Industry energy storage application

Economic Evaluation of Thermal Energy Storages via Top-down and Bottom-up Approach

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SUMMARY

The storage capacity costs (€·kWh_{cap}^{-1}) 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 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 main finding of the economic evaluation is that the annual number of storage cycles has by far the largest influence on the cost effectiveness of storages. At present, seasonal 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.

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. To evaluate storage costs, a Top-down and a Bottom-up approach have been applied in this study.

The Top-down approach assumes that the cost of energy supplied by the storage should not exceed the costs of energy from the market [1] (hereinafter referred to as *REC* = reference energy costs). This assumption can be taken as a kind of *first law of economics* [2] of energy storages. Following this assumption, the maximum acceptable storage capacity costs (hereinafter referred to as SCC_{acc}) are calculated from the discount rate of storage capital, the payback period of the investment, the number of storage cycles, and the reference energy costs.

On the other hand, 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 technical parameters the costs of the

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

[2] There are different definitions. We refer to the very basics (Gossen 1983).

storage divided into investment costs (storage material, storage container or reactor, charging and discharging device), operating costs, and additional costs, e.g. maintenance or installation costs. 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.

METHODS

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 (Broverman 2010). *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 class. 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 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*.

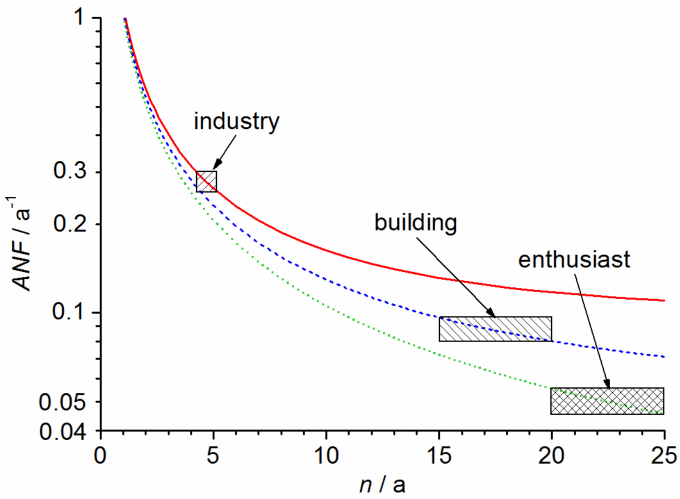

Figure 1. Annuity factor ANF as a function of payback period n for three user classes (industry i = 10%, building, i = 5% and enthusiast i = 1%); framed regions indicate acceptable annuity factors for these user classes.

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 ($€\cdot\mathrm{kWh}_{\mathrm{cap}}^{-1}$), are simply the product of the substituted reference energy costs *REC*, given in € per kWh energy ($€\cdot\mathrm{kWh}_{\mathrm{en}}^{-1}$), and the number of cycles per year N_{cycle} divided by the annuity factor *ANF*:

$$SCC_{acc} = \frac{REC \cdot N_{cycle}}{ANF} \qquad (2)$$

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* / $€\cdot\mathrm{kWh}_{\mathrm{en}}^{-1}$		*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.

The Bottom-up approach focuses on the realised storage capacity costs (SCC_{real}) of existing storage systems. SCC_{real} are simply the investment costs *INC* divided by the installed storage capacity *SC*:

$$SCC_{real} = \frac{INC}{SC} \qquad (3)$$

INC sums up 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 ($€\cdot\mathrm{kWh}_{\mathrm{cap}}^{-1}$).

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.

