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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,

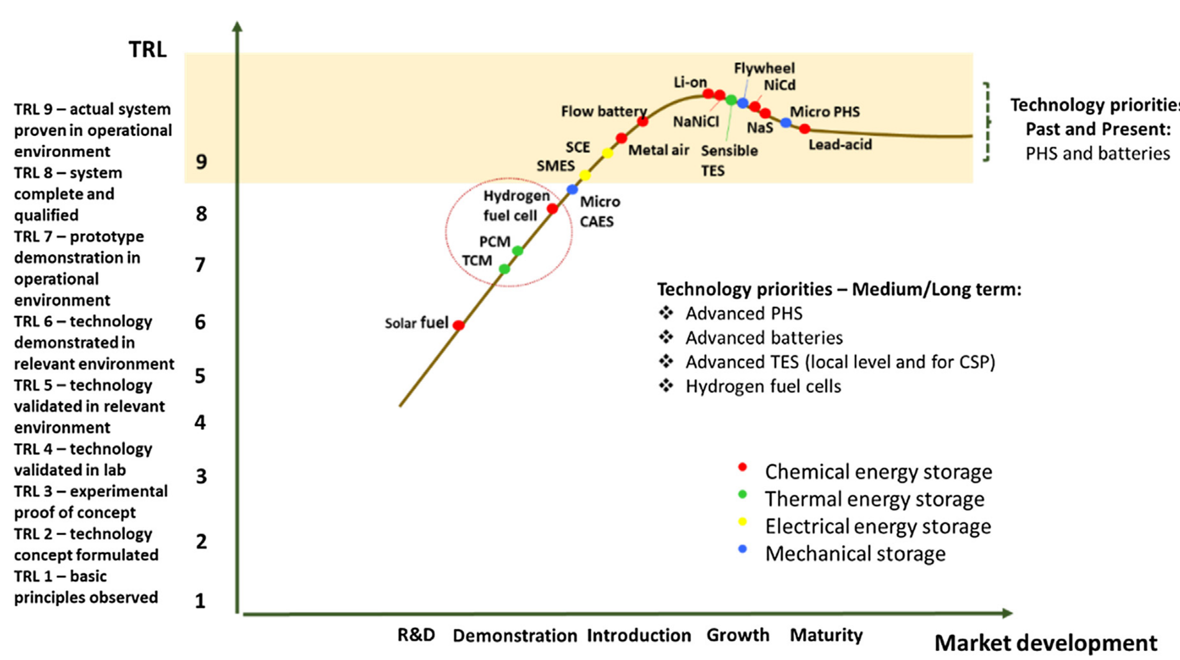

Fig. 1. Maturity curve for representative Energy Storage Technologies. Figure data taken from [4].

some of which are already in industrial use, while others are still under further development, before being commercialized. Fig. 1 presents storage methods of a varying range of technology maturity. According to [4] typical storage solutions include storage technologies to address the challenges faced by the energy system as those of (a) Mechanical Storage (e.g. compressed air heat storage, flywheel energy storage, pumped-storage hydroelectricity), (b) Electrical-Electromagnetic Storage (e.g. capacitor, super-capacitor), (c) Electrochemical-Battery Energy Storage (e.g. Flow battery, Rechargeable battery such as Lithium-ion and Lead acid battery), and (d) Thermal Storage (e.g. Pumped-heat electricity storage).

The criteria upon choosing the most optimal storage system for each specific energy distribution network, are primarily based on technical requirements as those of (a) the required storage capacity, (b) the available power production capacity, (c) the depth of required discharge or power transmission rate, (d) the discharge time, (e) the efficiency, (f) the durability (cycling capacity), and (g) the level of autonomy, without of course that meaning to be the only ones. Aspects as those of the associated costs of investment and operation, feasibility and adaptation to the generating source, and in addition environmental ones should be as well accounted for. Especially the environmental footprint of a solution, during its whole life cycle, is a parameter that recently is growing in interest, since in some cases, this is reflected as well to economic costs and social ones. To this end, the growing concern of the today's societies over future energy sources, have led to important inquiries, as for example to how much of the current available energy is used in the expense of producing goods and services and what is their expected impact on the climate.

To this direction, multiple Life Cycle Assessment (LCA) methodologies have been introduced during the last at least ten (10) years, which can quantify such type of impacts, from a holistic point of view, using numerous selected quantifiable indicators. The results of LCA contribute to inform the stakeholders, about the environmental impact of technologies/systems/products, along their whole production–consumption chain, thus contributing to their rational decision-making if it deserves investing or additional and of what type of advancements are still required. In general terms, the LCA is an instrument, which can quantify the environmental impacts of the whole energy supply chain of a product or a service, considering the cumulative energy demand (CED) of (a) its production, (b) its operation, during its whole life cycle up to (c) its decommissioning (followed by any possible recycling) phases. To do so, the whole product/component or service can be split up into individual phases increasing the precision of the life cycle environmental assessment. The energy and mass flows of each of these phases, are taken into consideration when quantifying the complete environmental footprint of a product or a service. Since up to nowadays fossil fuels have been mostly used for energy production, it is obvious that emissions savings are a priority, which needs to be considered and quantified, when renewable energy sources are used in the place of fossil-based ones. Fig. 2 presents namely all of the intermediate phases of a life cycle of a product or a service, each one requiring a specific amount of energy and water that needs to be consumed. As Fig. 2 depicts, this starts from raw material acquisition stage, and ends up to the product/service disposition, throughout a whole life cycle, during which wastes are continuously rejected.

