Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 73 (2015) 272 – 280

Energy Procedia

9th International Renewable Energy Storage Conference, IRES 2015

Mobile Sorption Heat Storage in Industrial Waste Heat Recovery

Andreas Krönauer[a]*, Eberhard Lävemann[a], Sarah Brückner[a], Andreas Hauer[a]

[a]ZAE Bayern, Walther Meissner Straße 6, 85748 Garching, Germany

Abstract

Mobile energy storage systems working with Zeolite in an open sorption system can utilize industrial waste heat in cases where a pipeline bound connection is not cost sufficient. A demonstration plant using extraction steam from a waste incineration plant to charge the storage with 130 °C hot air and an industrial drying process as customer 7 km far away from the charging station was built, operated and monitored over one year. The storage contains 14 tons of Zeolite and uses at the discharging station exhaust air from the dryer with 60 °C and 0.09 kg/kg humidity to realize a storage capacity of 2.3 MWh, saves 616 kg carbon dioxide per cycle and shows no degradation within accuracy of the measuring equipment. Maldistribution through the packed bed of zeolite prohibit the desired power output. The prime energy costs can be reduced down to 73 €/MWh considering a small scale mass production.

Peer-review under responsibility of EUROSOLAR - The European Association for Renewable Energy

Keywords: Mobile Storage, Open Sorption System, Zeolite, Waste Heat

1. Introduction

The use of industrial waste heat to supply energy in remote locations is one way to reach better energy efficiency. Mobile energy storage systems transported by truck may bridge the gap between heat source and demand site in cases where a pipeline-bound connection cannot be realized cost effectively.

* Corresponding author. Tel.: +49 89 329 44213; fax: +49 89 329 44223.
E-mail address: andreas.kroenauer@zae-bayern.de

Peer-review under responsibility of EUROSOLAR - The European Association for Renewable Energy
doi:10.1016/j.egypro.2015.07.688

For the transportable heat storage unit, phase change materials or sorption materials are promising candidates due to their high energy storage capacity. Different basic studies on the economics showed, that it should be possible to operate such an energy distribution system cost effectively in cases with heat demand during the whole year.

Based on this result ZAE Bayern and its partner IndustrieanlagenHoffmeier GmbH started a project to develop and build a prototype of a mobile storage based on an open sorption system, working with a packed bed of zeolite as adsorbent. A pilot plant with a waste incineration plant as heat source and an industrial drying process as customer was built and operated for more than one year. The major aim of the project was to demonstrate the practicabillity of a mobile heat storage based on an open sorption process and to determine the costs per MWh of transported energy to run the system cost effectively.

2. Methods

A pilot plant with two storages was built to test the system under real conditions. The storage design process was already described in [1]. Fig. 1shows the air flow and the principle of the charging process. Heat source for charging is extraction steam from a turbine of the waste incineration plant which heats up ambient air to 130 °C with a steam/air heat exchanger. For better energy efficiency a heat recovery system with a cross flow air/air heat exchanger was installed, which saved around 1 MWh at each cycle.

