Key performance indicators in thermal energy storage: survey and assessment

Luisa F. Cabeza[1,*], Esther Galindo[2], Cristina Prieto[3], Camila Barreneche[1,2], A. Inés Fernández[2]
[1]GREA Innovació Concurrent, Universitat de Lleida, Edifici CREA, Pere de Cabrera s/n, 25001 Lleida, Spain. Tel.: +34.973.00.35.76
[2]Department of Materials Science & Metallurgical Engineering, Universitat de Barcelona, Martí i Franqués 1-11, 08028 Barcelona, Spain
[3]Abengoa Research. C/Energía Solar 1,41012, Seville, Spain. Tel.: +34 954 93 71 11

Abstract

Thermal energy storage (TES) is recognised as a key technology for further deployment of renewable energy and to increase energy efficiency in our systems. Several technology roadmaps include this technology in their portfolio to achieve such objectives. In this paper, a first attempt to collect, organise and classify key performance indicators (KPI) used for TES is presented. Up to now, only KPI for TES in solar power plants (CSP) and in buildings can be found. The listed KPI are quantified in the literature and compared in this paper. This paper shows that TES can only be implemented by policy makers if more KPI are identified for more applications. Moreover, close monitoring of the achievements of the already identified KPI needs to be carried out to demonstrate the potential of TES.

Key-words: Thermal energy storage (TES), key performance indicator (KPI), solar power plants (CSP), buildings.

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[*] Corresponding author: Prof. Dr. Luisa F. Cabeza ✉ lcabeza@diei.udl.cat, Tel: +34.973003576

1. Introduction

Thermal energy storage (TES) systems can store heat or cold to use the heat when it is required, at different temperature, place or power. The main applications of TES are those scenarios where it is needed to overcome the mismatch between energy generation and energy use [1]. According to European Association for Storage of Energy (EASE) and European Energy Research Alliance (EERA) [2] these scenarios are:

- In the industrial process heat sector to be used as a heat management tool to increase efficiency and to reduce specific energy consumption of industrial manufacturing processes.
- In power generation with thermal conversion processes (combustion engines, steam or gas turbines, organic Ranking cycles (ORC), etc.) to make conventional power plants more flexible and to support chemical heat pump (CHP) implementation, where heat production can be stored temporarily for subsequent use.
- For seasonal heat storage in combination with district heating systems.
- For intermediate storage of compression heat in Adiabatic Compressed Air Energy Storage plants.
- In large scale solar thermal systems for heating and cooling, process heat and power generation including Concentrated Solar Power.
- For heating of residential buildings, whereas a demand side management system allows the use of electric energy from renewable sources for heating with electric storage heaters and / or heat pumps.
- For storage of heat from electric heating elements working as a fast balancing service in the electricity grid.

The main requirements for the design of a TES system are high energy density in the storage material (storage capacity), good heat transfer between the heat transfer fluid (HTF) and the storage material, mechanical and chemical stability of the storage media, compatibility between the storage material and the container material, complete reversibility of a number of cycles, low thermal losses during the storage period, and easy control of the system performance. Moreover, the most important design criteria are the operation strategy, the maximum load needed, the nominal discharge conditions and energy storage capacity, and the integration into the whole application system. Finally, cost is a main parameter for industry deployment.

A specific feature of TES is their diversity with respect to applications that require different temperatures, energy/power levels and use of different heat transfer fluids. That means a broad portfolio of TES designs are needed and good performance indicators have to be well defined for the comparison. In that sense, a Standardization technical committee of AENOR

(AEN/CTN/206/SC117) is working in a document to define parameters, evaluation procedures and methodology for the analysis of results for thermal energy system in concentrated solar power (CSP) plants.

Technology roadmaps match short-term and long-term goals with specific technology solutions to meet those goals [3]. The development of roadmaps helps to reach a consensus about the needs from the industry/transport/etc. and the technologies required to reach those needs; it provides a mechanism to help developing that technology; and it coordinates the different stakeholders needed to enhance or deploy the technology.

Recently, the technology roadmaps carried out in thermal energy storage or in energy applications including TES identify KPI for TES. Unfortunately, this first attempt has been done individually and no comparison has been carried out.

A key performance indicator (KPI) is a performance measurement that evaluates the success of a particular activity. Success can be either the achievement of an operational goal (e.g. zero defects, custom satisfaction, etc.) or the progress toward strategic goals. Accordingly, choosing the right KPI relies upon a good understanding of what is important to the application/technology/etc., therefore, its present state and its key activities need to be well assessed and are associated with the selection of the KPIs. This assessment often leads to the identification of potential improvements, so performance indicators are usually associated with "performance improvement" initiatives. KPI is extensively used in business and financial assessments, and getting more importance in technical assessments.

