Renewable Energy 83 (2015) 820–827

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Key performance indicators in thermal energy storage: Survey and assessment

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ARTICLE INFO

Article history:
Received 16 December 2014
Accepted 12 May 2015
Available online

Keywords:
Thermal energy storage (TES)
Key performance indicator (KPI)
Solar power plants (CSP)
Buildings

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.

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

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http://dx.doi.org/10.1016/j.renene.2015.05.019
0960-1481/

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 and 2030 and of 160 MW in 2050, the moderate goes from 5000 MW/year in 2015–40557 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.

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).

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 h 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

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	3400	3000	2800	2400
Investment billion €/year	1.924	2.043	1546	0.383
Employment job-year	9611	13,739	17,736	19,296
Moderate				
Annual Installation (MW)	5463	12,602	19,895	40,557
Cost €/kW	3230	2850	2660	2280
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)	6814	14,697	35,462	80,827
Cost €/kW	3060	2700	2520	2160
Investment billion €/year	20.852	39.683	89.356	174.585
Employment job-year	89,523	209,998	629,546	2,106,123