During the last years, a plethora of studies regarding LCA on RES integrated systems has been published. Within these LCA studies, a wide range of specific indicators assessing the energy and environmental performance of an integrated system have been found. After conducting an extended literature review, the most dominant Key Performance Indicators being identified, are:

- the "Energy Payback Time" indicates the time during which, the RES system, e.g. Photovoltaic (PV), will produce the same energy used for its construction. This time should be shorter than the expected life time of the RES system. Different calculation approaches concerning the ''Energy Payback Time'' can be found in the literature. In specific, single-crystalline silicon and thin film module photovoltaic technologies are investigated in [5] reporting energy payback time values range from 2.5 to 3 years for roof-top installations and 3–4 years for multi megawatt, ground-mounted systems including manufacturing phase only (i.e. energy inputs for material production, the processing of cells, modules and other system components and the manufacturing of production equipment). In addition, the energy payback time of the aforementioned PV technologies (i.e. single-crystalline silicon, multi-crystalline silicon and thin silicon) are examined in [6,7]. In specific, from findings of [6] the energy payback time of three systems ranges from 3.0 to 7.4 years by taking into consideration the mounting of the materials and structures, inverters, cables, control electronic devices, transportation, installation, maintenance and recycling. From the beginning of 2000, a plethora of studies conducted based on actual production data obtained from PV manufacturers [8–10] presenting a decrease in energy payback time for single crystalline silicon PV system over the years. However, the PV performance is mostly influenced by geographical location (i.e. climatic conditions) and architectural design (i.e. orientation, tilt angle) of the entire system. To determine the effects of architectural design in PV performance, [11] calculates energy payback time, for grid connected PV system by comparing tracking (of double and horizontal axis tracking) and fixed photovoltaic systems. The energy payback time ranges from 2 to 5 years. To the same direction, two hypothetical

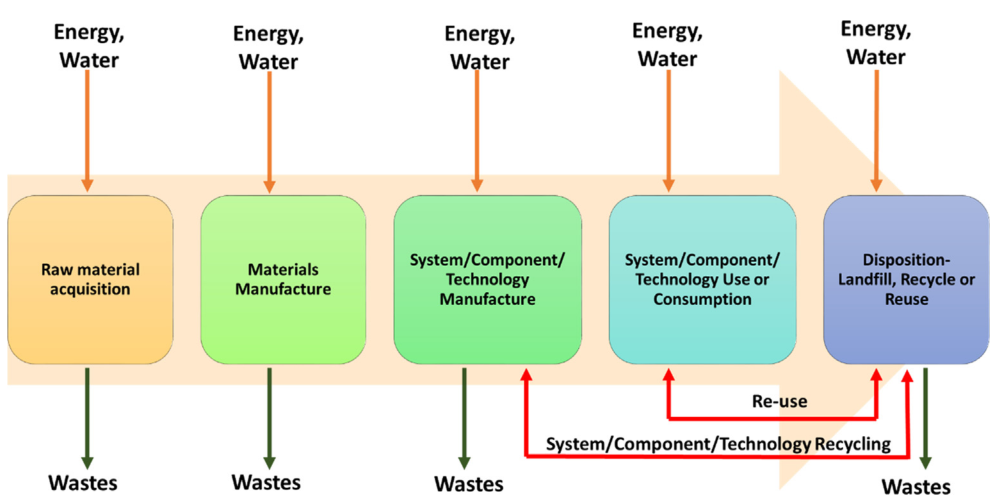

Fig. 2. LCA cradle-to-grave life cycle approach with the depiction of all intermediate life-cycle phases of a system/component/technology.

case studies in Japan and in China have been carried out [12]. In specific, energy payback time of a high-concentration photovoltaic power generation system and a multi-crystalline silicon photovoltaic power generation system are studied including manufacturing (i.e. mining of material, assembly, component processing), transportation, maintenance, usage and recycling. Since there is a growing interest in the Building Integration of Photovoltaics (BIPV), relevant surveys have been conducted. In study [13] the energy payback time of BIPV systems for three different orientations of PV modules (i.e. optimum tilt angle, horizontal and vertical orientations) ranges from 7.5 years to 16 years. Due to the fact that in the past 25 years there has been a rapid expansion in the use of photovoltaic systems worldwide, early PV systems are now coming to the end of their life. This raises a big disposal challenge in the coming years. Recent evidence by [14] for estimating energy savings from recycling photovoltaic suggests that as the efficiency increases, the energy payback time savings from recycling decreases. Many efforts are recently being dedicated to the calculation of energy payback times for photovoltaic systems when integrated with storage solutions. For the case of a rooftop PV in Australia with battery storage [15], the energy payback times range ranges from 1.75 to 14 years taking into consideration manufacturing, purchasing, installation and operation phase.