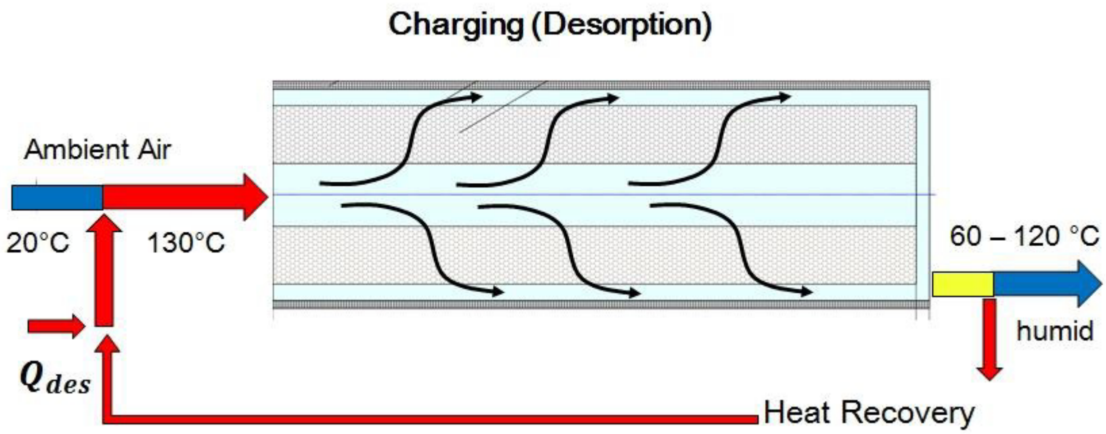

Fig. 1. Schematics of the chaging process with heat recovery.

Fig.2 showed the principle of the discharging process. The air flow through the storage is reversed compared to the charging process. This design minimizes the heat losses during charging and discharging because of the insulation effect of the packed bed. The zeolite storage is used as fuel saver to support the gas burner in the drying process and uses the humid exhaust air form the dryer to release the stored energy.

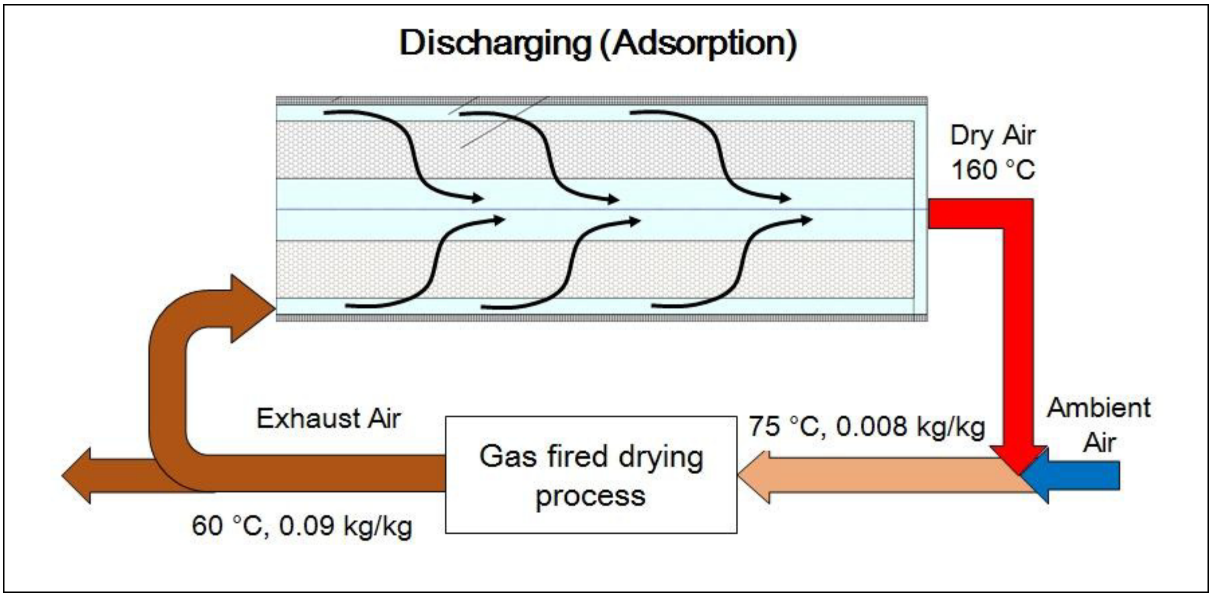

Fig.2. Schematics of the discharging process. The zeolite storage is used as fuel saver and supports the gas burner in the drying process.

To determine the performance data of two built storages, their operation over one year was monitored with extensive measuring equipment. An eventual degradation of the zeolite was tried to investigate by weighting the storage after each cycle to determine the water uptake, and by inspection of the packed bed.

