Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 69 (2018) 206 – 211

www.elsevier.com/locate/procedia

25th CIRP Life Cycle Engineering (LCE) Conference, 30 April – 2 May 2018, Copenhagen, Denmark

Life cycle assessment of innovative materials for thermal energy storage in buildings

Rafael Horn[a]*, Matthias Burr[a], Dominik Fröhlich[b], Stefan Gschwander[b], Michael Held[a], Jan Paul Lindner[a], Gunther Munz[b], Björn Nienborg[b], Peter Schossig[b]

[a] *University of Stuttgart, Institute for Acoustics and Building Physics, Department of Life Cycle Engineering, Wankelstraße 5, 70563 Stuttgart , Germany*
[b] *Fraunhofer Institute for Solar Energy Systems (ISE), Heidenhofstr. 2, 79110 Freiburg, Germany*

* Corresponding author. Tel.: +49-711-970-3188. *E-mail address:* rafael.horn@iabp.uni-stuttgart.de

Abstract

The politically endorsed reduction of greenhouse gas emissions entails the transformation of thermal energy systems towards renewable energies, especially in the building sector. This comes along with a demand in energy storage, as there is a time offset between energy availability and demand. As sensible heat storages induce major losses and have limited energy density, current water-based solutions are only partially sufficient to meet these demands. Within the project “Speicher-LCA” the environmental performance of a variety of innovative materials available for energy storage in buildings is assessed. The project provides the first extensive comparison of environmental profiles of various thermal energy storage materials, including phase change, thermochemical and sorption materials. The specific performances in the storage cycle are taken into account. All results will be publically accessible through a spreadsheet tool including a comprehensive set of materials, components as well as their integration into different building types.

This paper discusses the methodological framework of the study and presents the environmental assessment results for selected materials. It highlights the main challenges in the assessment of innovative storage materials on different system levels which require specific definition of functional units accordingly. The first assessment results on material level for selected phase change (PCM) and thermo-chemical materials (TCM) allow an environmental characterization regarding their potential application in thermal storages. In addition, ranges of required numbers of storage cycles for amortization have been calculated for the non-renewable primary energy demand. For PCMs amortization cycles range between ~20 to 150 cycles for salt hydrates and up to ~280 cycles for paraffins. Regarding TCM, energetic amortization of silica gel and zeolite 13x is reached after ~60 and ~260 cycles respectively. Since the realization of storage components and systems which can actually be used in real applications will further increase the cycle number required for amortization, these storage materials may thus not be suitable for applications with a low number of cycles over lifetime, such as seasonal storage.

Keywords: Thermal energy storage; life cycle assessment; phase change materials; thermochemical storage materials

1. Introduction

Domestic hot water (DHW) and space heating are responsible for around 25 % of primary energy (PE) consumed in European households. As they are mainly provided through the combustion of fossil fuels, this amounts up to 33% of the European greenhouse gas emissions [1]. Hence, in order to face the ambitious goals of climate policy, the reduction of building related emissions is an important measure. This can be achieved by the reduction of energy

doi:10.1016/j.procir.2017.11.095

demand such as insulation and the optimization of energy supply [1]. Thermal energy storages (TES) combined with solar heating systems promise significant reductions of non-renewable primary energy consumption by changing the energy source and optimizing its utilization [2–4].

To achieve a broader application, solar heating systems must overcome the discrepancy between the availability of solar energy and the demand for thermal energy. Due to the limited energy density, conventional sensible heat storages require rather large storage volumes. Furthermore, these storage systems experience high energy losses due to temperature differences between the storage and its surroundings and due to large surface areas. In order to overcome these issues, current developments are focusing on innovative storage materials and systems, tailored to the requirements of thermal energy systems in buildings [5]. The heat supply within buildings defines the temperature requirements either due to space heating (min. 35°C for surface heating) or use of domestic hot water (min. 60°C). DHW is characterized by a daily energy consumption which is constant throughout the year, whereas the demand for space heating mainly depends on the seasonal climate. Thus, depending on the specific requirements of use profiles in buildings, different storage materials and systems have to be taken into consideration.

