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IEA SHC Task 42 / ECES Annex 29 – A simple tool for the economic evaluation of thermal energy storages

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Abstract

Within the framework of IEA SHC Task 42 / ECES Annex 29, a simple tool for the economic evaluation of thermal energy storages has been developed and tested on various existing storages. On that account, the storage capacity costs (costs per installed storage capacity) of thermal energy storages have been evaluated via a Top-down and a Bottom-up approach. The Top-down approach follows the assumption that the costs of energy supplied by the storage should not exceed the costs of energy from the market. The maximum acceptable storage capacity costs depend on the interest rate assigned to the capital costs, the intended payback period of the user class (e.g. industry or building), the reference energy costs, and the annual number of storage cycles. The Bottom-up approach focuses on the realised storage capacity costs of existing storages. The economic evaluation via Top-down and Bottom-up approach is a valuable tool to make a rough estimate of the economic viability of an energy storage for a specific application. An important finding is that the annual number of storage cycles has the largest influence on the cost effectiveness. At present and with respect to the investigated storages, seasonal heat storage is only economical via large sensible hot water storages. Contrary, if the annual number of storage cycles is sufficiently high, all thermal energy storage technologies can become competitive.

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1. Introduction

Heat and cold storage are key technologies for increasing energy efficiency and a more extensive utilisation of renewable energy sources. A major barrier to the development of thermal energy storage (TES) technologies is cost uncertainty [1]. In order to make a rough estimate of the economic viability of an energy storage for a specific application, a simple tool was developed, which consists in determining the maximum acceptable storage capacity costs via a Top-down approach and the realised storage capacity costs via a Bottom-up approach.

Nomenclature

ANF	annuity factor / a^{-1}
i	interest rate
INC	investment costs / €
n	payback period / a
N_{cycle}	number of storage cycles per year / a^{-1}
REC	reference energy costs / $€\cdot kWh_{en}^{-1}$
SC	storage capacity / kWh_{cap}
SCC_{acc}	maximum acceptable storage capacity costs / $€\cdot kWh_{cap}^{-1}$
SCC_{real}	realised storage capacity costs / $€\cdot kWh_{cap}^{-1}$

2. Methods

2.1. Top-down approach

The Top-down approach assumes that the cost of energy supplied by the storage should not exceed the costs of energy from the market [†] (hereinafter referred to as *REC* = reference energy costs). Following this assumption, the maximum acceptable storage capacity costs (hereinafter referred to as SCC_{acc}) are calculated from the discount rate of storage capital i, the payback period of the investment n, the number of storage cycles N_{cycle}, and the reference energy costs [2]. To simplify the evaluation, this analysis neglects operating costs and changes in the cost of energy production over time. Detailed information about the storage technology or implementation are not required for this approach.

Using the interest rate assigned to the capital costs and the payback period, the present value annuity factor *ANF* can be calculated to determine the present value of the energy storage capital. *ANF* as a function of payback period n and interest rate i can be calculated via Eq. (1):

$$ANF = \frac{(i+1)^n \cdot i}{(i+1)^n - 1} \tag{1}$$

Interest rate i and payback period n depend on the user. Three classes of users are referred to in the following discussion. In the *industry* sector, high interest rates of 10% and above and short payback periods of 5 years and

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[†] Communicated e.g. by Dr. Rainer Tamme, German Aerospace Center (DLR), in many presentations since 20 years.

below are usual. For *building* applications, moderate interest rates of 5% and longer payback periods of 15 – 20 years are acceptable. In addition, one might also assume a user that can tolerate even longer payback periods of 25 years and low interest rates of 1%. The latter user class has probably political or ecological reasons for the investment and is hereinafter referred to as *enthusiast*. In Figure 1, the annuity factor *ANF* is plotted as a function of the payback period *n* for interest rates of 10% (red solid line) indicating *industry*, 5% (blue dashed line) indicating *building*, and 1% (green dotted line) indicating *enthusiast*.