KPI can be categorized as:

- Quantitative vs. qualitative indicators: it may be measurable by giving a magnitude value or by giving an adjective without scale.
- Leading vs. lagging indicators: it predicts the outcome of a process or present the success or failure *post hoc*.
- Input process vs. output indicators: it measures the amount of resources consumed during the generation of the outcome, represents the efficiency of the production of the process, or reflects the outcome or results of the process activities.
- Directional indicators: it specifies whether or not one technology/application is being promoted and getting better.
- Financial indicators: it takes into account the economic aspects of one technology/application/etc.

Key performance indicators have been used in other energy topics. For example, Personal et al. [4] defined KPI to be a useful tool to assess smart grid goals. These authors claimed that an advantage of using KPI as metric is its capacity of assist in assessing the smart grid concept even though its multidisciplinary character, since it involves a stack to technologies. Similarly, González-Gil et al. [5] stated that KPI enable a holistic approach considering the numerous interdependences between subsystems when evaluating urban rail systems to minimise their energy consumption and reduce their operational costs and environmental impact.

KPI have been recently used to evaluate the energy efficiency performance of energy equipment, processes and systems as first step to effective energy management in production. A novel method was presented by May et al. [6], pointing out that the main drawback of such systems is the difficulty to obtain all the necessary energy data. Similarly, Hanak et al. [7] defined KPIs to assess the performance of a coal power plant. These authors claimed that high reliability indices obtained in the analysis would lead to reduced application of conservative safety factors on the plant equipment.

The aim of this paper is to survey all KPI for TES technology used in documents aimed for policy makers and to try to classify them in order to do an assessment and a first attempt of unification. The organisation of the paper is based on TES final applications.

2. KPI for TES in concentrated solar power plants (CSP)

Studies published by European Solar Thermal Electricity Association (ESTELA) show that the development and deployment of CSP will be increased hugely during the future period between 2015 and 2050 (Table 1) [8]. The reference scenario presented shows an annual installation of about 550 MW between 2015-2030 and of 160 MW in 2050, the moderate goes from 5000 MW/year in 2015 to 40557 MW in 2050, and the advanced scenario up to 80,827 MW/year in 2050. These projections show an employment rate from 10,000 jobs/year in 2015 in the reference scenario to more than two million jobs/year in 2050 the advanced scenario.

Table 1. Scenarios for Concentrating Power Development between 2015 and 2050 under conservative, moderate and aggressive development scenarios [9]

Annual and cumulative capacity	**2015**	**2020**	**2030**	**2050**
Reference				
Annual Installation (MW)	566	681	552	160
Cost €/kW	3,400	3,000	2,800	2,400
Investment billion €/year	1.924	2.043	1546	0.383
Employment job-year	9,611	13,739	17,736	19,296
Moderate				
Annual Installation (MW)	5,463	12,602	19,895	40,557
Cost €/kW	3,230	2,850	2,660	2,280
Investment billion €/year	17.545	35.917	52.921	92.470
Employment job-year	83,358	200,279	428,292	1,187,611
Advanced				
Annual Installation (MW)	6,814	14,697	35,462	80,827
Cost €/kW	3,060	2,700	2,520	2,160
Investment billion €/year	20.852	39.683	89.356	174.585
Employment job-year	89,523	209,998	629,546	2,106,123

This growth is also reflected in the International Energy Agancy (IEA) CSP roadmap [9], which projects an electricity share of total energy consumption from CSP plant of 15% in Europe up to 40% in Australia, Chile, India, and other regions of the world (Table 2).

Table 2. Electricity from CSP plants as share of total electricity consumption [10]

Countries	**2020**	**2030**	**2040**	**2050**
Australia, Central Asia*, Chile, India (Gujurat, Rajasthan), Mexico, Middle East, North Africa, Peru, South Africa, United States (Southwest)	5%	12%	30%	40%
United States (remainder)	3%	6%	15%	20%
Europe (mostly from imports) Turkey	3%	6%	10%	15%
Africa (remainder), Argentina, Brazil, India (remainder)	1%	5%	8%	15%
Indonesia (from imports)	0.5%	1.5%	3%	7%
China, Russia (from imports)	0.5%	1.5%	3%	4%

*Central Asia Includes Afganistan, Kazakhstan, Kyrgyzstan, Pakistan, Tajikistan, Turkmenistan and Uzbekistan

The KPI for CSP plants found in the different roadmaps are summarised in Table 3. The collection is based on the KPI defined by ESTELA [10] and it is completed by those given by the European Industrial Initiative on solar energy – CSP [11] and SETIS [12].