Innovative thermal energy storages can be based on thermochemical (TCM) and phase-change materials (PCM), which require a different integration in the heating system. In order to gain comparability between different storage systems and materials, the method of Life Cycle Assessment (LCA) according to ISO 14040 [6], ISO 14044 [7] and EN 15804 [8] provides a reliable basis for decision support as it accounts for all environmental impacts that occur throughout the whole life cycle of considered systems. Furthermore, this method allows an objective comparison of products or systems as it refers to the distinct function of the analyzed application. However, the reliability of LCA is strongly depending on comprehensive process data which in most cases goes in line with an increasing complexity. To facilitate the applicability of such detailed analyses in justifiable expenditure of time and hence make it available for practitioners, the project "Speicher-LCA" [9] develops generic models for the environmental assessment of storage systems on component and material level, using the GaBi ts software [10]. As the energetic performance of storage materials in stand-alone and building context is crucial, extensive simulations are carried out by the partners Fraunhofer Institute for Solar Energy Systems ISE and Bavarian Center for Applied Energy Research. To allow a broader use of gained knowledge, these models are merged within a calculation tool running on Microsoft Excel©, which allows to assess the global warming potential (GWP) and primary energy demand on different levels. The tool will be released online at the website of the University of Stuttgart (www.iabp.uni-stuttgart.de) and will support TES experts in science and industry to gain insight in the environmental impacts of innovative thermal energy storage materials and their implementation in buildings.

Nomenclature

DA	Dubinin-Astakhov
DHW	domestic hot water
EoL	End-of-Life
GWP	global warming potential
LCA	life cycle assessment
PCM	phase change material
PE	primary energy
PEC	primary energy consumption
PENRT	total use of non-renewable primary energy resources
PERT	total use of renewable primary energy resources
TCM	thermochemical material
TES	thermal energy storage
TRL	technology readiness level

2. Goal and Scope

The goal of the study is to facilitate a comparison between different TES systems with regard to their environmental impact during a life cycle focusing on its implication on climate change, including the production, use phase and end of life phase of the system. Due to the different system compositions depending on the considered storage material, a three-level approach has been chosen. Thus, the environmental analysis within the "Speicher-LCA" project occurs on material-, component- and system level, including the corresponding distribution and heating systems (see Fig. 1). Within this paper, the environmental impacts on material level are displayed for selected PCM and TCM materials. This allows a first characterization of materials with respect to their required minimum amortization cycles and hence, requirements for a beneficial use. However, as the materials are applied in building application, the impacts on material level do not allow a direct comparison for decision making without taking their performance and application context (e.g. specific systems solutions) into account.

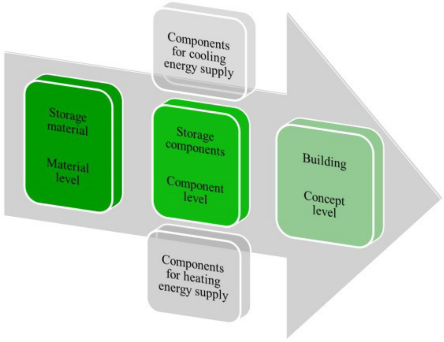

Fig. 1. Modular structure of the system in which innovative storage materials are embedded.

2.1. Functional unit

As Fig. 1 shows, the analysis of storage materials meets the challenge of varying functionalities of the three systems levels. This results in the requirement of defining different functional units depending on the considered system level.

The storage materials show great differences concerning their usage (e.g. daily storage vs. seasonal storage, heat vs. cold storage, central vs. decentral) and their capability of storing energy. While this comes along with the necessity of different functional units on material and on system level, it also requires consistency of the units among each other.

The functional unit of the storage materials is defined as 1 kWh of thermal energy stored within the materials ideal operating point as a material property without taking potential system based energy losses into consideration. It is applied for comparisons on material level, but does not facilitate an embedded assessment on component or building level. Thus, the functional unit is supported through the application of a declared unit according to EN 15804 [8] defined as 1 kg of storage material. This definition applies to the results presented in the present paper and comes along with a restricted applicability of the results in terms of building related decision support.