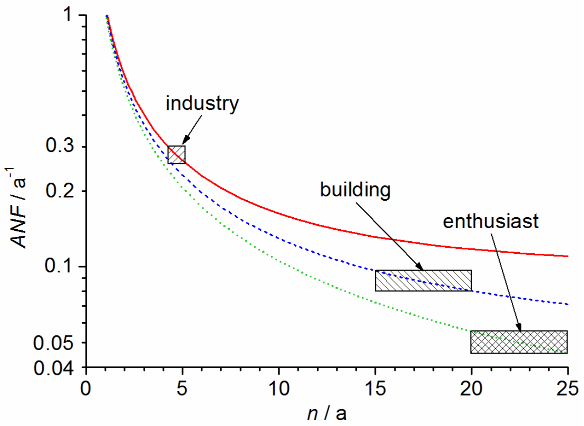

Fig. 1. Annuity factor *ANF* as a function of payback period *n* for three user classes (industry i = 10%, building i = 5%, and enthusiast i = 1%); framed regions indicate acceptable annuity factors for these user classes.

In the *industry* sector, a payback period of 5 years yields an *ANF* of about 0.26. Therefore, a range of *ANF* from 0.25 to 0.30 is considered as storage capacity cost annuity for industrial users. In the *building* sector, *ANF* are within 0.07 – 0.10, and in the case of *enthusiasts*, consequently, low *ANF* between 0.04 and 0.06 can be achieved.

The maximum acceptable storage capacity costs SCC_{acc}, calculated in € per kWh installed storage capacity (€·kWh$_{\mathrm{cap}}^{-1}$), are simply the product of the substituted reference energy costs *REC*, given in € per kWh energy (€·kWh$_{\mathrm{en}}^{-1}$), and the number of storage cycles per year N_{cycle} divided by the annuity factor *ANF*:

$$SCC_{acc} = \frac{REC \cdot N_{cycle}}{ANF} \tag{2}$$

Eq. (2) neglects operating costs and changes of *REC* over the payback period. Nevertheless, this analysis illustrates the relationship between acceptable storage capacity costs, the frequency of storage handling, and the costs of reference energy that is substituted by the storage system.

Similar to *ANF*, a range is considered for *REC*. As the focus of this work is to evaluate the costs of thermal energy storages, *REC* given in Table 1 correspond to heat or cold supply costs. Table 1 summarises the economic boundary conditions of the three user classes that are taken into account in the Top-down evaluation.

Table 1. Economic boundary conditions: costs of substituted reference energy *REC* and storage annuity factor *ANF* calculated via Eq. (1).

User class	*REC* / €·kWh$_{\mathrm{en}}^{-1}$		*ANF* / a^{-1}	
Industry	0.02	0.04	0.25	0.30
Building	0.06	0.10	0.07	0.10
Enthusiast	0.12	0.16	0.04	0.06

As an aid to orientation, expectable ranges for the costs of substituted reference energy *REC* and the storage annuity factor *ANF* are considered. In this way, a high and a low cost case are analysed for each user class. The high case considers the max. *REC* and the min. *ANF*, and the low case the min. *REC* and the max. *ANF*, respectively. Future changes of the reference energy costs *REC* can be taken into account by adjusting the values of *REC* given in Table 1 appropriately, e.g. by considering average *REC* for the intended payback period. According to Eq. (2), SCC_{acc} is proportional to *REC* and, hence, an increase in *REC* will cause a similar increase in SCC_{acc}. Operating costs should be taken into consideration if they are not negligible compared to the capital costs. Especially in the case of mobile storages, operating costs are expected to have a significant influence on the economic viability. To consider operating costs requires a modification of the Top-down approach. According to the procedure outlined above, the Top-down approach calculates the costs per storage capacity. However, if operating costs have to be included, the costs per stored energy have to be determined, for instance on an annual basis.