A model for an idealized packed bed of zeolite was set up in MATLAB considering the heat and mass transfer between the air stream and the packed bed. The model was used to compare an ideal sorption storage based on zeolite with the built storage to determine how far away it is from the optimum.

To evaluate the economics the annuity method according to the VDI 2067 code was used to rate the investment costs, the costs to run (fuel and electric energy), and the costs to operate the system (labor and maintenance). This method makes it possible to combine investment costs and regular payments for a system, and disperse it equally over the period in which the system will be used.

Files must be in MS Word only and should be formatted for direct printing, using the CRC MS Word provided. Figures and tables should be embedded and not supplied separately.

3. Results

Table 1 shows the achieved performance data during test operation. Note that storage 1 made 99 cycles in total and storage 2 36 cycles. But not every cycle was suitable for evaluation because of their shortness, failures at the charging or discharging station or in the drying process.

Table 1: Performance data for both storages with their mean, max and minimum values obtained during the pilot operation.

		Storage 1 60 cycles 29 November 2013 – 30 September 2014			Storage 2 27 cycles 12 May 2014 – 30 September 2014			
	Line	Min	Max	Mean	Min	Max	Mean	Calculation
Aux. el. Energy demand Charging/kWh	1	132.80	185.95	156.04	140.20	178.20	154.07	
Aux. el. Energy demand Discharging/kWh	2	19.00	31.82	25.38	19.10	33.83	26.03	
Heat demand Charging/kWh	3	2569.50	5649.78	3959.64	2797.20	4349.20	3707.07	
Gas saving per Cycle/kWh	4	2255.00	4729.63	3800.64	2629.00	4680.93	3559.64	
Energyconversion @ Charging /kWh	5	-3600.54	-2364.98	-2731.60	-2884.56	-2434.50	-2673.22	
Energyconversion @ Discharging /kWh	6	1159.00	2836.78	2384.82	211.05	2660.65	2203.69	
Mean charging power /kW	7	209.60	285.15	225.29	199.40	240.40	219.29	
Maxn charging power /kW	8	301.79	502.90	392.13	299.60	468.70	399.21	
Mean discharging power /kW	9	60.25	187.69	154.63	111.70	182.28	157.35	
Max discharging power /kW	10	185.86	295.25	242.23	214.74	326.26	246.04	
Thermal loss @ Charging /kWh	11	36.59	86.81	49.58	13.40	51.64	43.06	
Thermal loss @ Discharging /kWh	12	19.00	73.25	40.99	23.61	44.17	31.74	
Total thermal loss per cycle /kWh	13	42.66	147.09	88.47	18.97	90.94	70.76	11+12
Charging time demand /h	14	10.70	13.58	12.13	11.10	13.70	12.16	
Discharging time demand /h	15	9.00	41.50	15.79	11.31	21.60	14.92	
electrical COP 1 /-	16	0.38	14.87	12.53	7.38	24.77	13.64	6/(1+2)
electrical COP 2 /-	17	0.59	26.06	19.68	14.05	152.67	26.66	4/(1+2)
Thermal COP 1 /-	18	0.02	0.93	0.59	0.35	1.14	0.66	6/3
Thermal COP 2 /-	19	0.02	1.41	0.92	0.67	1.61	1.03	4/3
Tranportation COP /-	20	1.16	59.12	44.32	32.86	58.51	44.50	4/80[kWh]
Gas savings with heat recovery at user site	21	23.16	1414.17	903.16	582.33	2275.02	949.16	(4-6)*0,7
Power factor for Charging	22	0.45	0.73	0.58	0.47	0.72	0.55	7/8
Power factor for Discharging	23	0.26	0.79	0.64	0.36	0.76	0.64	9/10