- the "Cumulative Energy Demand", which expresses the required amount of energy invested (in infrastructure and extraction/transport processes in addition to the primary energy related to the energy product itself) in relation to the amount of delivered energy (over the lifetime of the plant). Cumulative energy demand for the Lebanese electricity mix was estimated by [16] for PV installation (both with and without battery integration) in various locations in Lebanon. Within the survey conducted by [17], three grid-connected photovoltaic systems (single crystalline silicon, poly-crystalline silicon and amorphous silicon) are examined for several European countries: Germany, France, Spain, Italy, Netherlands, Austria and Sweden. Experience curves for cumulative energy demand from production of mono and polycrystalline silicon based PV systems were developed by [18]. Supplementary calculations for the cumulative energy demand of the materials used for a free-stand photovoltaic and BIPV system in Hong Kong presented by [19]. Furthermore, the cumulative energy demand required to fabricate small molecule and polymer photovoltaics were found to be similar from 2.9 to 5.7 MJ/Wp calculated by [20] and in which cumulative energy demand shows a trend of decreasing value with increasing device efficiency.
- the "Gross Energy Requirement" which indicates the energy inputs required (over a life cycle period) to deliver a product/technology or service the point of interest, including its assembly and decommissioning. The issue of gross energy requirement for a photovoltaic system has received considerable attention. Recently, [15] estimated that the PV panel has the highest contribution in gross energy requirement for a PV system integrated with battery, comparing to battery, inverter, frame and cabling. Currently, many research works have been carried out focusing on optimization of PV systems. A comparison between lead-acid and li-ion accumulators in the case of stand-alone photovoltaic system using the gross energy requirement criteria is performed by [21], focusing on the optimal sizing of the PV system. Sizing optimization of a stand-alone photovoltaic system is being investigated also by [22], concluding that the minimization of the gross energy requirement of such a system, leading to the optimization of the resemblance of the load and production profiles
- the "Embodied Energy of the materials" which is useful for the comparison of the energy systems by estimating the energy consumed during all of the processes associated with the production of a system/component/technology. Several attempts have been made to study the embodied energy requirement of crystalline silicon photovoltaic system in order to determine its feasibility and durability to replace non-renewable energy resources. The first discussions about the embodied energy requirement emerged during the 1970 s by [23] which estimated an energy requirement value of 3588 kWh/kg to produce silicon solar cells from raw silica material. In 1990, [24] conducted an LCA study on a 300 kW single crystalline silicon PV plant in Austin and stated that the total embodied energy requirement was 6300 kWh/m^2. This includes the manufacturing of PV modules and the Balance of System components, as well as the indirect energy demands for installation/site preparation. In 1995, [25] performed a life-cycle assessment on multi-crystalline silicon photovoltaic modules and concluded that embodied energy content was 1145 kWh/m^2. The PV cells accounts for 85% of total embodied energy content while the frame module accounts for the remaining 15%. In 1998, [7] investigated the embodied energy requirement for single-crystalline silicon photovoltaic production modules for silicon wafer production. The energy allocations in wafer silicon production were between 1155 kWh/m^2 and 4312 kWh/m^2. Recently, researchers have examined the effects of location in embodied energy requirement. Hence [10] carried out a study on a single crystalline silicon photovoltaic module in various locations and regions with different energy demands, i.e. from 1095 kWh/m^2 for Norway to 1415 kWh/m^2 for Korea. The embodied energy for production of PV module based on single crystal silicon, as well as for the manufacturing of other system components have been computed at macro- and micro-level in different climatic zones in India by [26].
- the "Global Warming Potential" measures the total emissions of the three main Green House Gases (i.e. carbon dioxide, methane and nitrous oxide) from energy production and use, which have a direct impact on climate change. The environmental profit gained by of the replacement of a traditional coal-fired power plant with a RES based power plant is under investigation in the last decades. Studying the GHG emission rates for both those systems, [27] investigated the emission profit of the multi-crystalline (multi-Si) photovoltaic installations by conducting relevant life cycle assessments for the aforementioned systems. The estimated GHG emission rates for the examined systems were 975.2 g $CO_{2,eq}$ /kWh and 36.75 g $CO_{2,eq}$ /kWh. During the manufacturing stage of PV, the construction PV cell is considered the highest contributor to the GWP accounting for around 50% of the GWP as estimated by [28]. Moreover, life-cycle greenhouse gas emissions for four types of major commercial photovoltaic system such as multi crystalline silicon, monocrystalline silicon, ribbon silicon and thin-film cadmium telluride estimated by [29]. Among the current types of technologies, thin-film cadmium telluride PV emits the least amount of air emissions as it requires the least amount of energy during the module production. The production of polycrystalline silicon is the most energy-consuming stage of the silicon module's life cycle accounting for 45% of the total primary energy used. Hence [30] studied a thin film photovoltaic module including BOS, inverter installations and transportation reporting life cycle emissions of 34.3 g$CO_{2,eq}$/kWh. To the same direction, [31] reports life cycle emissions of 39 g$CO_{2,eq}$/kWh for thin film PV installations in United States.

