Journal of Energy Storage 17 (2018) 29–46

Contents lists available at ScienceDirect

Journal of Energy Storage

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

Energy and cost analysis of an Air Cycle used as prime mover of a Thermal Electricity Storage

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ARTICLE INFO

Article history:
Received 7 February 2017
Received in revised form 20 December 2017
Accepted 9 February 2018
Available online xxx

Keywords:
Energy Storage
Thermal Electricity Storage
Air Cycle
Energy analysis
Economic analysis
Numerical modelling

ABSTRACT

The increment of greenhouse gas emissions from human activities have forced the world authorities to ratify stringent environmental protection measurements devoted to the reduction of primary energy consumption and to the spread of Renewable Energy Sources (RES). To reach the fixed targets, governments have established subsidies especially to support the electricity generation from RES like wind and solar. However, the large penetration of variable and intermittent RES is stressing the need of large-scale energy storage able to stabilize the electric grids. But, available large-scale energy storage technologies like Pumped Hydro, Compressed Air Energy Storage or Flow Batteries, suffer of geographical constrains, require fossil fuel streams or are characterized by low cycle life. For this reason, in the present paper, a new Thermal Electricity Storage configuration based on the Air Bottoming Cycle (ABC) concept is proposed and tested. The off-peak power is firstly converted into thermal energy using an electric heater and, then, stored in a high temperature sensible heat storage. When the power demand is high, using a modified ABC the thermal energy is converted back into electricity. Using the plant mathematical model, an energy and a cost analyses are carried out to estimate the performance and the system feasibility.

1. Introduction

The world energy demand is growing year by year due to the rapid growth of population, urbanization and industrialization [1]. But, more than 85% of this demand is covered by fossil fuels (coal, natural gas and oil), resources which create environmental concerns and economic and political crises [2].

For these reasons, several researchers have decided to study and develop environmentally friendly technologies able to produce energy from renewable sources. In this manner, the utilization of Renewable Energy Sources (RES) has become more and more important and, in the last decade, hundreds of new RES plants have been installed. An emblematic example is represented by the Italian wind and photovoltaic (PV) sectors (data available on [3]). In 2006, the PV plants were 14 with an installed power and an annual gross electricity production equal to 7.17 MW and 2.3 GWh, respectively. In 2007, the PV plants have become 7647 with an installed power of 86.80 MW and an annual gross electricity production equal to 39.10 GWh. An increment of 1109.3% of the installed power in one year. After 10 years (2016), the installed PV plants were 732,053 while their power and annual gross electricity production were 19,283.17 MW and 22,104.3 GWh, respectively. A similar trend can be observed analysing the wind power sector. In 2006, the installed wind turbines were 169 while 10 years later they were become 3598. The installed power and the annual gross electricity production were 1908.3 MW and 2970.7 GWh in 2006 while, in 2016, they were become 9409.9 MW and 17688.7 GWh, respectively.

Wind, solar, hydro, etc. are environmental friendly energy sources which guarantee to produce electricity in eco-friendly ways but, unlike the hydroelectric power, wind and solar production suffer of high variability, unpredictability and uncontrollability. Characteristics which cause large fluctuations in their daily, monthly or even annually power production. In fact, as in the Italian case, the large number of plants fed by Variable Renewable Energy Sources (VRES) added to the traditional electric grid introduces management and control issues because, with a high number of users and producers, the demand and the plants production become difficult to forecast. Thus, there can be areas characterised by over-capacity and areas with under-capacity. Unbalances between production and demand are difficult to predict and manage and can cause local o even global blackouts.

Note that, the above-mentioned issues will grow with the increment of VRES plants because, as remarked in [4], the grid is able to absorb fluctuations only if the VRES power is up to 10% of the system installed capacity. Therefore, being expected a large

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https://doi.org/10.1016/j.est.2018.02.007

Nomenclature

C_p	specific heat, J/(kg K)
$\dot{m}$	mass flow rate, kg/s
A	area, m^2
C	cost, $
D_e	equivalent diameter of material element, m
G	mass velocity, kg/(s m^2)
L	length, m
N	number of element
NTU	Number of Transfer Units
Nu	Nusselt number
P	power, W
Re	Reynolds number
T	temperature, K or °C
U	overall heat loss coefficient, W/(m^2 K)
V	volume, m^3
f	friction factor
h_v	volumetric heat transfer coefficient, W/(m^3 K)
k	thermal conductivity, W/(m K)
p	pressure, bar
r_c	compression ratio
r_e	expansion ratio
t	time, s
tol	tolerance