On component level, the functional unit is determined as 1 kWh of thermal energy delivered to the distribution system within the lifetime of the storage system and includes losses throughout loading, storing and unloading of the thermal energy. Lifetime and duration of the storage cycles determine the number of charging/ discharging cycles of a storage in its life time and hence, the overall energy delivered by the storage system. On building level, the functional unit is further enhanced and defined as functional equivalent according to EN 15643-1 [11].

2.2. System boundaries

This paper presents the results of selected storage materials (PCM, TCM) on material level. This comprises the life cycle stages from resource extraction, production of intermediates up to the final production process (cradle-to-gate) and end of life processing including potential avoided impacts. The system boundaries are chosen consistent to EN 15978 [12], including the production phase (A1 – 3), the End-of-life (C1 – 4) and the benefits and loads beyond system boundary (D). Within the production process, the raw material supplies as well as the energy consumption during the manufacturing process have been included.

2.3. Assumptions and limitations

The investigation of innovative storage materials includes the assessment of materials with varying technology readiness level (TRL) from commercially available materials with TRL 9 to materials under scientific investigation not further developed than TRL 4 [13]. In order to gain comparability between their environmental impacts, different generic production models have been developed in cooperation with experts from material development and industry. This process is applied to all materials to ensure comparability and to facilitate the investigation of established and innovative materials. This approach also includes assumptions of an extrapolation of material production processes towards industrial applicability and does not consider potential problems that may occur by enhancing the TRL of materials and systems. For transparency, materials that are not available on a commercial level yet are specified as such. As there are no commercial disposal and recycling options for most materials available on industrial scale, End-of-Life (EoL) scenarios were chosen that refer to the calorific value and the aggregate conditions of the materials. The main aim of these scenarios is to allow rough estimates on EoL impacts. To do this, organic PCMs are assumed to be thermally recovered, salt hydrate PCMs are assumed to be diluted and disposed as waste water, solid TCMs are assumed to be landfilled, as they are inert and non-solvable.

The values on material level do not necessarily provide reliable information on the suitability of the material in terms of environmental impacts on building level as their performance due to application context and energy availability strongly varies. Thus, the material assessment has to be perceived as an indicator for general suitability and needs to be complemented by the specific application context on component and concept level which will be provided by the “Speicher-LCA”-tool.

2.4. Assessed inventory quantities and impact categories

For the assessment of TES materials the following impact categories have been chosen, following the standards EN 15804 [8] and EN 15978 [12]:

- The primary energy consumption (PEC), which is divided into the “total use of non-renewable primary energy resources (PENRT) [MJ]” and the “total use of renewable primary energy resources (PERT) [MJ]”.
- The global warming potential (GWP) 100 years is used to describe the impact of the greenhouse gases of a one kg of CO_2 equivalent within the next 100 years.

These impact categories are chosen as they enable the calculation of energy and GWP payback times of the different storage materials, depicting information about a minimum number of charging/ discharging cycles a material has to complete in order to have a positive effect on the environment with regard to these categories. Although the consideration of further categories is recommended in the framework on a comprehensive LCA, the results of the project “Speicher LCA” are restricted to the abovementioned categories as the intended use and audience focuses on implications on climate change and energy shifting.

3. Selection and characterization of investigated materials

Within the “Speicher-LCA” project the potential environmental impacts of a large variety of TCM and PCM materials are under assessment. The materials have been chosen according to their thermal properties and the associated likeliness of being used in future heating/ cooling systems. Table 1 summarizes the energy storage materials that are presented in the course of this paper and allow a preview of future results. The LCA tool will provide a more comprehensive selection of materials, which will be available at the end of the project in 2018.