The heat demand in Table 1refers to the steam used for charging. The gas savings (Line 4 in Table 1) describes the benefit for the user, which includes the heat recovery ability of the storage. To calculate the transported energy the reference temperature for the gas savings is the ambient air temperature, because this is the air the drying process normally uses. The reference temperature to calculate the energy conversion value for discharging (Line 6 in Table 1) is the air inlet temperature of the storage.This energy value describes the energy delivered by the storage without the heat recovery effect. As it can be seen in Fig. 3, the difference between the air outlet temperature of the storage (T_G_exp Air Outlet) and the ambient temperature is bigger than the difference between air outlet temperature and the air inlet temperature of the storage (T_G_exp Air Inlet). The difference in temperature corresponds directly with the calculated energy value. Line 21 in Table 1shows the pure heat recovery potential of the discharging station if instead of the sorption storage a heat exchanger is used. For the transportation COP a fuel demand of 80 kWh for transportation was generously assumed. Thermal COP`s below 1 indicate, that it is important to use waste heat for this application, or install a better heat recovery system (which was not in budget) or use higher charging temperatures to improve charging performance. A comparison between the performance figures of both storages shows, that they are nearly identical. The carbon dioxide savings are 616 kg per cycle calculated with gas savings of 3.5 MWh per cycle and taking into account that the electric energy at the charging station has only 60 % of the carbon dioxide emissions compared to conventional electricity because of the biogenic fraction in the waste. One problem for the evaluation of performance data was that at the discharging station a drying process not working in a steady state defined the power delivered by the storages. So, the storages were not often discharged with full power. To compensate this influence some special performance test were carried out, to compare the built storages with the ideal sorption storage modeled in MATLAB.

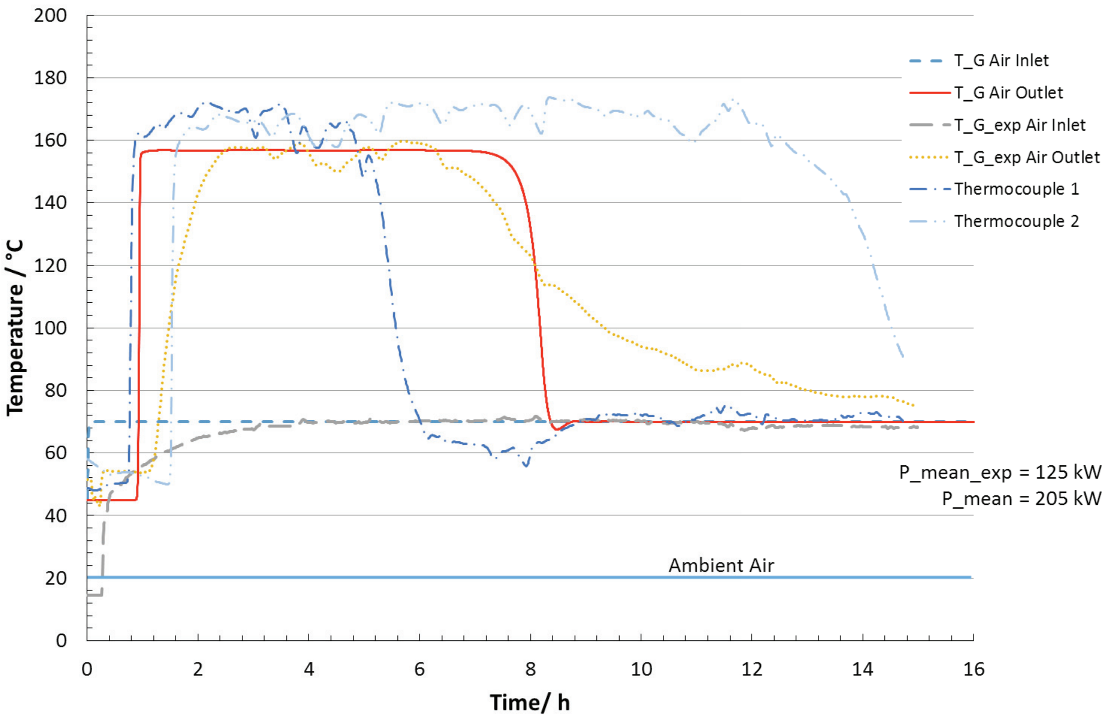

Fig. 3. Comparision between real storage and the ideal sorption storage.