ESTELA defined KPI-1 for CSP plants as the overarching KPI power purchase agreement (PPA) [10]. The PPA (or feed-in tariff [FiT] in specific countries) is the value that will be accepted by the promoter and which de facto triggers the building of the plants. The PPA depends on many factors, some of them related to the technology (direct normal irradiance

(DNI) and plant size) and other factors related to financial conditions (duration, escalation factors, public support such as grants, concessional loans, guaranty coverage, etc.). In that study, the standard reference project was defined as 150 MW, 4 hours storage plant, with fixed 25 year. For a DNI of 2050 kWh/m^2/year, the PPA is expected to decrease from 19 c€/kWh in 2013 to 12 in 2020, and for a DNI of 2600 kWh/m^2/year, the PPA is expected to decrease from 16 c€/kWh in 2013 to 10 in 2020.

The other KPI aim to increase efficiency and reduce costs (KPI-2 to KPI-8), to improve dispatchability (KPI-9 and KPI-10), and to improve the environmental profile (KPI-11 and KPI-12).

The increase of efficiency and reduction of costs in 2050 should be achieved by the increment of solar-to-electricity conversion efficiency (KPI-2), where the increase varies through technologies for ESTELA [10], from 20% for trough to 65% for tower, and it is 20% for the European Industrial Initiative on solar energy – CSP (this value is not related to any technology) [11]; the increase of the heat transfer fluid (HTF) temperature (KPI-3), higher than 500 ºC or 900 ºC depending on the technologies; the reduction of cost of installed products and O&M (operations and maintenance for state-of-the-art commercial plants (KPI-4), reduction of 20% of capital expenditures (CAPEX) both for ESTELA and the European Industrial Initiative on solar energy – CSP; the reduction of power block costs in Ranking cycles (KPI-5), reaching 1,200 €/kWp when using advanced HTF and 800 €/kWp when using hybrid plants; the reduction of collector costs (KPI-6), going from 250 €/m^2 with trough collectors and thermal oil as HTF in 2010 to 200 €/m^2 with advanced hybrid plants (hybridation understood as when solar energy is complemented with other energy sources such as biomass or gas) in 2050; the reduction of the specific cost of the HTF system, aiming to go down to 100 €/kWth with advanced hybrid plants in 2050. This list is completed by SETIS with the increase of operating hours (KPI-8), going from 2000 hours/year in 2010 to 2830 hours/year in Europe and 3260 hours/year in North Africa in 2050.

The improvement of dispatchability would be achieved by the reduction of the investment on cost of storage (KPI-9), the same of ESTELA and SETIS, from 35,000 €/kWh$_{th}$ in 2010 to 15,000 €/kWh$_{th}$ in 2050; and by the increase of efficiency of storage (KPI-10), from 94% to 96%.

Improvement of the environmental profile of CSP technology would be achieved by a substantial reduction of water consumption with minimum performance reduction (KPI-11), highlighted by ESTELA and the European Industrial Initiative on solar energy – CSP, and substantial reduction of CO_2 emissions (KPI-12), highlighted by SETIS.

Table 3. KPI collected among three different sources for CSP.

Description	**Metric**		**BASELINE**	**TARGETS**	
			2010	**2015**	**2020/2025**
Overarching KPI	**KPI-1**	PPA	See values on Table 4 [10]		
1. Increase efficiency and reduce costs	**KPI-2**	Increased solar-to-electricity conversion efficiency	15% Trough [10] 8.5% Fresnel [10] 17% Dish [10] 12.5% Tower [10]	(relative to baseline) +5% Trough [10] +15% Fresnel [10] +15% Dish [10] +50% Tower* [10]	1. (relative to baseline) +20% Trough [10] +18% Trough [13] +30% Fresnel [10] +14% Fresnel [13] +30% Dish [10] +65% Tower [10] +20% Tower [13] 20% (respect 2009) – not technological specific [11]
	KPI-3	Increase HTF Temperature	400°C Trough [10] 280°C Fresnel [10] 650°C Dish [10] 250°C Tower [10]	560°C Tower [10] 420°C Fresnel [10]	>500°C Trough [10,13] >500°C Fresnel [10,13] >900°C Dish [10,13] >900°C Tower [10,13]
	KPI-4	Reduce cost of installed products and O&M for state of-the-art commercial	2% of CAPEX [10]	-10% [10]	-20% [10,13,14] -20% (respect 2009) [9]