2.2. Bottom-up approach

The Bottom-up approach focuses on the realised storage capacity costs of existing storage systems (hereinafter referred to as SCC_{real}). To investigate particular storages, a questionary was developed which inquires among other technical parameters both actual and expectable investment costs *INC* of the storage divided into costs of the heat storage material, costs of the storage container or reactor, and costs of the charging/discharging unit. For the Bottom-up approach, sensible heat storage, latent heat storage via PCM, and thermochemical heat storage including sorption storage have been investigated. Besides commercially available storage systems, innovative prototypes which are subject of ongoing research have been analysed [3]. The realised storage capacity costs SCC_{real} are simply the investment costs *INC* divided by the installed storage capacity *SC*:

$$SCC_{real} = \frac{INC}{SC} \tag{3}$$

INC sums up heat storage material costs, storage container or reactor costs, and cost of charging and discharging device. As in the case of SCC_{acc}, SCC_{real} are calculated in € per kWh installed storage capacity (€·kWh$_{\mathrm{cap}}^{-1}$).

3. Results

The maximum acceptable storage capacity costs SCC_{acc} for the three user classes calculated via Eq. (2) are plotted as a function of the annual number of storage cycles N_{cycle} in Figure 2.

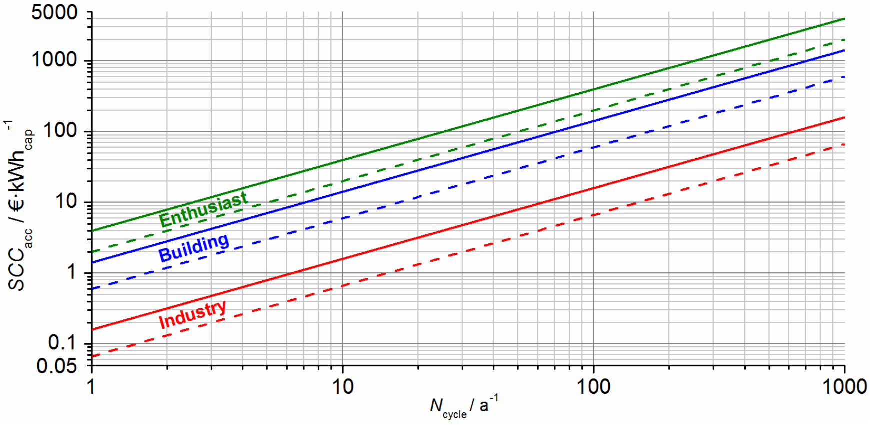

Fig. 2. Maximum acceptable storage capacity costs SCC_{acc} for three user classes as a function of storage cycles per year N_{cycle}; enthusiast high/low case (green solid/dashed line), building high/low case (blue solid/dashed line), and industry high/low case (red solid/dashed line).

Solid lines indicate the high case of each user class and dashed lines the low case, respectively. A double-logarithmic scale was chosen to visualize both SCC_{acc} of long-term storages with only few cycles per year and short-term storages with several hundred cycles per year. The results of the Top-down evaluation as shown in Figure 2 indicate that, for a fixed cycle period N_{cycle}, SCC_{acc} depend on the user's economic environment. The low case of the industry sector and the high case of enthusiasts differ by a factor of about 60 in costs. Short-term storage with several hundred storage cycles per year, however, allows several hundred times higher storage costs because of the larger energy turnover.

For reasons of clarity, the comparison of SCC_{acc} (Top-down approach) with SCC_{real} (Bottom-up approach) is split up into four figures: long-term storages (Figure 3), hot-water storages up to 30 m³ storage volume (Figure 4), and short-term storages (Figure 5 and 6). Relevant specifications of the investigated storage systems are listed in Table 2.

