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A review of key environmental and energy performance indicators for the case of renewable energy systems when integrated with storage solutions

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HIGHLIGHTS

- Introduction of new proposed indicators and consolidation of available ones.
- Proposition of adaptable indicators to various Renewable Energy System modes.
- A "cradle-to-grave" study of an integrated photovoltaic and storage system.
- Introduction of Stakeholders' needs as part of the proposed Life Cycle Analysis.

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ABSTRACT

During the last years a variety of numerical tools and algorithms have been developed aiming at quantifying and measuring the environmental impact of multiple types of energy systems, as those based on Renewable Energy Sources. Plenty of studies have proposed the use of a Life Cycle Assessment methodology, to determine the environmental impact of renewable installations when coupled with storage solutions, based on a pre-selected repository of Key Performance Indicators. The main scope of this paper is to propose a limited number of best fitting, and at the same time easily adaptable to various configurations, list of Key Performance Indicators for the case of renewable energy systems. This is done by capitalizing on the environmental and energy performance indicators tracked in the open literature (e.g. "Global Warming Potential", "Energy Payback Time", "Battery Total Degradation", "Energy Stored on Invested", "Cumulative Energy Demand") and/or other proposing new simple, scalable and adaptable ones, (e.g. "Embodied Energy for Infrastructure of Materials and for the building system", "Life Cycle CO_2 Emissions", "Reduction of the Direct CO_2 emissions", "Avoided CO_2 Emissions", "CO_2 equivalent Payback Time"). Moreover, the proposed indicators are distributed according to the individual phases of the entire life-cycle of a related component of a renewable energy system, each time the environmental impact refers to, i.e. manufacturing, operational and end-of-life. Apart from that, the current paper presents a necessary base grounded approach, which can be followed for a holistic approach in environmental point of view of renewable-based technologies, by addressing the potential competing interests of the relevant stakeholders (e.g. profit for the market operator in contrast to low-cost services for the consumer). All in all, the scalar quantification of the environmental impact of multiple energy systems, through a list of proposed assessment criteria, being evaluated in terms of the selected repository of indicators, enables the comparison on a fair basis of the available energy systems, irrespective if they are fossil-fuel or renewable based ones. As a typical example, a simple standard model of a photovoltaic integrated with an electric battery is selected, for which indicative indicators are provided.

1. Introduction

Emissions of Green House Gases (GHG) grew at a faster rate over the decade from 2000 to 2010 than they had done over the previous three decades, reaching the highest levels in human history, despite world's policy coordinated efforts to limit them. In European Union in 2017, the

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Nomenclature

BIPV	Building Integrated Photovoltaic
BOS	Balance of System
CAES	Compressed Air Energy Storage
$CO_{2,eq}$	Carbon dioxide equivalent
CSP	Concentrated Solar Power
DER	Distributed Energy Resources
DNO	Distribution Network Operator
DOD	Depth of Discharge
DSO	Distribution System Operator
ES	Energy Storage
EU	European Union
GHG	Green House Gases
HV	High Voltage
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
Li-ion	Lithium-ion Battery
LV	Low Voltage
MV	Medium Voltage
NaNiCl	Molten salt battery
NaS	Sodium Sulfur Batteries
PCM	Phase Change Materials
PHS	Pumped Hydro Storage
$PO_{4,eq}$	Phosphate equivalent
PV	Photovoltaic
R&D	Research and Development
RES	Renewable Energy System
SCE	Supercapacitor Energy Storage
SMES	Superconducting Magnetic Energy Storage
$SO_{2,eq}$	Sulfur dioxide equivalent
TCM	Thermo-Chemicals Materials
TES	Thermal Energy Storage
TRL	Technology Readiness Level
TSO	Transmission System Operator