Fig. 3 shows the results of one performance test compared with the simulated data. Input for the MATLAB model were the mean air inlet data of the experiment (see T_G Air Inlet in Fig. 3), and it calculated the Air outlet data of the ideal sorption storage (see T_G Air Outlet in Fig. 3). The comparison in Fig. 3 shows a steep rise for both nearly at the same time. The time delay for the temperature rise after starting the discharging process is caused by a sensible heat up of the packed bed. After a short time a temperature plateau at 160 °C is reached, which lasts different times in the simulation and the real storage. The air outlet temperature of the real storage begins earlier to drop as in the simulation, and the evolution is not as steep, too. This indicates maldistribution of the air flow through the packed bed. To monitor this phenomenon, 88 thermocouples were installed within the packed bed. Thermocouple 1 and 2 in Fig. 3 are two of them and illustrates clearly the maldistribution. The air flow through the segment which is monitored by thermocouple 1 is about twice as big as through the segment which is monitored by thermocouple 2. This discrepancy in the air flow caused an earlier temperature drop at thermocouple 1 and a later one at thermocouple 2. The result of this maldistribution is an earlier but slower decrease of the air outlet temperature of the real storage. This means, that the mean power of the real storage during discharging is lower as in the simulation and more time is needed to discharge the storage completely. A good indicator for benchmarking the storage is the ratio of the mean power during the discharging process from the model and the experiment. It is 0.61 for the performance test which is showed in Fig. 3. Compared to the mean value in Line 23 in Table 1 it is lower. The reasons are the not steady state operation of the drying process and the fact that it was not possible to deliver the energy at full power capacity. Therefore it was possible to decrease the air flow through the storage during the time where it delivers its energy at the temperature plateau, and to increase the air flow when the temperature drop of the air outlet begins. However at the performance test the air flow remains constant. The same comparison can be made for the charging process, but the chosen Zeolite 13 X optimizes the discharging process with its steep temperature evolution at the air outlet. At the charging process, the temperature evolution of the air outlet of the ideal storage is much less steep at the given charging temperature of 130 °C. The difficulties to measure all necessary data accurate enough makes the charging process not favorable for a comparison to the ideal sorption storage.

Table 2 Parameters and boundary conditions for the economic calculation. All performance data are mean values according to the operation over on year.

Storage	Unit	Value
Energy density	kWh/t	0.33
Zeolite mass dry	T	14.0
Energy content storage	MWh	4.6
Number of storages	-	2
Charging time per storage	h	15.6
Discharging time per storage	h	19.5
Electricity demand @ charging	MWh/cycle	0.221
Electricity demand @ discharging	MWh/cycle	0.026
Steam demand @ charging	MWh/cycle	5.85
Costs		
Invest costs per storage including zeolite	€	89500
Invest costs discharging station	€	122500
Invest costs charging station	€	112000
2 Trailer	€	34000
Transportation costs	€/h	45.5
Costs auxiliary energy @ charging	€/MWh	40
Costs auxiliary energy @ discharging	€/MWh	80
Electricity loss caused by steam extraction from turbine	MWh/MWh	0.1
Costs for steam	€/MWh	4.0
Boundary conditions		

Simple Distance	km	7.0
Cycles per year	cycle/a	240
Transported energy per year	MWh/a	1104
Time for storage handling and transportation	h	1.5
Finance conditions		
Interest rate	%	5.0
Periode of consideration	a	15
Maintenance factor	%	1.0
Rate of price increase (labor, electricity)	%/a	2.0
Rate of price increase (conventional energy)	%/a	5.1

The water uptake was subject to the seasonal weather fluctuations and the not steady state working conditions at the drying process, caused by the humidity variation of the drying goods. Therefore the water uptake sometimes fluctuated more the 10 % between two cycles what it makes difficult to come to a valid conclusion. The monitoring over one year shows not a clear trend of a decreasing water uptake capacity from the zeolite. The inspection of the packed bed through the air inlet connections showed no damage to the zeolite pellets because of mechanical stress.