Although the importance of performing environmental studies in the energy field by providing quantified values for representative indicators is high, there have been no LCA studies done for the identification of performance indicators from a purely environmental perspective. Consequently, there is a need for indicators that can cover the linkages between the environmental and the energy performance dimension, in terms of sustainability. Hence, two main issues have been identified as gaps in the literature.

The first one refers to the lack of environmental indicators targeting to their quantified impact on the environment, with a mutual and replicable manner for the case of RES when integrated with storage solutions. In view of that, this review study presents a guideline for the environmental performance of RES with storage systems, based on both already existing energy performance indicators and new introduced environmental ones.

The second issue concerns the lack in literature of the most meaningful indicators addressing the primary interests of the relevant stakeholders such as Utility, Distribution System Operators (DSOs), Transmission System Operators (TSOs) and consumers. Therefore, the present study tries to include this parameter as well, and present a preliminary connection between the relevant stakeholder group interests and the proposed energy and environmental KPIs. In specific, the main objective of this study is to present the basic principles of an essential base grounded approach, which is necessary for a holistic environmental assessment of RES based technologies, since the latter are continuously increasing interest. At this point, and as afore-explained the environmental assessment is strongly linked with the corresponding energy assessment of the technologies and as such, a reference and link to that is made. However, beforehand a necessary definition of the most appropriate repository of indicators need to be set, as limited as possible, which will be simultaneously in position to quantify the total environmental impact. In that respect, available energy and environmental Key Performance Indicators (KPIs) are tracked in the open literature (e.g. “Global Warming Potential”, “Energy Payback Time”, “Energy Storage Potential”, “Energy stored on Invested”), which list is though populated by the introduction, definition and explanation of additional new simple scalable and adaptable proposing, ones (e.g. “Life Cycle CO_2 emissions”, “Reduction of the direct CO_2 emissions”, “Avoided CO_2 emissions”, “CO_2 equivalent Payback Time”), consolidating some of the already existing ones into fewer ones.

2. Methodology

2.1. Definition of environmental Key Performance Indicators

Environmental KPIs are commonly used metrics for environmental data management, eco-efficiency measurement, environment target setting and monitoring of them in real-life. Such KPIs are used to measure, quantify and evaluate the performance of a system/component/technology in relation to the scope, targets and objectives, this was designed to achieve during its demonstration and application [32], always from the perspective of the impact it has on the environment. In this sense, environmental KPIs are used, to set measurable objectives, evaluate progress, monitor trends, make improvements, and support decision making about that, always in relation with its expected and foreseen environmental footprint, having as a timeframe its whole life cycle, as illustrated in Fig. 3. Since these KPIs are strongly linked with all the intermediate steps of a life cycle of a system, as explained in Fig. 2, any changes in each of the indicator values over time, mark progress or lack of progress, towards its more self- sustainable development. The indicators are not merely data; rather, they extend beyond basic statistics to provide a deeper understanding of the main issues and to highlight important relations that are not evident using basic statistics. This is owed to the fact that nowadays self-sustainability requires for an associated low cost on use of continuously depleting nature resources. The previous paragraph presents an overall and generic overview of the role of the environmental KPIs. However, since the current study focuses on energy and primarily RES based networks, the KPIs under selection should consider as well associated technical aspects either in a direct or in an indirect fashion. Technicalities are evaluated by technical oriented KPIs, which both (a) act as a metric for efficiency and quality of the energy network and (b) contribute in the shaping of the future energy planning priorities, starting from its generation, until its consumption with the intermediate step of energy distribution. Therefore, there should be a strong link of environmental KPIs with technical corresponding ones for all the intermediate steps of energy flow. This bond can be clearly explained if one thinks that the value of the first ones are highly influenced by the seconds ones, especially when a reference to the phase of production use or consumption (Fig. 2), of a system/component/technology is made. As an example, an integrated system of Photovoltaic (PV) and Battery Energy Storage (PV-battery) is used, upon which the proposed LCA methodology approach is formed to evaluate the overall impact assessment of such an integrated system.

2.2. Classification of KPIs

Before the first step towards building up and selecting the most appropriate repository of KPIs, it needs to clear the purpose they are expected to serve. In general, the available different types of indicators can be classified into four major domains, i.e. (a) the Social, (b) the Economic, (c) the Environmental and (d) the Technical, depending on the type and role they are selected and formulated to serve. The Environmental domain, which is the focus of this study, includes three main sub-categories, i.e. (i) Atmosphere, (ii) Water and (iii) Land impact categories, addressing the type of impact each product/technology has on the main earth resources, from a different perspective. The Atmosphere includes Climate Change (Greenhouse gas) and Air Quality indexes, such as sulphur oxides, nitrogen oxides, carbon monoxide and particulates, as these pollutants can damage human health, leading to respiratory problems, cancer, etc. Water quality type of impacts, is primarily controlled by the discharge of contaminants from energy systems in liquid effluents; particularly from the mining of energy resources, while Land impact category is affected by energy transformation processes that often produce solid wastes, including radioactive wastes, which require very careful and well-followed disposal guidelines.