		plants			
	KPI-5	Reduce power block costs (Rankine cycle)	1,300 €/kWp Trough with thermal oil [10]	1,300 €/kWp Molten Salt as HTF [10] 1,000 €/kWp Hybrid plant [10]	1,200 €/kWp Advanced HTF [10] 800 €/kWp Advanced hybrid plant [10]
	KPI-6	Reduce collector costs	250 €/m^2 Trough with thermal oil [10]	250 €/m^2 Molten Salt or Hybrid plant [10]	200 €/m^2 Advanced hybrid plant [10]
	KPI-7	Reduce the specific cost of the HTF system	330 €/kW$_{th}$ Trough with thermal oil [10]	295 €/kW$_{th}$ Molten Salt as HTF [10] 165 €/kWth Hybrid plant [10]	120 €/kW$_{th}$ Advanced HTF [10] 100 €/kWth Advanced hybrid plant [10]
	KPI-8	Increase operating hours	2000 hours /year [12]	---	2830 hours/year in Europe and 3260 hours/year in North Africa**[12]
2. Improve dispatchability	**KPI-9**	Investment cost of storage	35,000 €/MWh$_{th}$ [10,12]	20,000 €/MWh$_{th}$ [10,12]	15,000 €/MWh$_{th}$ [10, 12-14]
	KPI-10	Increase efficiency of storage	94% [10]	---	96% [10,13,14]
3. Improve the environmental profile	**KPI-11**	1. Substantial reduction of water consumption with only minor loss of	3.5 litres/kWh [10,12]	---	< 1 litre/kWh [10,12,14,] < 15 litre/year/m^2 [13]

		performance relative to current water cooling system [10] 2. = (but without specify litres) and Substantial reduction in land use per MW installed [11] 3. Reduce water consumption			
	KPI-12	If the maximum potential for CSP is realised it could avoid up [12]	---	---	to 35 Mt/ year CO_2 in 2020 and 130 Mt/year CO_2 in 2030. This could amount to a cumulative saving of 1035 Mt of CO_2 for 2010-2030 [12]

* After Gemasolar breakthrough

**To realise this, CSP systems with thermal storage and consequently larger collector fields are needed. A CSP system with 6 h of thermal storage would need a solar field about double the size than one without.

Table 4. Values of KPI PPA [10]**

PPA **in c€/kWh**	**2013**	**2015**	**2020**
DNI 2050 (kWh/m^2/year)	19 [10]	16 [10]	12 [10,13,14]
DNI 2600 (kWh/m^2/year)	16 [10]	13 [10]	10 [10,13,14]

** PPA (no escalation) and without any kind of public support (no grants, no soft loans, etc.). The CAPEX for this typical plant is currently in the range of 550 million €.

According to International Renewable Energy Agency (IRENA), in a solar power plant the solar field components are the most capital-intensive part (Figure 1). The price of a solar collector in through technology is mainly determined by the cost of the metal support structure, the receiver, the mirrors, the heat transfer system and the HTF. The thermal energy storage system varies from 10 to 20% of total costs depending of the selected storage system (direct-indirect, storage fluids, temperature, etc.) and the size of the storage system (hours). In the case of molten salt systems, the salt and the storage tanks are the largest contributors to this cost [15].

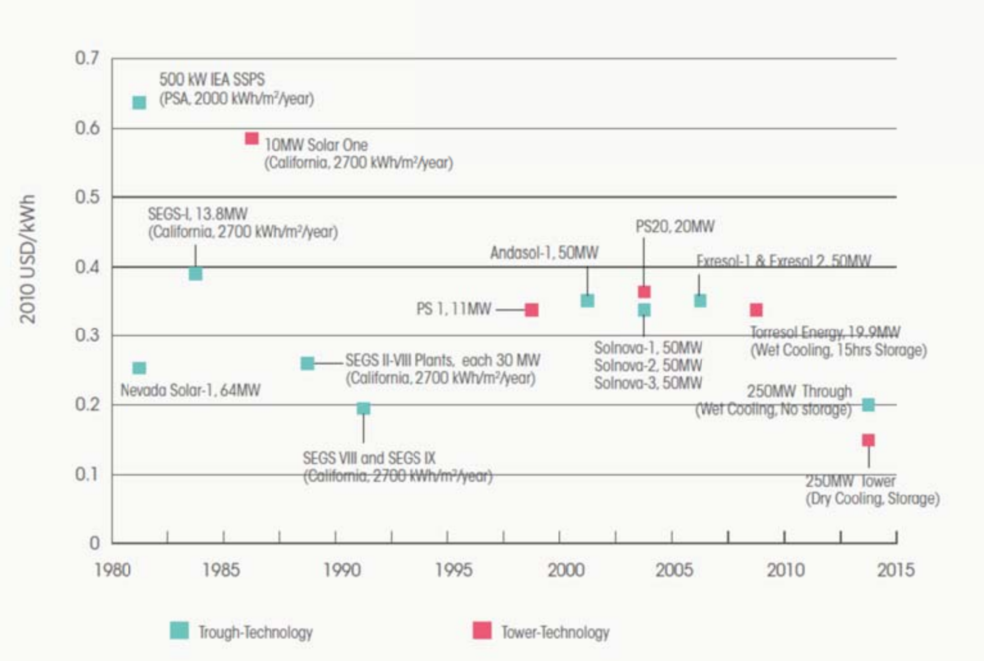

Figure 1. IRENA estimated LCOE for existing and proposed parabolic trough and solar power CSP plants[15].