Tab. 1. Presented energy storage materials

Type	Material	Specification	Ref.
PCM	RT21	Paraffin	[14]
	SP21EK	Salt hydrate	[15, 16]
	SP58		[17, 18]
TCM	Zeolite 13 X	Zeolite	[19]
	Silica gel	Silica gel	[19]
	Al –Fumarate*	Metal organic framework	[20]
	CAU-10-H*		[21]
	Mg – Sulphate*	Salt hydrate	[22]
	Lithium Bromide	Salt Solution	[23]

*not yet available as energy storage material on commercial level

To allow the comparison of the environmental impacts of different storage materials, the functional unit is applied. In case of the PCMs, the impacts are therefore divided by the material specific energy density - a combination of the enthalpy of fusion and the specific heat capacity in the temperature range of its melting point as specified by the manufacturer. In terms of the TCM materials, energy density is a more complex matter as it is strongly depended on the specific application defining the adsorption/ desorption and evaporator/ condenser temperatures. As defined in the functional unit, the theoretical maximum storage capacity as a material property is defined through the maximum adsorbent loading. To provide an insight on the applicability of these values, two TCM materials, namely Zeolite 13X and silica gel, are assessed applying exemplary temperatures of a typical solar based seasonal storage scenario. The applicable storage density is calculated using a Dubinin-Astakhov (DA) fit, which is commonly applied to facilitate sorption based energy storage systems [19, 24]. Using the thermodynamic material properties provided by [19], the loading in dependence to the adsorption potential is depicted in Fig. 2. In addition to the DA fits, the applied exemplary temperatures are depicted. For desorption, a solar thermal energy system with a return temperature of 100°C is chosen. For adsorption, underfloor heating with a temperature of 35°C is chosen. These values do not include temperature gradients and energy losses. In terms of the low temperature sink/source, geothermal energy is assumed with a temperature of 10°C.

Tab. 2. Energy densities of TCM

TCM	Energy density [kWh/kg]	
	Full working range	Exemplary solar thermal application
Zeolite 13 X	0.21	0.07
Silica gel	0.20	0.08

The DA fit allows the calculation of the theoretical energy density value for given temperatures depicting the maximum possible theoretical value under the given conditions. In practice, these values have to be further reduced due to energy efficiencies, dynamic aspects and auxiliary energy demand. The results for optimum temperatures and the exemplary temperatures of the selected TCM materials are summarized in table 2.

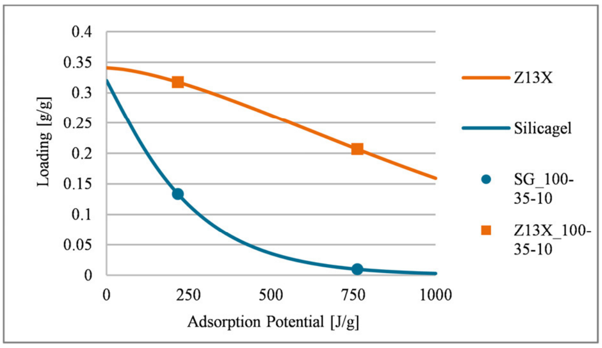

Fig. 2. Dubinin-Astahkov fits for Zeolite 13X and silica gel including the working points for the chosen temperature levels

4. Global warming potential and non-renewable primary energy demand of thermal energy storage materials

The following chapter presents the global warming potential (GWP) and non-renewable primary energy demand (PENR) for selected storage materials, differentiated for the storage principles. In addition, a net amortization time for PCMs and for selected TCMs is depicted. The amortization time is calculated through a comparative assessment of the GWP and PENR of the materials assuming a burden free loading and no storage losses and the impacts of a gas boiler that provides the thermal energy for the reference system. Thus, the minimum number of full loading/ unloading cycles of the TES system can be stated, which is required to be beneficial against a conventional, fossil fueled system. Due to losses as well as the necessary containment and auxiliary components, the number of cycles is increased for real application conditions.

4.1. Phase change materials

For PCMs, a wider range of commercially available materials has been assessed. Depending on the required raw materials for the production of PCMs, significant bandwidths are identified for the global warming potential (Fig. 3). RT21 is a paraffin based material and stands exemplarily for all fossil based paraffins, as they originate from the same source and processing route.