leading countries in GHG emissions are Germany (23% share of EU total CO_2 emissions), United Kingdom (11% share of EU total CO_2 emissions) and Italy (10.7% share of EU total CO_2 emissions) according to [1]. CO_2 emissions are a major contributor to global warming and account for around 80% of all European Union greenhouse gas emissions [1]. The application of renewable energy system (RES) technologies is currently considered as the most widely endorsed answer towards achieving the international climate protections goals, being agreed among most countries during the Paris Agreement in 2015 [2]. Consequently, advancements in RES based systems has experienced over the last years, the fastest growing research and development being followed by business emerging sectors towards greenhouse emissions mitigation. In fact, since 2011 RES innovation and action accounted for more than half of all capacity built in the power sector. Currently, the share of renewable energy in the total final energy consumption stands for 18.3% [3]. However, RES inherent characteristic of intermittence and high fluctuation sets a series of limitations for their further penetration in the global energy market, since the increasing penetration of local renewable generation and the emergence for fast demand response enabling solutions, are placing new requirements on the transmission and distribution networks. Such can be counterbalanced by the introduction of energy storage solutions, which can cover demand fluctuations as well as enhance security of supply, and in that respect, increase reliability and efficiency of RES based technologies. Therefore, Energy Storage (ES), as a whole both in terms of electricity and heat/cooling, is continuously attracting increasing attention as it improves the dispatchability of RES technologies, while can handle in an efficient way the emerging and steadily uprising needs of the various energy carriers, such as electricity, heat and gases, when integrated on a distribution network. The application of storage solutions, can allow the electricity and/or heat produced during 'off-peak' hours, to be stored and be used later to meet demand spikes; thus reducing the additional need for expensive spinning reserve and utilization of existing fossil based power plants in a non-efficient way followed by a less environmental friendly operation, when compared to that of RES. Towards this direction, there are various types of storage, e.g. long or short termed,

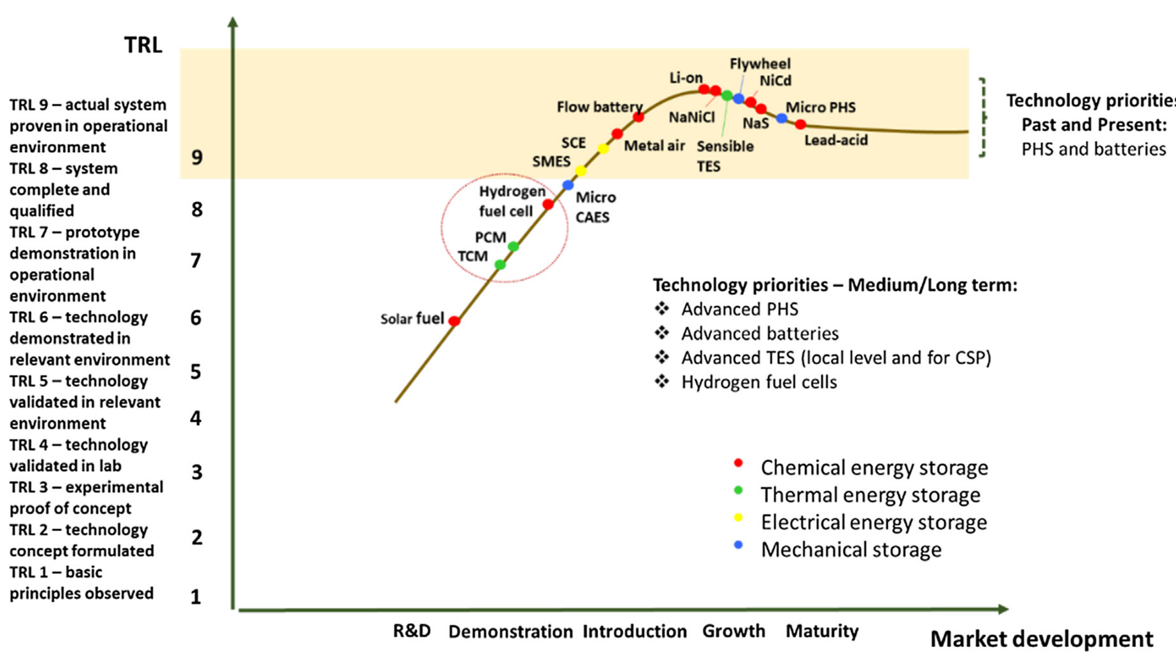

Fig. 1. Maturity curve for representative Energy Storage Technologies. Figure data taken from [4].