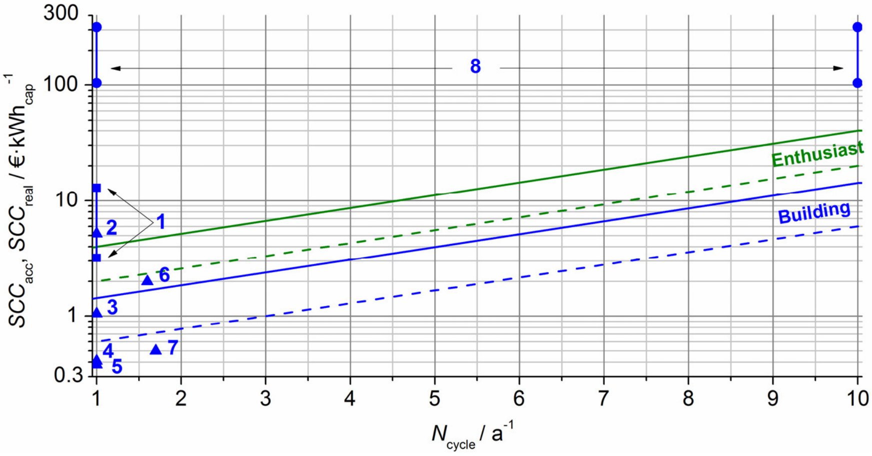

Fig. 3. Maximum acceptable storage capacity costs (SCC_{acc}) and realised storage capacity costs (SCC_{real}) for long-term storages.

Seasonal TES with max. 2 cycles per year requires storage capacity costs below 3 €·kWh$_{cap}^{-1}$ in the building and below 0.4 €·kWh$_{cap}^{-1}$ in the industry sector, respectively. With respect to the storages under investigation, seasonal TES is only economical via large sensible hot water storages (cf. systems 3 – 7, Figure 3).

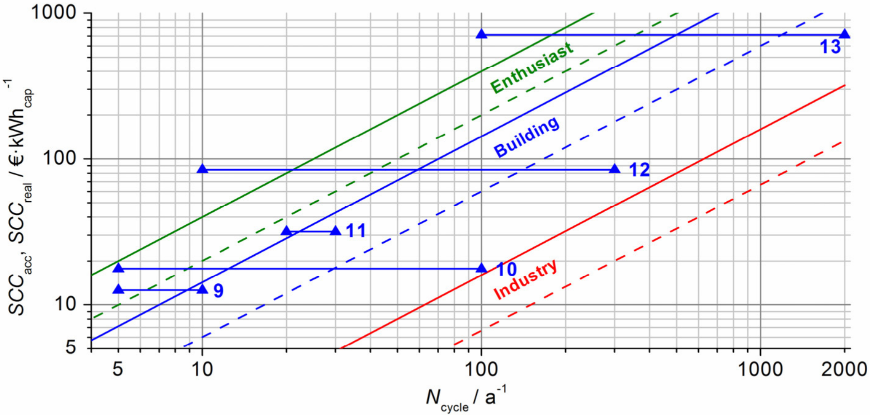

Fig. 4. Maximum acceptable storage capacity costs (SCC_{acc}) and realised storage capacity costs (SCC_{real}) for hot water storages up to 30 m^3 storage volume.

In the case of hot-water storages up to 30 m³ storage volume, the *building* sector is usually targeted. However, these storage can become financially attractive for *industrial* applications if N_{cycle} is sufficiently high. Since these storages can be integrated in a variety of systems, exemplary ranges are indicated for N_{cycle}. The storage capacity SC of the storages 9 – 13 is calculated for the maximum technically permissible temperature ranges indicated in Table 2. To evaluate the economics under application conditions, these temperature ranges have to be adjusted.

On the other hand, in the case of short-term storages, storage systems are intended for either *industry* or *building*. Among the investigated short-term storages, systems 14 – 17 and 18 – 26 have been developed for *industry* and *building* applications, respectively.