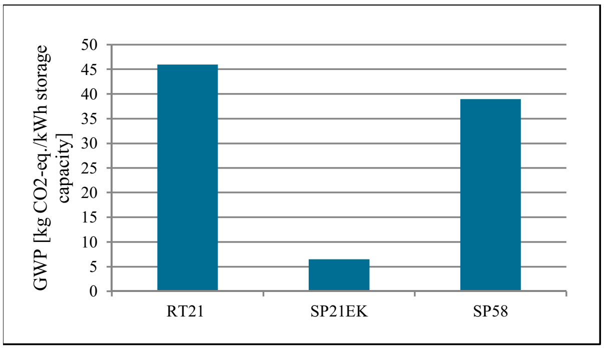

Fig. 3. Global warming potential of phase change materials per storage capacity, not including any losses.

Fig. 3. clearly shows, that the salt hydrate based materials (SP21EK, SP58) have a significantly lower contributions to the GWP. As the temperature level of the materials is indicating different applications, a GWP amortization time is not applicable on material level, as different reference energy systems have to be considered.

Fig. 4 presents the primary energy demands and amortization times of analyzed PCM materials. In addition, the energetic amortization cycles are presented. Assuming 25 cycles over the lifetime for a seasonal storage, only SP21EK shows a potential suitability for this application, even though losses and auxiliary energy as well as the life cycle impacts of the storage system are not yet considered.

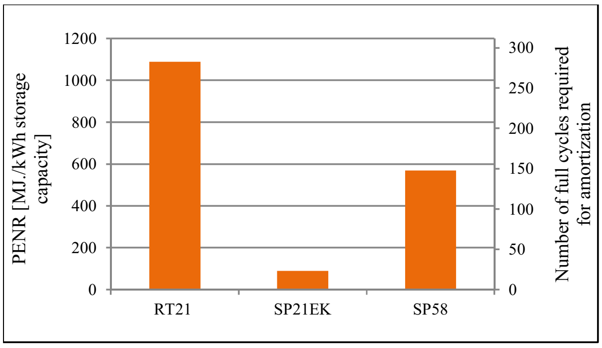

Fig. 4. Non-renewable primary energy demand of phase change materials per storage capacity, not including any losses. The secondary axis shows the number of minimum number of full cycles that would be required to regain the additional impacts caused by the materials life cycle

4.2. Sorption materials

In comparison to phase change materials, the energy density and the accordingly required amount of material of thermochemical materials is strongly depending on the intended application. Thus, Fig. 5 presents the GWP of the presented TCMs with regard to their declared unit.

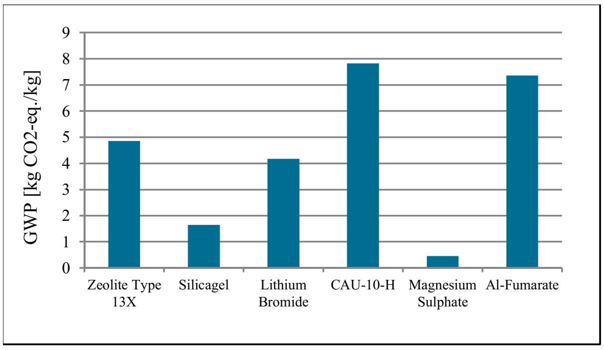

Fig. 5. GWP based on the declared unit for selected thermochemical storage materials

Compared to PCMs, the TCMs require a more complex manufacturing, which comes along with a high impact per declared unit. However, TCMs show higher energy densities and the losses in application are presumably lower due to the avoiding of sensible energy losses. However, it can be seen that especially the production of innovative materials show high GWP values, caused by both elaborate manufacturing processes and input materials of high environmental impacts. Due to their comparably low TRL, there is still a strong potential to improve the environmental profile during development.