The second step, before the definition of the most suitable KPIs, is the good and in depth understanding of the process, they will be requested to assess, to allow for the proper collection of the inputs needed for the KPIs calculation. This process, being defined from the LCA methodology (ISO 14040:2006), includes all the primary or secondary data that are necessary for the calculations. Details about this discretization are presented in Section 3 of this paper.

Finally, the third step of KPIs classification, after their selection, lies on putting in place verification measures to ensure that the KPIs meet quality expectations in terms of decision-making [33]. By using the appropriate KPIs, it is feasible to achieve the need for scalability and replicability of the assessment results, and in that way increase the impact and the benefit of the assessment.

2.3. Environmental KPIs in relation with energy performance indicators

As afore-explained and especially during the stage of a system/solution operation, the measurement of energy consumption is relevant to greenhouse gas emissions and climate change. Hence, the environmental KPIs are strongly linked with the energy performance indicators.

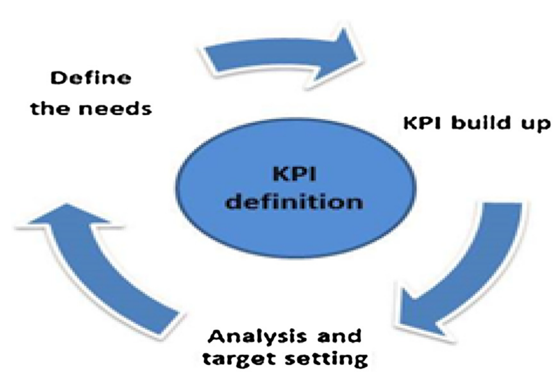

Fig. 3. Methodological elementary approach for KPI definition.

To meet the aims formulated in the Kyoto Protocol and to reduce the risk of severe climate change, energy demand needs to be lowered. This can be achieved through more efficient energy use and replacement of fossil fuel energy sources with renewable ones. Therefore, environmental strategies, such as (a) the lowering of the direct energy consumptions, (b) the design of energy-efficient processes and (c) the reduction of indirect energy consumptions should be taken into consideration through the corresponding energy performance indicators for the needs of the life cycle analysis.

2.4. A short review of available assessment methodologies

For the case of impact assessment, it should be underlined that the available LCA methodologies can be divided in two categories, i.e. (a) those that focus on the amount of resources used per unit of product/process under evaluation (upstream category), and (b) those which estimate the expected emissions of the system (downstream category).

Therefore, the available in the open-literature impact assessment primary categories, followed by a representative list of associated KPIs, are the (a) Global Warming Potential, (b) the Acidification and (c) the Eutrophication categories, depicted in Tables 1–3 respectively. Since, these indicators evaluate the effect of a system/process on the climate change and water chemistry, they are categorized as downstream.

The main criteria for the selection of the most appropriate LCA method, required to be followed, are (a) the type of emissions that need to be estimated (for example Green House Gas emissions, Particulate emissions) (b) the performance of the system after being normalized on the basis of different profiles (for example characterisation, weighting, damage assessment), (c) the time horizon for which the impact is estimated (e.g. 20, 100 years), and (d) the calculation method (e.g. single or multitasking impact method). For the latter, there is a plethora of calculation methodologies per impact category. The methodologies are distinguished as either (a) single issue ones that focus on the estimation of one impact category (e.g. the global warming potential impact) or (b) the typical European methods that evaluate more than one impact categories by taking into consideration the most appropriate weighting factors.

CO_2 was chosen by the Intergovernmental Panel on Climate Change (IPCC), as the reference unit for greenhouse emissions, because it is the most emitted substance from human activities. Hence, the reference unit upon which all emissions corresponding to the global warming potential impact are performed, is the $CO_{2,eq}$. $CO_{2,eq}$ signifies the amount of CO_2 emitted, which would result in an equivalent global warming impact, as of the origin. A distinction between fossil carbon emissions and biogenic carbon emissions is taken into consideration within the framework of the single issue impact methodology named as “Greenhouse Gas Protocol”. This distinction is made, based on the fuel source type (fossil and biomass), each time CO_2 is produced from, in order to avoid overlaps in the estimation. According to the guidelines compiled by the IPCC, CO_2 emissions from bioenergy sources should not be counted in national greenhouse gas inventories, because these are already inherently included in the Agriculture, Forestry and Other Land-Use sectors.