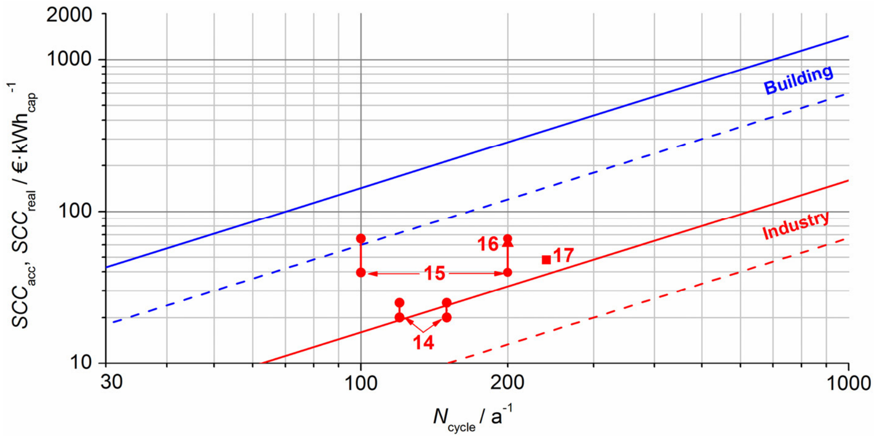

Fig. 5. Maximum acceptable storage capacity costs (SCC_{acc}) and realised storage capacity costs (SCC_{real}) for industrial short-term storages.

Considering the investigated short-term storages for industrial applications (cf. Figure 5) it turns out that ice storages (system 14) are cost-effective, and other technologies are within reach.

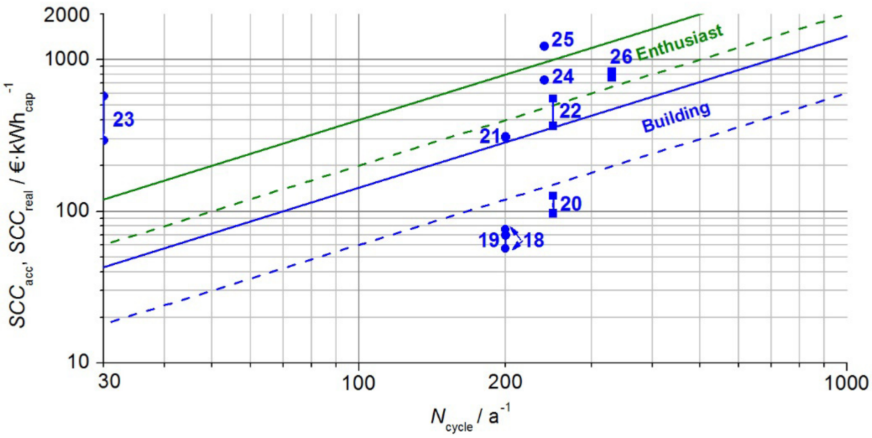

Fig. 6. Maximum acceptable storage capacity costs (SCC_{acc}) and realised storage capacity costs (SCC_{real}) for short-term storages in buildings.

In the case of the systems 1, 8, 14, 15, 18, 20, 22, 23 and 26, cost ranges are given for SCC_{real} indicating the interval between actual costs (upper limit) and expectable costs that can be achieved in the near future (lower limit).

The mobile PCM storage (system 15) is intended to be operated for 100 – 200 cycles per year with a storage capacity between 1,500 and 2,500 kWh depending on the degree of optimisation.

INC of the large water storages 2-7 are DMC (direct material costs) of the installed systems. *INC* of the commercial water storages 9-13 are list prices [4]. In the case of the other investigated systems, *INC* correspond to DMC of prototypes or estimated DMC and, therefore, numbers are roughly rounded. In addition, most of these prototypes are subject of ongoing research and, hence, at a lower TRL with higher investment costs.

Table 2. Specifications of thermal energy storages investigated via Bottom-up approach: annual number of storage cycles N_{cycle}, investment costs *INC*, installed storage capacity *SC*, realised storage capacity costs SCC_{real}.