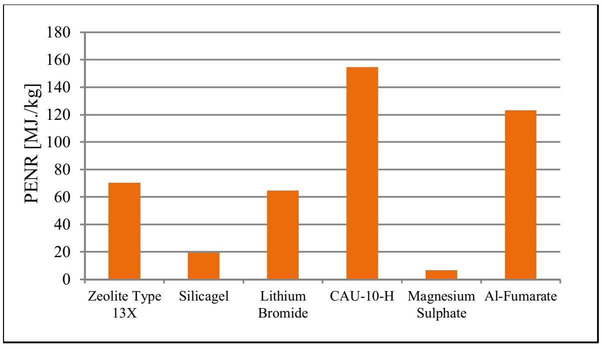

Fig. 6. Non-renewable primary energy demand based on the declared unit for selected thermochemical storage materials

For the non-renewable primary energy consumption (Fig. 6) the same structure can be identified, indicating a significantly higher impact of the TCMs and demand for improvement for the innovative materials. However, as these values are not including the actual energy storage capacity, they cannot be used for a direct comparison of the materials. This requires that temperatures are chosen for both charging and uncharging of the storages.

4.3. Environmental amortization time of TCMs with regard to solar based seasonal storage application temperature

To assess the impact of the TCMs to the GWP and PENR according to their functional unit, the intended application has to be specified in order to calculate their energetic performance. When applying the values calculated using the DA fits developed in [19], the environmental profiles can be derived. Fig. 7 shows the non-renewable primary energy demand for Zeolite 13X and silica gel in relation to their environmental performance and the resulting required number of full cycles compared to fossil energy sources. The displayed maximal theoretic value takes the full adsorption capacity into account, the DA fit based value is created using realistic application temperatures as described above, but not accounting for potential losses. While the silica gel shows a relatively low number of required full cycles, it is not possible to regain the environmental impacts of the Zeolite 13X life cycle within 100 full cycles of application. In conclusion, this material is not suitable for seasonal storage in terms of the investigated impact categories for the depicted application conditions.

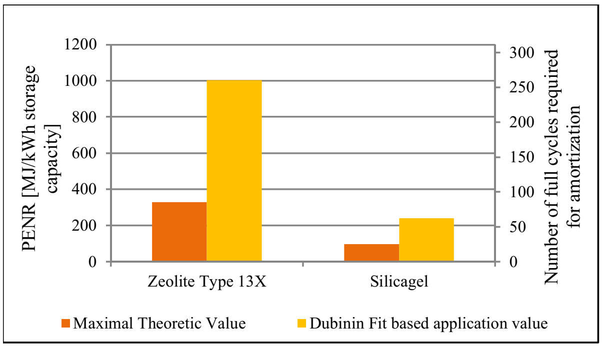

Fig. 7. Non-renewable primary energy demand for Zeolite 13X and silica gel in relation to the functional unit, both for theoretical optimum and temperatures representing a realistic application scenario

5. Conclusion and Outlook

Although the development of innovative thermal energy storages is seen as a crucial aspect of the energy transformation towards a sustainable energy landscape, no comprehensive environmental life cycle assessments of innovative TES materials has been conducted. In the project “Speicher-LCA” a variety of these materials is assessed with regards of their application context. The main goal of “Speicher-LCA” is to facilitate the assessment of environmental performance of innovative materials to TES experts in science and industry as well as practitioners in construction that may apply TES systems in buildings. In order to allow first estimates on the GPW and PENR of storage materials and systems, an Excel based screening tool is developed, that incorporates relevant influencing factors for reliable analysis, such as storage systems, building types and climate zones.

This paper gives an overview of the methodological approach used for the developed tool and presents GWP and PENR results for selected TES materials focusing on their thermochemical properties, including potential number of full cycles for environmental net amortization. For both PCM and TCM the amortization in seasonal storage application is to be carefully implemented, as only few materials offer low amortization cycle numbers. For a significant reduction of environmental impact of buildings through innovative TES applications leading to a higher cycle number over lifetime need to be identified.

However, it has to be stated that the assessment should be complemented through consideration of the overall system, as the performance of storage materials is strongly dependent on application context.

Acknowledgements

This work has been created as part of the project “Speicher LCA” funded by the German Federal Ministry for Economic Affairs and Energy under grant agreement FKZ 03ET1333C.