In Table 1, the most applicable methods for the estimation of the global warming potential are summarized along with the two most representative emissions types, i.e. those of $CO_{2,eq}$ and CH_4. ReCiPe is the successor of the methods Eco-indicator 95 and CML-IA. In ReCiPe, it is feasible for the user to choose midpoint indicators or endpoint indicators. ReCiPe implements the disability-adjusted life year (DALY) in the category of Human Health endpoint impact, which considers the year of life lost and the year of life disabled due to environmental interventions The CML-IA is the impact assessment methodology oriented to the midpoint approach. Specifically, for each of the above-mentioned methodologies, the major key notices include that the EPD (2013) impact assessment methodology applies the same impact assessment algorithm for the estimation of the global warming potential with the CML-IA baseline method. As concerns the fossil CH_4 emissions, a wide range between 11 and 85 kg $CO_{2,eq}$/kg is noticed among the various methodologies, since different horizon impact periods are taken into consideration for each of them. The highest value is being tracked in the IPCC 2013 20y methodology, owed to the fact that the horizon impact period referring to 20 years is very short, with a result that methane (CH_4) has an equivalent impact of 27.75 kg$CO_{2,eq}$/kg over 100 years, but 82.65 kg$CO_{2,eq}$/kg over 20 years according to IPCC 2013 GWP 20a.

Five methods, out of them, e.g. EPD 2013, ReCiPe Midpoint, CML-IA baseline, CML-IA non-baseline, Greenhouse Gas Protocol apply the same indicators for the CH_4 fossil estimation. This rate is about 25 kg$CO_{2,eq}$/kg, since they are based on the same impact assessment algorithm. Specifically, in the EPD all impact categories are built on the CML-IA baseline, with the CML non-baseline method being an extended version of CML-IA baseline and ReCiPe being created by CML. A similar fluctuation is found in the estimation of biogenic CH_4 emissions with the highest value (82.5 kg$CO_{2,eq}$/kg) appearing in IPCC 20 years methodology. Regarding N_2O emissions, the lowest value is noticed in IMPACT 2002+, since this methodology applies the characterizations factors from IPCC 2001, which has a time horizon of 500 years. Moreover, Impact 2002+ is a combination of four methods, e.g. those of (a) Impact 2002, (b) Eco-indicator 99, (c) CML and (d) IPCC. It is

Table 1
Impact factors of the Global Warming Potential (kg $CO_{2,eq}$/kg) calculation, for each of the different assessment methodologies.

	Calculation factor for GHGs / Methods	GLOBAL WARMING POTENTIAL				
		CO_2 Factor in fossil (kg $CO_{2,eq}$/kg)	CO_2 Factor in biogenic (kg $CO_{2,eq}$/kg)	CH_4 Factor in fossil (kg $CO_{2,eq}$/kg)	CH_4 Factor in biogenic (kg $CO_{2,eq}$/kg)	N_2O Factor (kg $CO_{2,eq}$/kg)
Multitasking Methods	Impact 2002+	1	–	27.75	25	156
	EPD (2013)	1	–	25	22.25	298
	Eco-Indicator 95	1	–	11	8	270
	ReCiPe Endpoint	0.0000035 (DALY/kg)	–	0.0000267(DALY/kg)	0.000017(DALY/kg)	0.00537(DALY/kg)
	ReCiPe Midpoint	1	–	25	22.3	298
	CML-IA baseline 100 years	1	–	25	22.25	298
	CML-IA non-baseline (100 years)	1	–	25	–	298
Single issue methods	IPCC 2013 GWP 100a	1	–	30.5	27.75	265
	IPCC 2013 GWP 20a	1	–	85	82.65	264
	Greenhouse Gas Protocol (identical to IPCC 2007 GWP 100 years	1	1	25	25	298

Table 2
Impact factors of the Acidification calculation for different assessment methodologies (kg $SO_{2,eq}$/kg).

Kg $SO_{2,eq}$/kg		HF factor*	HCL factor*	NH_3 factor*	NO_x factor*	NO factor*	SO_2 factor*
			ACIDIFICATION				
Multitasking Methods	Impact 2002+	1.6	0.88	1.88	0.7	1.07	1
	EPD (2013)	1.6	0.88	1.88	0.7	1.07	1
	Eco-Indicator 95	1.6	0.88	1.88	0.7	1.07	1
	ReCiPe Endpoint	–	–	0	0	–	0
	ReCiPe Midpoint 100 years	–	–	2.45	0.56	–	1
	CML-IA baseline (100 years)	–	–	1.6	0.5	0.76	1.2
	CML-IA non-baseline (100 years)	1.6	0.88	1.88	0.7	1.07	1

* HF = Hydrogen Fluoride, HCL = Hydrogen Chloride, NH_3 = Ammonia, NO_x = Nitrogen Oxide, NO = Nitric Oxide, SO_2 = Sulfur Dioxide.