Storage system (Institution)	Description	N_{cycle} / a^{-1}	*INC* / €	*SC* / kWh_{cap}	SCC_{real} / $€\cdot\text{kWh}_{\text{cap}}^{-1}$
1: NaOH storage (Empa)	NaOH sorption; seasonal storage for domestic applications	1	8,000 – 32,400	2,500	3.2 – 13.0
2: Ottrupgård, 1995 (PlanEnergi)	Hot water; 1,500 m³; 35 – 60 °C	1	225,500	43,500	5.18
3: Sunstore 2, 2003 (PlanEnergi)	Hot water; 10,000 m³; 35 – 90 °C	1	671,100	638,000	1.05
4: Sunstore 3, 2013 (PlanEnergi)	Hot water; 60,000 m³; 10 – 90 °C	1	2,671,100	6,960,000	0.38
5: Sunstore 4, 2012 (PlanEnergi)	Hot water; 75,000 m³; 10 – 90 °C	1	2,281,900	5,570,000	0.41
6: Ackermannbogen (ZAE Bayern)	Hot water; 6,000 m³; 20 – 90 °C	1.6	942,400	472,400	1.99
7: Attenkirchen (ZAE Bayern)	Hot water + borehole heat exchanger; 7,000 m³; 10 – 90 °C	1.7	327,300	654,600	0.50
8: SAT storage [5, 6] (DTU, Univ. Graz)	Supercooled sodium acetate trihydrate, seasonal storage modular system	1 – 10	2,700 – 4,120	13 – 26	104 – 317
9: VSI – 30 m³ (ZAE Bayern, Hummelsberger GmbH)	Vacuum super insulated hot water storage; 30 m³; 5 – 95 °C	5 – 10 [a]	37,888	3,020	12.5
10: allSTOR VPS/3 2000/3-7 (Vaillant GmbH)	Hot water; 2,000 l; 5 – 95 °C	5 – 100 [a]	3,559	202	17.6
11: VSI – 5 m³ (ZAE Bayern, Hummelsberger GmbH)	Vacuum super insulated hot water storage; 5 m³; 5 – 95 °C	20 – 30 [a]	15,962	504	31.7
12: actoSTOR VIH RL 500-60 (Vaillant GmbH)	Hot water; 500 l; 5 – 110 °C	10 – 300 [a]	4,953	58.7	84.4
13: actoSTOR VIH CL 20 S (Vaillant GmbH)	Potable water; 20 l; 10 – 70 °C	100 – 2000 [a]	965	1.35	715
14: Ice storages (Cristopia)	Storages with nodules filled with water/ice; installations in Europe	120 – 150	-	-	20 – 25
15: NaOAc mobile storage (Univ. Bayreuth, LaTherm)	Mobile PCM storage (sodium acetate trihydrate); 40 – 90 °C	100 – 200	99,000	1,500 – 2,500	39.6 – 66.0
16: Dual media storage (ZAE Bayern, Gießerei Heunisch)	Sensible storage; stone + heat transfer oil; up to 300 °C	200	400,000	6,500	61.5
17: MobS (ZAE Bayern)	Mobile sorption heat storage (2x14 t zeolite); industrial waste heat recovery	240	440,000	9,200	47.8
18: SolarHeatCool+PCM (ZAE Bayern)	1 m³ PCM storage ($CaCl_2{\cdot}6H_2O$); 22 – 36 °C	200	4,700 – 6,300	83	56.6 – 75.9

19: TubeICE (VITO)	Modular PCM tubes (Salt hydrate + graphite); 30 – 70 °C	200	900	13	69.2
20: Dishwasher (ZAE Bayern)	Dishwasher with sorption drying (1.5 kg zeolite)	250	29 – 38	0.3	96.7 – 127
21: RT58 storage (VITO)	0.2 m³ PCM storage (RT58); 30 – 70 °C	200	1,850	6	308
22: LiBr storage (ZAE Bayern)	Sorption storage (aqueous LiBr solution); domestic applications	250	31,000 – 47,000	85	365 – 553
23: PCM-Air [7, 8] (Univ. Zaragoza)	Free-cooling; PCM-Air heat exchanger; RT27 as PCM	30	2,000 – 3,900	6.8	294 – 574
24: VDSF (Univ. Lleida)	Free cooling; ventilated double skin facade + PCM (SP21)	240	5,133	7	733
25: Hydroquinone storage (Univ. Lleida)	Solar applications; hydroquinone as PCM; 145 – 187 °C	240	16,768	13.7	1,223
26: RT60 storage [9] (Univ. Basque Country UPV-EHU)	Plate based PCM storage (RT60) for a domestic micro-CHP installation	330	5,500 – 6,000	7.2	764 – 833

[a] storages can be integrated in a variety of systems with different N_{cycle}

In order to identify major cost drivers and cost reduction potentials for the investigated storages, the composition of the investment costs *INC* has been analysed. Figure 7 illustrates how *INC* of the thermal energy storages under investigation are divided into costs of the heat storage material itself and costs of the surrounding container or reactor incl. charging/discharging device. If available, both actual (a) and expectable (b) costs are given.