References

[1] Lapillonne B, Pollier K, Samci N. Energy Efficiency Trends for households in the EU; 2017.
[2] Alizadeh M, Sadrameli SM. Development of free cooling based ventilation technology for buildings: Thermal energy storage (TES) unit, performance enhancement techniques and design considerations – A review. Renewable and Sustainable Energy Reviews 2016; p. 619–645.
[3] Department for Business, Energy & Industrial Strategy. Evidence Gathering: Thermal Energy Storage (TES) Technologies. London; 2016.
[4] Köll R, van Helden W, Fumey B. COMTES - Combined development of compact thermal energy storage technologies: Description of experimental systems; 2016.
[5] Schossig P, Haussmann T. Wärme- und Kältespeicherung - Stand der Technik und Ausblicke; 2011.
[6] DIN EN ISO 14040. Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen. Berlin. Beuth Verlag GmbH; 2006.
[7] DIN EN ISO 14044. Umweltmanagement – Ökobilanz – Anforderungen und Anleitungen. Berlin. Beuth Verlag GmbH; 2006.
[8] DIN EN 15804. Nachhaltigkeit von Bauwerken – Umweltproduktdeklarationen – Grundregeln für die Produktkategorie Bauprodukte. Berlin. Beuth Verlag GmbH; 2013.
[9] Forschungsinitiative ENERGIEWENDEBAUEN ,2015. Life Cycle Assessment für thermische Energiespeicher: Neuigkeiten aus der Forschung. https://projektinfos.energiewendebauen.de/forschung-im-dialog/neuigkeiten-aus-der-forschung/detailansicht/life-cycle-assessment-fuer-thermische-energiespeicher/. Accessed 14 November 2017.
[10] thinkstep AG. GaBi ts; 2016.
[11] EN 15643-1: Sustainability of construction works - Sustainability assessment of buildings - Part 1: General framework. Charlottenlund. DS; 2010.
[12] DIN EN 15978. Nachhaltigkeit von Bauwerken – Nachhaltigkeit von Bauwerken – Bewertung der umweltbezogenen Qualität von Gebäuden – Berechnungsmethode. Berlin. Beuth Verlag GmbH; 2012.
[13] European Commission. HORIZON 2020 – WORK PROGRAMME 2014-2015. General Annexes: G. Technology readiness levels (TRL); 2014.
[14] Rubitherm Technologies Gmbh. Technisches Datenblatt RT21; 2015.
[15] Rubitherm Technologies Gmbh. Technisches Datenblatt SP21EK; 2016.
[16] Rubitherm Technologies Gmbh. Sicherheitsdatenblatt SP21EK; 2016.
[17] Rubitherm Technologies Gmbh. Technisches Datenblatt SP58; 2015.
[18] Jänchen J, Wagner W, Schranzhofer H, Gantenbein P, Daguenet-Frick X, Englmair G, Dannemand M, Furbo S, Badenhop T. Report about the materials handling & recycling path; 2016.
[19] Frazzica A, Freni A. Adsorbent working pairs for solar thermal energy storage in buildings. Renewable Energy 2017; p. 87–94.
[20] Elsayed E, AL-Dadah R, Mahmoud S, Elsayed A *et al.* Aluminium fumarate and CPO-27(Ni) MOFs: Characterization and thermodynamic analysis for adsorption heat pump applications. Applied Thermal Engineering 2016; p. 802–812.
[21] Fröhlich D, Pantatosaki E, Kolokathis PD, Markey K *et al.* Water adsorption behaviour of CAU-10-H: A thorough investigation of its structure–property relationships. J. Mater. Chem. A 2016; p. 11859–11869.
[22] van Essen VM, Zondag HA, Gores JC, Bleijendaal L *et al.* Characterization of MgSO4 Hydrate for Thermochemical Seasonal Heat Storage. Journal of Solar Energy Engineering 2009; p. 41014.
[23] N’Tsoukpoe KE, Le Pierrès N, Luo L. Numerical dynamic simulation and analysis of a lithium bromide/water long-term solar heat storage system. Energy 2012; p. 346–358.
[24] El-Sharkawy II, Kuwahara K, Saha BB, Koyama S *et al.* Experimental investigation of activated carbon fibers/ethanol pairs for adsorption cooling system application. Applied Thermal Engineering 2006; p. 859–865.