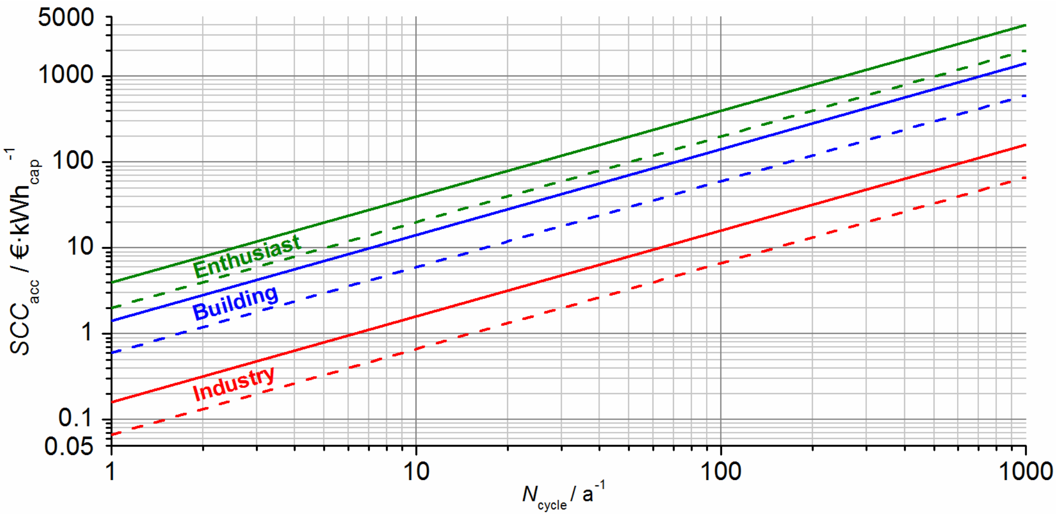

Figure 2. Maximum acceptable storage capacity costs SCC$_{acc}$ calculated via Eq. (2) for three user classes as a function of storage cycles per year N$_{cycle}$; enthusiast high/low case (green solid/dashed line), building high/low case (blue solid/dashed line), and industry high/low case (red solid/dashed line). Economic boundary conditions for high/low cases are given in Table 1.

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 up to thousand cycles per year. For reasons of clarity, the comparison of *SCC*$_{acc}$ (Top-down approach) with *SCC*$_{real}$ (Bottom-up approach) is split up into four parts: 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.

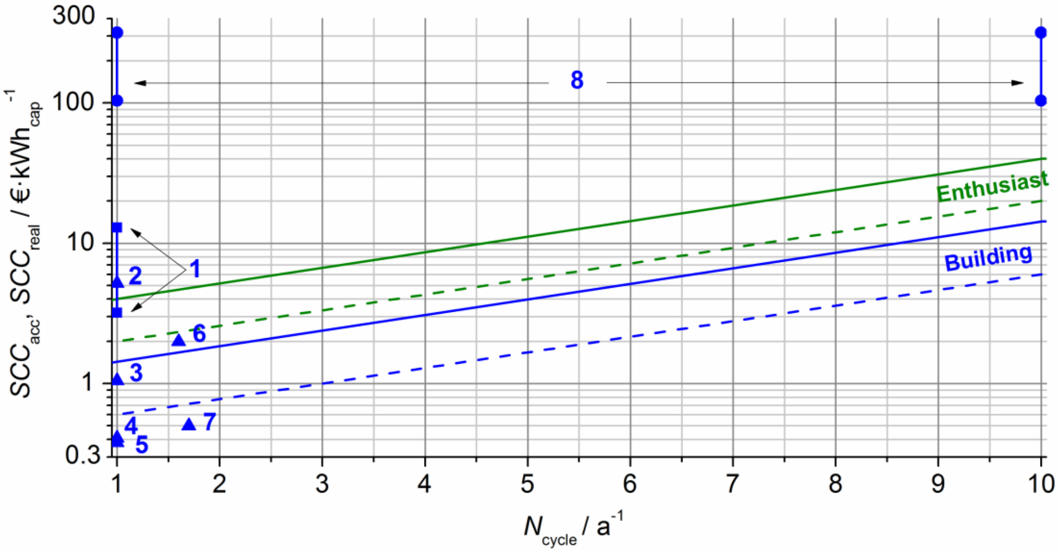

Figure 3. Maximum acceptable storage capacity costs (SCC$_{acc}$) and realised storage capacity costs (SCC$_{real}$) for long-term storages.

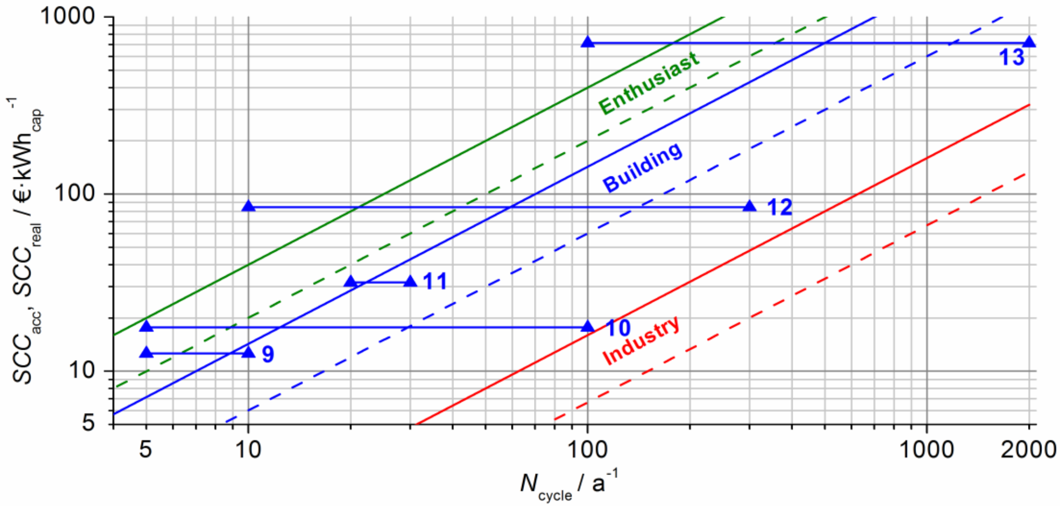

Figure 4. Maximum acceptable storage capacity costs (SCC_{acc}) and realised storage capacity costs (SCC_{real}) for hot water storages up to 30 m^3 storage volume.