Table 3
Impact factors of the Eutrophication calculation for different assessment methodologies (kg PO_4P-lim/kg).

	kg PO_4P-lim/kg AIR-WATER-SOIL	H_3PO_4 factor	PO_4^{3-} factor	P_4O_{10} factor	$_{15}P$ factor	NO_x factor	NO factor
				EUTROPHICATION			
Multitasking Methods	Impact 2002+	0.97	1	1.34	3.06	0	0
	EPD (2013)	0.97	1	1.34	3.06	0.13	0.2
	Eco-Indicator 95	0.97	1	1.34	3.06	0.13	0.2
	ReCiPe Endpoint	~0	~0	~0	~0	–	–
	ReCiPe Midpoint kg P_{eq}/kg	0.32	0.33	0.44	1	–	–
	CML-IA baseline kg $PO_{4,eq}$/kg	0.97	1	1.34	3.06	0.13	0.2
	CML-IA non-baseline kg $PO_{4,eq}$/kg (100 years)	–	–	–	–	1.2	1.84

*H_3PO_4 = Phosphoric acid, PO_4^{3-} = phosphate, P_4O_{10} = Phosphorus pentoxide, $_{15}P$ factor = phosphorus, NO_x = Nitrogen Oxide, NO = Nitric Oxide.

mentioned that IPCC 2013 does not include any indirect formation of dinitrogen monoxide from nitrogen emissions. Hence, the N_2O factor is lower (264–265 kg$CO_{2,eq}$/kg) comparing to the other global warming potential impact methods.

In order to describe the acidifying effect of substances, their acid formation potential is calculated and set against a reference substance, $SO_{2,eq}$. The substances normally considered as contributors to acidification are: (a) hydrogen fluoride (HF), (b) hydrogen chloride (HCl), (c) ammonia (NH_3), (d) nitrogen oxides (NOx), (e) Nitric Oxide (NO) and (f) sulfur dioxide (SO_2). Acidification potential is expressed using as reference unit, the kg SO_2 equivalent. $SO_{2,eq}$ is used as a basis for determination of the acidification potential. The method of establishing effect factors for acidifying substances is based on stoichiometric considerations and it is internationally accepted. The most common impact methodologies and representative emissions are summarized in Table 2. In contrast to the Global Warming Potential impact, single issues methodologies focusing only on the estimation of $SO_{2,eq}$ emissions are not applied. As a result, the estimation of the acidification potential is carried out only by the application of the multitasking impact methodologies. According to all of them, the emissions corresponding to Hydrogen Fluoride and Hydrogen Chloride have the same contribution to the acidification potential impact. It is mentioned that ReCiPe and CML-IA baseline impact methods do not consider this type of emissions. According to the ReCiPe all the impact factors are approximately equal to zero, because the time horizon in these methods is set equal to eternity and the geographical scale varies between local scale and continental. Impact 2002+ calculation factors are taken directly from CML-IA method. Concerning the EPD (2013) impact category for acidification, the method is the same with that of the CML-IA non-baseline method and as a result, it uses exactly the same calculation factors.

Eutrophication (also known as nutrification) includes all impacts caused by the excessive levels of macro-nutrients in the environment, caused primarily by emissions of nutrients to air, water and soil. Thus, Eutrophication (or nutrient enrichment) can be defined as an enrichment of the aquatic environment with nutrient salts leading to an increased production of plankton, algae and higher aquatic plants. In time this leads to a reduction in the water quality and in the value of the exploitation, which occurs in the area [34]. The reference unit is the $PO_{4,eq}$. The factors for eutrophication for each type of emission are quite similar for the most of the methods. Three methods (CML-IA non-baseline, EPD and Eco-indicator) apply the same indicators for the calculation of the impact factors. EPD (2013) impact category for eutrophication is taken directly from CML-IA baseline method and consequently uses exactly the same impact factors. In what concerns for the ReCiPe Midpoint methodology, the phosphoric acid, phosphate, phosphorus pentoxide and phosphorus factors used are lower than in the rest of methods, because this is a midpoint approach method. CML-IA non-baseline has only factors related to Nitrogen oxide and Nitric Oxide, which are significantly greater comparing to other multitasking methods. EPDs all impact categories are taken from CML-IA baseline, with the CML non-baseline method being an extended version of CML-IA baseline.

3. Calculation steps

The paper focuses mainly on the determination of Environmental KPIs using as a basis, feedback from the linked Energy Performance KPIs following a systematic methodology. The repository of the KPIs corresponds to the phases of manufacturing, operation and end-of-life.

In more detail, the following list of KPIs for the RES based systems address the needs for environmental and energy assessment of technologies during (a) the manufacturing phase (e.g. "Embodied energy for infrastructure of materials and for the building system", "Gross Primary Energy Requirement", "Net Energy Ratio", "Cumulative Energy Demand"), (b) the operational phase in which included generic environmental indicators (e.g. "Life Cycle CO_2 Emissions", "Global Warming Potential" as well as energy performance indicators (e.g. "Electricity used from On-Site Generation", "Share of RES", "Delivered Energy",) and environmental indicators (e.g. "Reduction of the Direct CO_2 emissions", "Avoided CO_2 Emissions") with RES orientation and energy indicators for battery storage applications ("Specific Energy

Density", "Energy Storage Potential", "Net Delivered Electricity", "State of Health", "Storable Energy"), (c) the end-of-life phase (e.g. "Energy Returned on Energy Invested", "Battery Calendar Life", "Battery Cycle Life", "Battery Total Degradation", "Energy Payback Time", "CO_2 equivalent Payback Time", "Energy Stored on Energy Invested"). Furthermore, the calculated values of KPIs are calculated based on two different types of input data, those called primary, which represent data actually measured (e.g. "Net Energy Ratio", "Delivered Energy", "Electricity used from On-Site Generation", "Gross Primary Energy Requirement", "Cumulative Energy Demand") and the theoretical ones named as secondary, mainly tracked and calculated either using as a basis literature data and/or the results of simulation platforms/tools ("Life Cycle CO_2 Emissions", "Embodied Energy for Infrastructure of Materials and for the building system", "Global Warming Potential", "Avoided CO_2 Emissions", "$CO_{2,eq}$ Payback Time").