In 2012 the International platform of climate change - Special Report on Renewable Energy Sources and Climate Change Mitigation (IPCC SRREN) [16] showed that cost reduction for

CSP technologies are expected to come from plant economies of scale, reducing costs of components through material improvements and mass production, and implementing higher-efficiency processes and technologies (Figure 2).

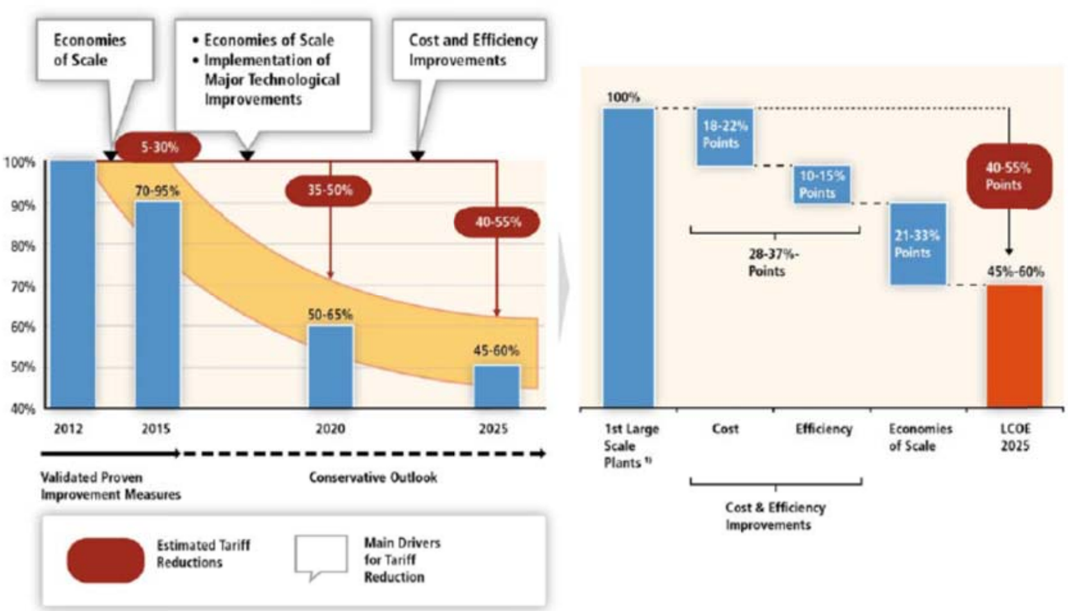

Figure 1. Expected cost decline for CSP plants from 2012 to 2025.
The cost number includes the cost of the plant plus financing [17] . As reduction ranges for cost, efficiency and economies of scale in the right panel overlap, their total contribution in 2025 amounts to less than their overall total [16]
Notes: 1) Referring to 2010 to 2013 according to planned commercialization date of each technology (reference plant).
2) Tariffs equal the minimum required tariff, and are compared to 2012 tariffs.

An analysis of how to achieve the projected costs showed in Figure 1 and Figure 2with the KPI listed in Table 3 shows that:

- New heat transfer fluids working at 900ºC (KPI-3) will improve storage possibilities, reducing cost.
- In parallel, higher efficiency in power cycles can be reached (supercritical cycle with eff>50%) (KPI_2 and KPI-5).
- The storage system efficiency is closely tied to the heat transfer fluid as well as to higher temperatures. But other criteria as new storage systems with higher energy density (>400 kJ/kg), lower market costs, design with lower heat losses and parasitic (in molten salt) and other proposals are under development (KPI-9 and KPI-10).

Advance key components have been also considered in Figure 2:

- Larger aperture collectors are in development (KPI-6).
- Higher optical efficiency in the mirror (KPI-2).
- Reduction of the emissivity in receivers while maintaining the high absorption (KPI-2).

- Finally, the learning curves of the current plants in operation will allow a reduction in O&M costs and bottoms-up engineering will be applied (KPI-4).
- Also dry cooling systems that are being installed currently help in the achievement of KPI-11.

3. Buildings

Energy consumed in the building sector is growing in several countries, most of them developing countries, because the population is increasing the use of heating/cooling systems, number of appliances, number of smart phones/laptops/etc., that is, the amount of energy services. However, this increment is not as high as expected due to the implementation of new energy efficiency policies (mostly in developed countries). This trend was state by Urge-Vorsatz et al. [18].

On the other hand, it is interesting to note the big penetration of solar energy for heating purposes estimated by the IEA [19] (see Figure 3)..