In the case of long-term storages and hot-water storages up to 30 m³ storage volume, the *building* sector is usually targeted. Therefore, SCC_{real} of these storages are compared with SCC_{acc} corresponding to the user classes *building* and *enthusiast*. Since these storages can be integrated in a variety of systems, exemplary ranges are indicated for N_{cycle}.

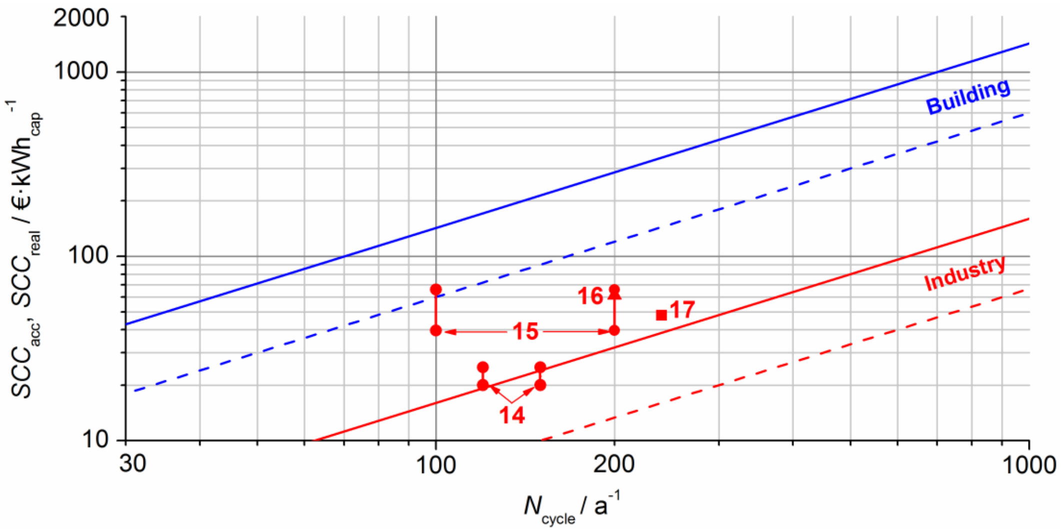

Figure 5. Maximum acceptable storage capacity costs (SCC_{acc}) and realised storage capacity costs (SCC_{real}) for short-term storages in the industry sector.

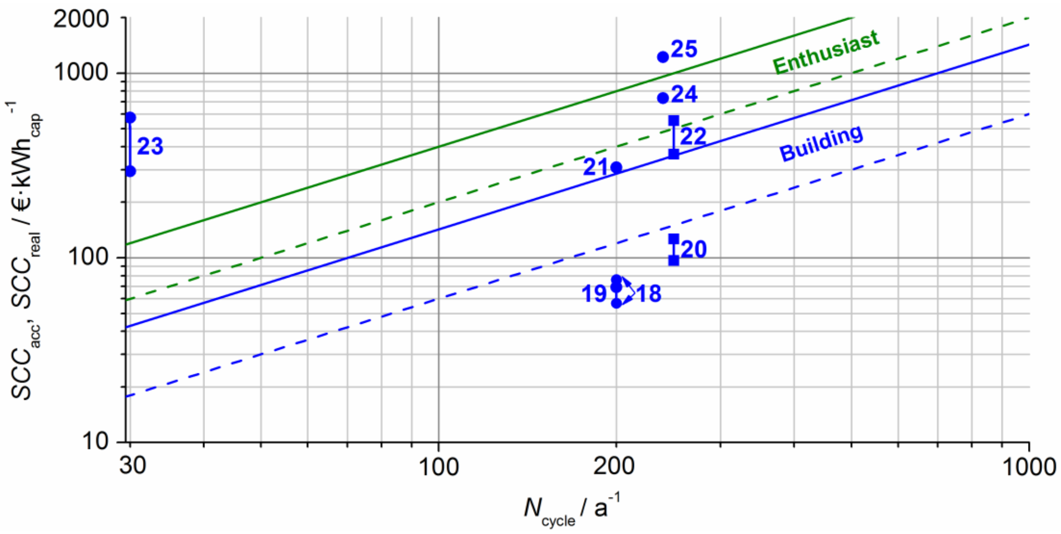

Figure 6. Maximum acceptable storage capacity costs (SCC_{acc}) and realised storage capacity costs (SCC_{real}) for short-term storages in the building sector.