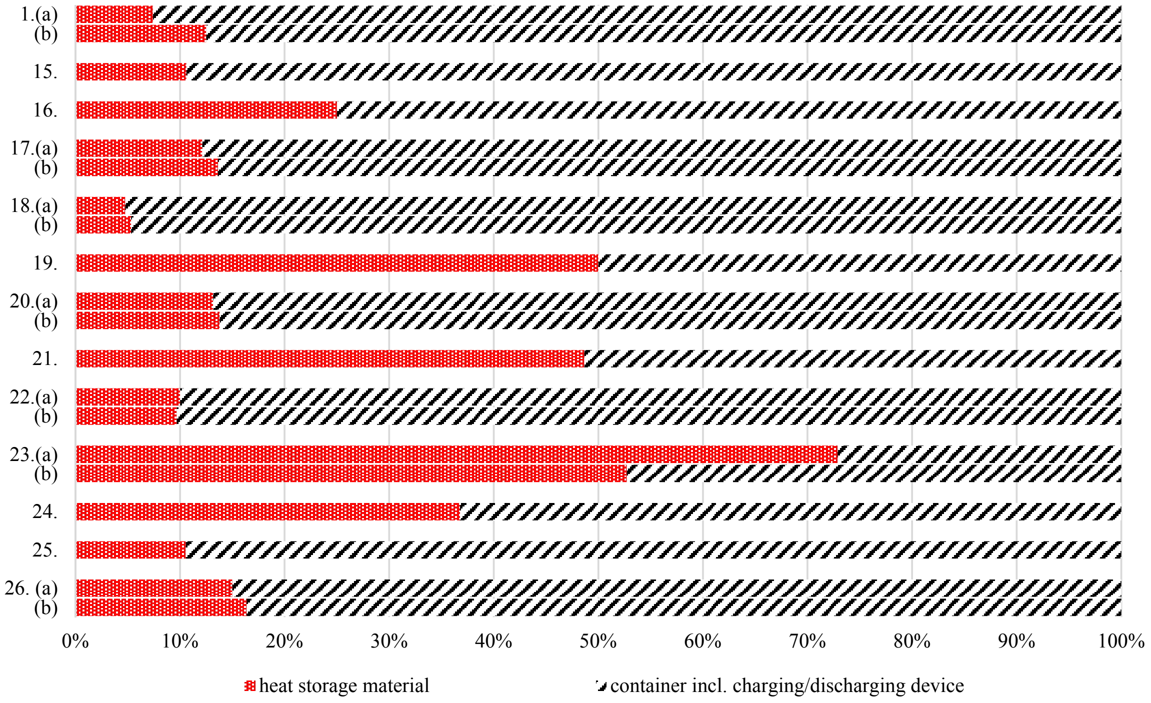

Fig. 7. Actual (a) and expectable (b) Investment costs *INC* of the thermal energy storages under investigation divided into costs of the heat storage material and costs of the container incl. charging/discharging device.

In the majority of cases, the costs of the container incl. charging/discharging device exceed the costs of the heat storage material by far. For 9 out of 13 investigated storages, the costs of the heat storage material account for 25% or less of the total *INC*. Just in one case, the costs of the heat storage material account for more than 50% of *INC*. The composition of both actual and expectable investment costs indicates the significant potential to reduce storage costs by developing cost-effective storage containers and charging/discharging devices.

4. Discussion

The Top-down approach indicates some important findings in thermal energy storage economics that have often been ignored. First, for a fixed storage period, the maximum acceptable storage costs depend on the user's economic environment (e.g. *industry* or *building*) due to variances in payback period, discount rate, and costs of reference energy from the market. Second, the annual number of storage cycles has by far the largest influence on the maximum acceptable storage capacity costs and the cost effectiveness of storages. Third, scenarios exist under which most storage technologies are economical. In this case, systems should be compared with regard to physical and technical attributes.