Abbreviations

A-CAES	Adiabatic Compressed Air Energy Storage
ABC	Air Bottoming Cycle
AC	air compressor
ARES	Advanced Rail Energy Storage
AT	air turbine
CAES	Compressed Air Energy Storage
CES	Chemical Energy Storage
COMP	compressor
CS	cold storage
D-CAES	Diabatic Compressed Air Energy Storage
EH	electric heater
ES	Energy Storage
ESS	energy storage system
EXP	expander
GES	Gravity Energy Storage
GGHX	gas-to-gas heat exchanger
GT	gas turbine
HS	hot storage
HX	heat exchanger
I-CAES	Isothermal Compressed Air Energy Storage
I-ESS	Integrated Energy Storage System
LAES	Liquid Air Energy Storage
LH	Latent Heat
LPES	Liquid Piston Energy Storage
MES	Mechanical Energy Storage
MG	motor/generator
ORC	organic Rankine cycle
PHS	Pumped Hydro Storage
PTES	Pumped Thermal Electricity Storage
PV	photovoltaic
RES	Renewable Energy Sources
SH	sensible heat
SMES	superconducting magnetic energy storage
SRC	steam Rankine cycle
TCES	Thermochemical Energy Storage
TES	Thermal Energy Storage
UW-CAES	Underwater Compressed Air Energy Storage
VRES	Variable Renewable Energy Sources

Greek letters

Δ	difference
ε	void fraction of bed
η	efficiency
μ	dynamic viscosity, kg/(m s)
ϕ_1, ϕ_2, ϕ_3	parameters
ψ	sphericity
ρ	density, kg/m^3

Subscripts

a	air
amb	ambient
b	bed
e	element
i	initial
m	element m
max	maximum
s	storage material

integration of VRES in the near future to guarantee the energy transition, there is an urgent need of developing and installing large-scale electric energy storage systems able to control the mismatch between supply and demand. The International Energy Agency estimates that an electricity capacity of 7200 GW needs to be built worldwide by 2040 to cover the increasing energy demand. But also a capacity of 310 GW of additional electric energy storage needs to be built in US, Europe, China and India to compensate the presence in the electric grid of a large number of intermittent (such as wind, solar, etc.) and non-flexible (e.g. nuclear) plants [5,6].

Today, in periods with low or no wind or solar radiation, the mismatch between supply and demand is covered with fossil fuelled thermal power plants which are used as backup units. Therefore, the thermal plants capacity is not directly displaced by renewables, thus resulting in an installed overcapacity of power generation plants [7]. Thus, the RES overcapacity causes two main consequences [8]: on the one hand, existing thermal power plants are underutilized and their operational utilization factors tend to decline with the increasing quota of wind and solar units. On the other hand, in large electric grids, strong power fluctuations result in management and control problems that only the installation of large-scale Electric Energy Storage units can help to manage. But, the installation of large-scale ESS results in additional overcapacity if they are not well integrated into the existing fossil fuel thermal power plants.

With the aim of overcoming the above-mentioned issues, a new concept of large-scale ESS, called “Integrated Energy Storage System” (I-ESS) has been developed. The Integrated Energy Storage System concept is really simple: devices like gas turbines, electric generators, step-up transformers, transmission lines, etc. which constitute existing fossil fuel thermal power plants characterised by low operational utilisation factors (therefore underutilised fossil fuel thermal power plants) can be used to build I-ESS plants. In this manner, the installation of the storage unit does not result in additional overcapacity, helps to revamp underutilised unit and guarantees to satisfy the pressing need of network flexibility in terms of load levelling.

Baring in mind the I-ESS concept, the Authors have developed an energy storage system able to be integrated into underutilised fossil fuel thermal power plants. In the present work, the new I-ESS configuration is presented, modelled and compared with other available large-scale energy storage technologies with the aim of understating its performance and feasibility.