Table 2shows parameters and boundary conditions used to calculate the economics. All performance data are values obtained during the operation of the pilot plant. The costs of the charging station may vary from application to application. All costs in Table 2are project costs taking a price drop of 30 % into account, considering a small scale mass production. The energy density of the zeolite given inTable 2can be achieved with the use of Zeolite 13 X and a charging temperature of 250 °C.

The electricity loss caused by steam extraction from the turbine is considered in the steam demand for charging in Table 2. The auxiliary energy demand per storage cycle includes the electricity demands of charging and discharging station. The time demand for handling and transportation refers to an optimized scenario with two separate trailers for both storages, and includes transportation and handling time at the station for both storages at one cycle. The used swap body system was very time consumptive because of the intensive handling work at the stations. The charged storage is delivered to the station and parked. The discharged storage is then loaded on the trailer, carried away from the station and parked. Then the charged one is loaded again on the trailer and parked at the station. Fig. 4showsbothstorages at thisprocess.

Fig. 4. Storage exchange at the discharging station. The storage handling system is based on heavy load swap bodies.

After that, the discharged one was loaded again and carried away to the other station. This park and loading work caused about one hour additional time demand for the handling per cycle. The transported energy in a year is 1,104 MWh/a assuming one cycle a day, consisting of charging one storage and discharging the other and 20 cycles per month during the whole year. Prime energy costs for this setup are 73 €/MWh and are dispersed to 62 % at the investment and 38 % at the running costs. To determine the influence of the operation conditions a sensitivity analysis was carried out. Table 3 shows the parameter range used for the sensitivity analysis and the resulting prime energy costs.

Table 3. Parameter Range for the sensitivty analysis and resulting prime energy costs.

Sensitivity		50 %	75%	100%	125%	150%
Transportation time	h	0.75	1.125	1.5	1.875	2.25
Prime energy costs	€/MWh	66	70	73	79	83
Cycles per Year	-	120	180	240	300	360
Prime energy costs	€/MWh	122	90	73	65	59
Storage Capacity	MWh	2.3	3.45	4.6	5.75	6.9
Prime energy costs	€/MWh	147	98	73	59	49

For better illustration the results of the sensitivity analysis are plotted in Fig. 5.

