higher storage efficiency and a higher storage density. However, they are much more expensive than lead acid batteries [24,25]. Thus, for further comparison between the LOHC storage and battery storage, the lead acid battery was chosen.

The efficiency of the Lead-Acid battery was assumed to be 85% [26] and the simulation of this system was done with the same capacity was assumed at the simulation of the LOHC system.

Comparing both self-consumption rates it can be seen, that less than half of the electrical energy from the CHP system with the battery storage are self-consumed, whereas 100% of the electrical energy from the CHP system are used with the LOHC system. However, it can be seen that the high self-consumption rate of the LOHC system is caused by the lower storage efficiency compared to the lead acid battery. Therefore, a high self-consumption rate cannot be generally regarded as positive. Hence, considering the self-consumption rate the storage efficiency has to be taken into account.

This behavior is due to the different storage efficiencies. Fig. 6 also depicts the simulation result concerning self-sufficiency and it can be seen that with the Lead-Acid battery a significantly higher self-sufficiency can be reached as with the LOHC system.

The simulation results for the primary energy demand show, that even though efficiency of the battery system is higher, the primary energy demand of the CHP system with the Lead-Acid battery is 300 kWh per year higher than for the system based on the LOHC technology.

The decrease of the primary energy demand can be explained by the usage of waste heat from the LOHC system. Utilizing the thermal energy from the charging process of LOHC, the CHP system itself does not have to supply the whole thermal energy demand by its one, which results in a lower fuel (i.e. natural gas) demand for the combustion engine of the CHP system and therefore a lower primary energy demand. However, since the difference between the primary energy demands is less than 1% and the sensitivity analysis shows that a small deviation of the battery efficiency and the utilization degree of waste heat changes the primary energy demand more than 1%, this result should be considered with caution.

8. Conclusions

With the integration of an additional EES in a heat controlled CHP system primary energy demand can be reduced and self-sufficiency and self-consumption rate can be significantly improved.

However, it was observed that a high self-consumption rate has to be considered carefully, since a high value can also be caused by poor storage efficiency.

Overall it can be ascertained, that the primary energy demand of the CHP system can be decreased by more than 16% with the help of an LOHC storage system. With this reduction the operational cost for the CHP system can be reduced and CO_2 emissions can be avoided.

As expected, high storage efficiency leads to a high self-sufficiency. Therefore, the highest self-sufficiency of 91% in this work was reached with a Lead-Acid battery, which was simulated with a storage efficiency of 85%.

Considering the annual primary energy consumption, with the base case parameter values the CHP system with LOHC based electric energy storage reaches almost the same values as a CHP system with a Lead-Acid battery system.

Although the storage efficiency cannot compete with the storage efficiencies of batteries, the LOHC system is able to improve the usage of electrical energy from the CHP engine and save primary energy.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2016.10.129.

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