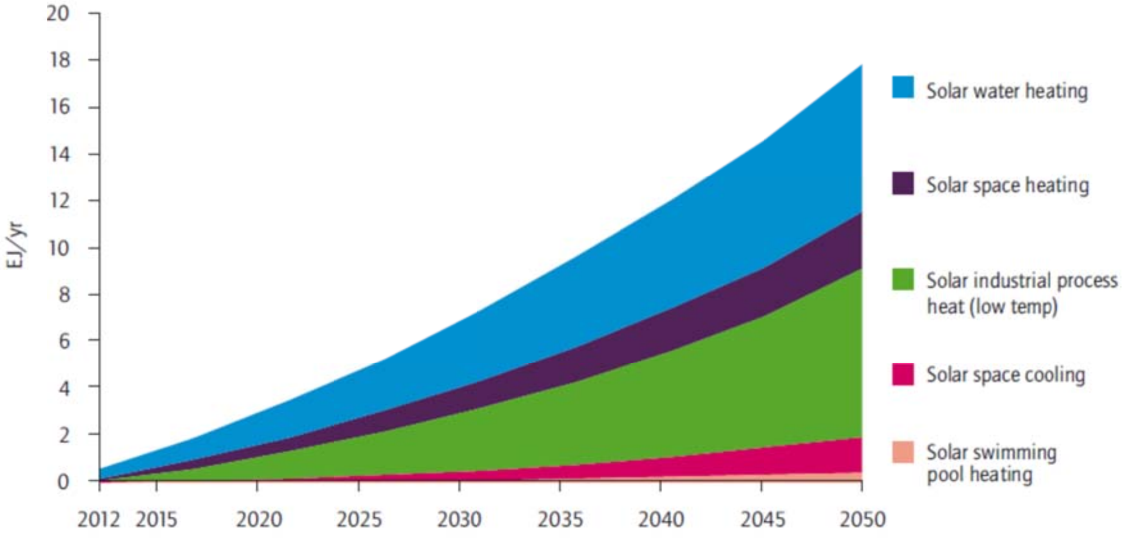

Figure 3. Roadmap vision for solar heating and cooling (Exajoule/yr)[19]

Moreover, the Roadmap EeB Heating and Cooling equipment [19] presented cost and performance goals for heating and cooling technologies of buildings in 2030 and 2050 (Table 5). According to this, thermal energy storage will be based in three different technologies, phase change materials (PCM), thermochemical and centralised, with a reduction of installed costs up to 85% of that in 2010, and a delivered energy cost that will depend on the cycle.

On the other hand, the cross-cutting panel of the European Technology Platform on Renewable Heating & Cooling (RHC Platform) published a roadmap where KPI for TES in building heating and cooling applications were identified and quantified (Table 6) [20]. The baseline in this roadmap is for 2012, with target for 2016 and 2020. Here the KPI are classified in TES technologies, sensible heat storage (KPI-1 to KPI-9), latent heat storage (KPI-10 to KPI-13), thermochemical heat storage (KPI-14 to KPI-17), and they are also given at system level (KPI-18 to KPI-22).

Table 5: Cost and performance goals for heating and cooling technologies, 2030 and 2050 [19]

	2030		**2050**	
Active Solar Thermal				
Installed cost	-50% to -75%		-50% to -75%	
Maintenance cost	0% to -40%		0% to -40%	
Delivered energy cost	-50% to -60%		-50% to -65%	
Thermal energy storage	PCM, thermochemical and centralised		PCM, thermochemical and centralised	
Installed cost	-50% to -75%		-65% to -85%	
Delivered energy cost	Depends on cycle regime		Depends on cycle regime	
Heat pumps	Space/water heating	Cooling	Space/water heating	Cooling
Installed cost	-20% to -30%	-5% to -15%	-30% to -40%	-5% to -20%
Coefficient of performance	30% to 50%	20% to 40%	40% to 60%	30% to 50%
Delivered energy cost	-20% to -30%	-10% to -20%	-30% to -40%	-15% to -25%
CHP	Fuel cells	Microturbines	Fuel cells	Microturbines
Installed cost	-40% to -55%	-20% to -30%	-60% to -75%	-30% to -50%
Electrical efficiency	35% to 40%	30% to 35%	35% to 45%	35% to 40%
Total efficiency	75% to 80%	70% to 75%	75% to 85%	75% to 85%
Delivered energy cost	-45% to -65%	-10% to +5%	-75% to -85%	-15% to +20%

Note: improvements in costs on performance are expressed in percentage relative to the base year (2010) specification. However, the electrical and total efficiencies for CHP are actual percentages, not improvements. For fuel cells, the delivered energy cost is for a thermal energy and is based on a long-run cost of CO_2 free hydrogen of between USD 15/GJ and USD 25/GJ in 2050.