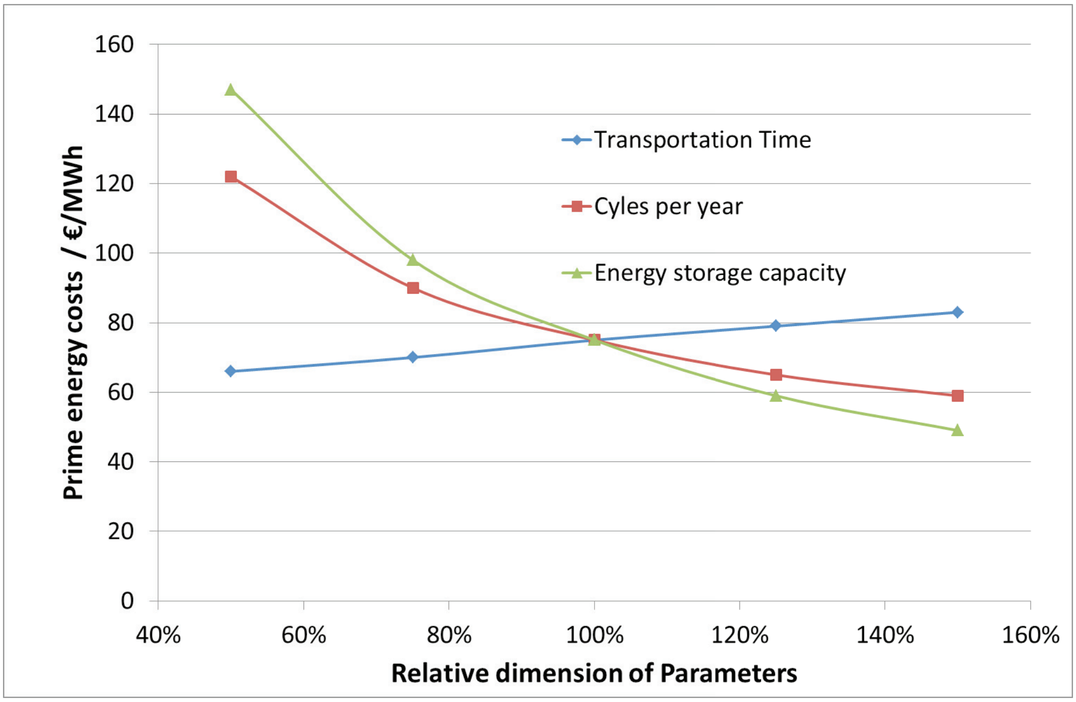

Fig. 5. Influence of the transportation time, the annual amount of cycles and the energy storage capacity to the prime energy costs.

The energy storage capacity has the strongest influence on the economics. Therefore it is necessary to charge the storage with sufficient temperatures and to transport as much as sorbent in the storage as possible. The annual number of cycles is important too. If an application with only seasonal heat demand is supplied, which correspond to the 50 % scenario in Fig. 5 the prime energy costs rises by 61 %. The transportation costs have only a linear and not so strong influence to the economics.

4. Conclusion

In this project a road legal mobile storage system for waste heat utilization based on zeolite was designed, built and operated for more than one year as a fuel saver in a drying process. The built storage achieved the calculated energy capacity of 2.3 MWh, but not the desired power output figures because of maldistribution through the packed bed of zeolite. The carbon dioxide savings in the chosen application were 616 kg per cycle. Within the accuracy of the measuring equipment there was no degradation of the zeolite detectable. The storage handling system was a critical point and has to be improved in an optimized scenario for time saving and to reduce the prime energy costs which were determined to 73 €/MWh. The sensitivity analysis shows that it is very important to charge the zeolite storage with sufficient high temperatures above 130 °C and chose an application with energy demand over the whole year. At the moment the road legal system is not competitive to conventional energy like oil or gas with prime energy costs of 36 €/MWh [3]. Heavier storages carrying 50 tons of zeolite transported within factory premises can overcome this barrier with potential prime energy costs of around 30 €/MWh. Another chance is the trade of carbon dioxide certificates.

Acknowledgements

The financial support by the German Federal Ministry for Economic Affairs and Energy (BMWi, promotional reference 0327383B) is gratefully acknowledged.The authors wish to thank the industrial partners HoffmeierIndustrieanlagen GmbH, JäckeringMühlen und Nährmittelwerke GmbH, MHB Hamm BetriebsführungsgesellschaftmbH, and Chemiewerk Bad Köstritz GmbH for the fruitful cooperation. The responsibility for the content rests by the authors.

References

[1] A. Krönauer et al, Mobile Sorption Heat Storage in Industrial Waste Heat Recovery, Innostock 2012, Proceedings, INNO ST 14
[2] W. Kast, Adsorption aus der Gasphase, VCH Verlagsgesellschaft mbH, 1988, ISBN 3-527-26719-0, Page 144 ff.
[3] Daten zur Energiepreisentwicklung, issue 28.01.2015, Statistisches Bundesamt, p 22.