The Bottom-up approach has been applied to analyse the costs of 26 thermal energy storages. Contrary to commercial water storages, several innovative storages are subject of ongoing research and, hence, their corresponding costs are roughly estimated. The comparison of SCC_{acc} and SCC_{real} indicates that, at present, seasonal storage is only economical using large hot water storages; other technologies require at least an order of magnitude reduction in costs. That implies that the development of storage systems which allow a high annual number of storage cycles is economically favourable over seasonal storages with exactly one cycle per year. In addition, the Bottom-up analysis showed that a major fraction of the investment costs of the investigated storages are not costs of the heat storage material itself but costs of the storage container or reactor incl. charging/discharging unit. Therefore, R&D activities on cost-effective TES systems have to consider both cost-effective heat storage materials and cost-effective storage container or reactor components.

The economic evaluation via Top-down and Bottom-up approach is not limited to thermal energy storage, it can also be applied to e.g. electrical energy storage. In this case, *REC* corresponds to the costs of electricity.

5. Conclusions

A simple tool for the economic evaluation of thermal energy storages via a Top-down and a Bottom-up approach has been developed and tested on various existing storages. This tool provides a rough estimate of the economic viability of an energy storage for a specific user and application. The main finding is that the number of storage cycles per year has the largest influence on the maximum acceptable storage capacity costs (costs per installed storage capacity). At present and with respect to the storages under investigation, seasonal TES is only economical via large sensible hot water storages. Contrary, short-term storages with several hundred cycles per year allow several hundred times higher costs because of the larger energy turnover. If the annual number of storage cycles is sufficiently high, all TES technologies can become economically competitive and systems should be compared with regard to physical and technical attributes.

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The responsibility for the content of this publication is with the authors.

References

[1] A. Hauer, J. Quinnell, E. Lävemann. *Energy storage technologies - characteristics, comparison, and synergies*, In: Transition to Renewable Energy Systems, 1st ed., Wiley-VCH, 2013.

[2] C. Rathgeber, E. Lävemann, A. Hauer. *Economic top-down evaluation of the costs of energy storages - A simple economic truth in two equations*. Journal of Energy Storage 2 (2015) 43-46.

[3] C. Rathgeber, S. Hiebler, E. Lävemann, A. Hauer. *Economic Evaluation of Thermal Energy Storages via Top-down and Bottom-up Approach*. Greenstock 2015 – 13th International Conference on Energy Storage, Beijing, China.

[4] VSI – Vacuum super insulated storage, price list 04/2015 and final report from www.vakuum-pufferspeicher.de

[5] J.B. Johansen, M. Dannemand, W. Kong, G. Englmair, J. Fan, J. Dragsted, B. Perers, S. Furbo. *Practical application of compact long term heat storage. Laboratory testing of solar combi system with compact long term PCM heat storage.* SHC Conference 2015, Istanbul, Turkey.

[6] G. Englmair, M. Dannemand, J.B. Johansen, W. Kong, J. Dragsted, S. Furbo, J. Fan. *Testing of PCM Heat Storage Modules with Solar Collectors as Heat Source.* SHC Conference 2015, Istanbul, Turkey.

[7] P. Dolado, A. Lázaro, J.M. Marín, B. Zalba. *Characterization of melting and solidification in a real scale PCM-air heat exchanger: Experimental results and empirical model*. Renewable Energy 36 (2011) 2906-2917.

[8] A. Lázaro, P. Dolado, J.M. Marín, B. Zalba. *PCM-air heat exchangers for free-cooling applications in buildings: Experimental results of two real-scale prototypes*. Energy Conversion and Management 50 (2009) 439-443.

[9] A. Campos-Celador, G. Diarce, J. Terés-Zubiaga, T. Bandos, A. García-Romero, L.M. López, J.M. Sala. *Design of a Finned Plate Latent Heat Thermal Energy Storage System for Domestic Applications*. SHC Conference 2013, Freiburg, Germany.