Sensible heat storage aims are a reduction of the costs in the cost of the containment (KPI-1), going from 400-900 € of a 1000 L tank (excluding insulation and VAT) in 2012 to 300-700 € in 2020; a reduction of the heat loss of the storage capacity, from 150-200 W for a storage vessel of 1000 L in 2012 to 50 W in 2020; a reduction of the cost of high performance insulation, down to less of 100 €/m^2 (excluding VAT). Related to underground thermal energy storage (UTES), there is an aim of increasing the energy efficiency up to 75% (KPI-4); increasing the lifetime of the systems at high temperature up to 20-30 years (KPI-5); and reducing the maintenance costs down to 2-4% of the operational cost (KPI-6). Finally, related to the heat transfer and storage fluids, the viscosity needs to be reduced (KPI-7), up to 30% in 2020; the annual consumption for pumping in DHW systems needs to be reduced (KPI-8), to a maximum of 50 kWh; and their energy density needs to be increased to reduce the storage volume (KPI-9), up to 30% in 2020.

In latent heat storage the objectives are to develop stable micro-encapsulated salt hydrate phase change materials (PCM) (KPI-10), with a production technology optimised and with material available at less than 2 €/kg in 2020; to develop micro-encapsulated PCM for medium and high temperatures (KPI-11), with the same aims as the one before; to develop new heat exchangers including PCM (KPI-12), commercialised in 2020 for several applications; and to develop new sensors to determine the PCM state of charge (KPI-13), starting TRL 1 in 2012 and reaching TRL 9 in 2020.

Thermochemical energy storage technology (TCM) is the least developed, and the KPI given show it. The aims for TCM are increasing the level of maturity of thermochemical solar collector concepts (KPI-14) and developing new sensors to determine the TCM state of charge (KPI-15), both starting TRL 1 in 2012 and reaching TRL 9 in 2020; improving seasonal solar TCM (KPI-16), from 60 kWh/m^3_{system} in 2012 to 250 kWh/m^3_{system} in 2020; and to develop novel thermochemical materials at laboratory stage (KPI-17), from 4 in 2012 to 100 in 2020.

At system level, the installation time needs to be reduced (KPI-18), 30% in 2016; the material cost for the end-user needs to be reduced (KPI-19), 20% in 2016; as well as the human interventions for maintenance and/or reparation needs to be reduced (KPI-20), up to 20% in 2016. Finally, the reference heat cost of district heating and cooling (DHC) systems should be reduced (KPI-21), from 50-200 €/MWh in 2012 down to 35-70 €/MWh in 2020; and their reference energy efficiency should increase (KPI-22), 20% in 2020.

Measuring heat loss of water storages is described in EN 12897. This method is also the basis for ErP classification. The heat loss in Watts is measured with a water temperature of 65°C in the storage in an environment of 20°C. The energy efficiency class in then calculated using these equations.

4. Discussion

Once the tables compiling all the data were drawn, it was seen that most of the referenced literature gave the same KPI values; therefore the possible analysis was very limited. Furthermore, comparison between the two applications included here was not possible, because the applications themselves and the KPI selected were very different from each other.

This first attempt to quantify the targets for TES technologies shows that this technology can only be implemented by policy makers if more KPI are identified for more applications. Moreover, close monitoring of the achievements of the already identified KPI needs to be carried out to demonstrate the potential of TES.

Moreover, as stated by Personal et al. [4], metrics used today to assess complex energy systems have different problems, such as making it difficult to assess projects that contain specific initiatives not easily represented in the metrics, or such as having difficulties in relating the metrics elements to the main goal of the project. Within this context, KPI are identified as tools allowing their users to translate the company/manager/policy visions and targets into indicators. Therefore, it is expected that KPI are used more and more to evaluate and assess energy systems/plants/technologies, such as TES systems/plants/technologies.

Table 6. KPI defined for TES in buildings [20]

Description	**Metric**		**BASELINE**	**TARGETS**	
			2012	**2016**	**2020**
1. Sensible heat storage	**KPI-1**	Cost of containment of 1000 L tank (excl. insulation and VAT)	400-900 €	350-800 €	300-700 €
	KPI-2	Heat loss related to storage vessel with capacity of 1000 L*	150 – 200 W (Label C,D)	76 W (Label A)	56 W (Label A+)
	KPI-3	Cost to customer (excl. VAT) of high performance insulation Thermal resistance (Rc) = 7 m2·K/W	300 €/m^2	230 €/m^2	<100 €/m^2
	KPI-4	UTES Energy efficiency (defined as the ration (heat out)/(heat in))	60%	65%	75%
	KPI-5	Lifetime of the UTES at elevated T (n of years)	10-25	15-30	20-30
	KPI-6	UTES maintenance cost as share of operational costs	4-8%	3-6%	2-4%
	KPI-7	Heat transfer and storage fluids: viscosity of the fluid (related to the energy required for pumping)	Water: 0.001002 Pa·s Slurries: > 0.001 Pa·s Mineral Oil (Therminol VP-01 at 400 ºC): 0.00000039049 Pa·s	25% reduction	30% reduction