On the other hand, in the case of short-term storages, storage systems are intended for both *industry* and *building*. Among the investigated short-term storages, systems 14 – 17 and 18 – 25 have been developed for *industry* and *building* applications, respectively.
In the case of the systems 1, 8, 14, 15, 18, 20, 22, and 23, cost ranges are given for SCC_{real} indicating the interval between actual costs (upper limit) and expected costs that can be considered to be possible 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.

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} / €·kWh$_{cap}^{-1}$
1: NaOH storage (EMPA)	NaOH sorption; seasonal storage for domestic applications	1	8,000 – 32,400	2,500	3.20 – 13.0
2: Ottrupgård, 1995	Hot water; 1,500 m³; 35 – 60 °C	1	225,500	43,500	5.18
3: Sunstore 2, 2003 (www.sunstore.dk)	Hot water; 10,000 m³; 35 – 90 °C	1	671,100	638,000	1.05
4: Sunstore 3, 2013 (www.sunstore.dk)	Hot water; 60,000 m³; 10 – 90 °C	1	2,671,100	6,960,000	0.38
5: Sunstore 4, 2012 (www.sunstore.dk)	Hot water; 75,000 m³; 10 – 90 °C	1	2,281,900	5,570,000	0.41

6: Ackermannbogen (ZAE Bayern) (Dallmayer et al. 2010)	Hot water; 6,000 m^3; 20 – 90 °C	1.6	942,400	472,400	1.99
7: Attenkirchen (ZAE Bayern)	Hot water + borehole heat exchanger; 7,000 m^3; 10 – 90 °C	1.7	327,300	654,600	0.50
8: SAT storage (DTU, Uni. Graz)	supercooled sodium acetate trihydrate, seasonal storage modular system	1 – 10	2.700 – 4.120	13 – 26	104 - 317
9: VSI – 30 m^3 (ZAE Bayern, Hummelsberger GmbH)	Vacuum super insulated hot water storage; 30 m^3; 5 – 95 °C	5 – 10 [a]	37,888	3,020	12.5
10: allSTOR VPS/3 2000/3-7 (Vaillant)	Hot water; 2,000 l; 5 – 95 °C	5 – 100 [a]	3,559	202	17.6
11: VSI – 5 m^3 (ZAE Bayern, Hummelsberger GmbH)	Vacuum super insulated hot water storage; 5 m^3; 5 – 95 °C	20 – 30 [a]	15,962	504	31.7
12: actoSTOR VIH RL 500-60 (Vaillant)	Hot water; 500 l; 5 – 110 °C	10 – 300 [a]	4,953	58.7	84.4
13: actoSTOR VIH CL 20 S (Vaillant)	Potable water; 20 l; 10 – 70 °C	100 – 2000 [a]	965	1.35	715
14: Ice storges (Cristopia)	Sstorages 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) (Krönauer et al. 2015)	Mobile sorption heat storage (2x14 t zeolite) for industrial waste heat recovery	240	440,000	9,200	47.8
18: SolarHeatCool+ PCM (ZAE Bayern) (Helm et al. 2013)	1 m^3 PCM storage ($CaCl_2 \cdot 6H_2O$); 22 – 36 °C	200	4,700 – 6,300	83	56.6 – 75.9
19: TubeICE (VITO NV)	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 NV)	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 (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

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

INC of the large water storages 2-7 and of the commercial water storages 9-13 are actual costs of the installed systems and list prices (VSI 2013), respectively. In the case of the other investigated systems, INC correspond to costs of prototypes or estimated costs and, therefore, numbers are roughly rounded.

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 SCC_{acc} and the cost effectiveness of storages. Third, scenarios exist under which most storage technologies are economical and, then, systems should be compared with regard to technical or physical attributes.

The Bottom-up approach has been applied to analyse the costs of 25 thermal energy storages so far. 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 sensible storage, e.g. large water storages. 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 order to identify major cost drivers and, thereby, cost reduction potentials for the investigated storage systems, the composition of the investment costs has to be analysed in detail.

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.

CONCLUSIONS

A Top-down and a Bottom-up approach have been applied to evaluate the economics of energy storages. The analysis shows that the annual number of storage cycles has by far the largest influence on the cost effectiveness of storages. At present, seasonal storage is only economical via sensible heat storage. Contrary, if the annual number of storage cycles is sufficiently high, all thermal energy storage technologies can become economically competitive.

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