			Silicone (Syltherm 800 at 400 ºC): 0.00025 Pa·s Molten salts: 0.000031-0.0005435 Pa·s		
	KPI-8	Annual electricity consumption for pumping in DHW systems	75 kWh	60 kWh	50 kWh
	KPI-9	Energy density (inversely related with the storage volume)	Water at 20 ºC: 1000 kg/m3 Slurries: n.a. Mineral Oil at 400 ºC; 694 kg/m3 Silicone at 400 ºC: 547 kg/m3 Molten salts at 400 ºC: 1787 kg/m3	20 % reduction of storage volume through increase of energy density	30% reduction of storage volume through increase of energy density
2. Latent heat storage	**KPI-10**	Stable, micro-encapsulated salt hydrate PCM	Only paraffin PCM available; price over 8 €/kg	Novel materials in pilot applications	Production technology optimised; material available at < 2 €/kg
	KPI-11	Micro-encapsulated PCM for medium and high T	Some pilot plants with bulk PCM for high T	Several materials developed; pilot applications	Production technology developed; materials available on a large scale at < 2 €/kg
	KPI-12	Novel heat exchangers including	Few concepts	Proof of concept for at	Several applications

		PCM		least 5 concepts; typical peak power 25 kW	commercialised
	KPI-13	New sensors for PCM state of charge	First concepts (TRL 1)	Industrial prototypes (TRL 5)	State of the art (TRL 9)
3. TCM	**KPI-14**	Level of maturity TC solar collector concepts	First concepts (TRL 1)	Industrial prototypes (TRL 5)	State of the art (TRL 9)
	KPI-15	New sensors for TCM state of charge	First concepts (TRL 1)	Industrial prototypes (TRL 5)	State of the art (TRL 9)
	KPI-16	Improved seasonal solar TCM	60 kWh/m^3_{system}	160 kWh/m^3_{system}	250 kWh/m^3_{system}
	KPI-17	Novel TC materials at laboratory stage	4	40	100
4. System	**KPI-18**	Installation time reduction	---	30%	---
	KPI-19	Material cost reduction for the end-user	---	20%	---
	KPI-20	Human interventions for maintenance/reparation reduction	---	20%	---
	KPI-21	Reference heat cost of DHC systems**	200-50 €/MWh	90-40 €/MWh	70-35 €/MWh
	KPI-22	Reference energy efficiency of DHC systems	Baseline index: 100	110	120

**The specific impact of TES application on the cost of heat delivered through DHC systems depends on the specific energy mix and boundary conditions of the system.

*Energy efficiency classes of hot water storage tanks

Energy efficiency class	Standing loss S in Watts, with storage volume V in litres
A+	$S < 5,5 + 3,16 \cdot V^{0,4}$
A	$5,5 + 3,16 \cdot V^{0,4} \leq S < 8,5 + 4,25 \cdot V^{0,4}$
B	$8,5 + 4,25 \cdot V^{0,4} \leq S < 12 + 5,93 \cdot V^{0,4}$
C	$12 + 5,93 \cdot V^{0,4} \leq S < 16,66 + 8,33 \cdot V^{0,4}$
D	$16,66 + 8,33 \cdot V^{0,4} \leq S < 21 + 10,33 \cdot V^{0,4}$
E	$21 + 10,33 \cdot V^{0,4} \leq S < 26 + 13,66 \cdot V^{0,4}$
F	$26 + 13,66 \cdot V^{0,4} \leq S < 31 + 16,66 \cdot V^{0,4}$
G	$S > 31 + 16,66 \cdot V^{0,4}$

5. Conclusions

The new roadmaps developed for different applications where TES is an enabling technology have started to define KPI for this technology. KPI for TES are defined for solar power plants (CSP) and for buildings.

In CSP ESTELA gave a first set of KPI that was completed by the European Industrial Initiative on solar energy – CSP and SETIS. In this application, already an overarching KPI is defined for TES: the power purchase agreement, setting the importance of cost for industry. The other KPIs aim to increase efficiency and reduce costs, to improve dispatchability, and to improve the environmental profile. IRENA and the IPCC have published projection on reductions of costs for CSP, which could only be achieved with the achievement of the targets on KPI presented in this paper: new HTF for higher temperatures, higher efficiency in power cycles, and more efficient and cheaper storage systems.

For buildings, the first set of KPI for TES technologies was given by the RHC roadmap. KPIs are identified for the three storage technologies (sensible, latent heat and thermochemical energy storage), but also at system level.

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