3.1. Energy performance indicators addressing the manufacturing phase

Manufacturing phase includes the extraction of raw materials from their mining area and the assembly of the components for the composition of the final product. Hence, indicators such as "Embodied Energy for Infrastructure of Materials and for the building of the system", "Gross Primary Energy Requirement", "Net Energy Ratio" and "Cumulative Energy Demand" are included in these phase. Specifically, the KPI named as "Embodied Energy for infrastructure of materials and for the building system (EEIM)" represents the energy consumed by all of the individual processes associated with the manufacturing of a product/technology, starting from the mining and processing of raw natural resources to assembly, transport and final product/technology delivery. According to study [35], a major objective of carrying out embodied energy analysis is to compute the amount of initial and/or recurring energy embodied within materials and thus to compare the total embodied energy content for different building materials, components, elements and designs. Initial and recurring embodied energy are the two major components of the embodied energy. Initial embodied energy represents the sum of the energy required for extraction and manufacture of a material together with the energy required for transportation of a material used for its initial building construction.

The calculation formula of that energy performance indicator, expressed in kWh, is an Energy Performance Indicator and its formula is:

$$\text{EEIM} = \sum_{i=1}^{n} (\text{Energy Consumption for the production of material})^{i} + \text{Assembly Energy}, \tag{1}$$

where

- the "Energy consumption for the production of the material" is the required energy (kWh) to produce each material including extraction and transportation of the raw materials from the mining area to manufacturing area and
- the "Assembly Energy" is the energy consumption (kWh) for the assembly of the individual operation system components towards the composition of the final product under examination.

The "Gross Primary Energy Requirement (GPER)" indicates the primary energy inputs required (over a life-cycle period) to deliver a product/technology or service to the point of interest, including its assembly and decommissioning. This includes the energy associated with its manufacturing, the assembly, and the range of products/services being consumed using natural resources (in most of the cases fossil fuels, e.g. coal, crude oil, natural gas, etc.) that have not undergone any anthropogenic conversion. The "Gross Primary Energy Requirement (GPER)" is expressed in MJ/kg of product/technology/service delivered, during the operational phase and the assembly/decommissioning phase, always per component.

$$\text{GPER} = \sum \text{Primary Assembly Energy} + \text{Primary Operational Energy} + \text{Primary Decommissioning Energy}, \tag{2}$$

where

- the "Primary Assembly Energy (MJ)" is the amount of energy expressed per component and reflects the sum of primary energy used for the assembly of the different materials towards the production of a single product/technology, as well as any indirect energy inputs, such as the embodied energy including in the materials;
- the "Primary Operational Energy (MJ)" per product/technology is the sum of primary energy including direct energy inputs, depending mainly on fuel properties, and indirect energy inputs regarding the embodied energy of the system operating and
- the "Primary Decommissioning Energy (MJ)" per component reflects the sum of primary energy used to decompose the product into the substantial ones, wherever possible taking into consideration the manufacturing specifications of the product.

During the manufacturing phase of an energy system, it is crucial to measure the correlation between the amount of delivered energy that a technology is capable of producing and the primary energy that is consumed for the installation of this specific technology. Hence, the "Net Energy Ratio (NER)" and the "Cumulative Energy Demand (CED)" are defined.

"Net Energy Ratio (NER)" is a major widespread indicator showing the amount of energy that a technology can produce to the total amount of energy consumed for its setup (including manufacturing), over its expected total life time. The Net Energy Ratio of an energy technology is used to show how 'efficient' that technology is in terms of providing energy to society.

$$\text{NER}=\frac{\text{Delivered Energy}}{\text{Required energy for infrastructure}+\text{Energy for extraction and transportation}+\text{Primary Energy}}, \tag{3}$$

where

- the "Required Energy for infrastructure (kWh)" is the amount of energy for building up the necessary infrastructure, being related to its extraction, its processing and transport of the fuel/energy source and energy required for building up the necessary infrastructure (e.g. system/component/technology) related to the conversion of the energy;
- the "Energy for extraction and transportation (kWh)" is the required energy for extraction, processing and transport of the fuel/energy source and energy required for maintenance of the conversion plant;
- the "Delivered energy" is the specified energy product from the energy plant (kWh) and
- the "Primary energy (MJ)" (related to the energy product) is the necessary amount of energy for the generation of a specific amount (e.g. 1 kWh) of the delivered energy [36].

"Cumulative Energy Demand (CED)" is expressed as the inverse of NER. CED expresses the required amount of energy invested (in infrastructure and extraction/transport processes in addition to the primary energy related to the energy product itself) in relation to the amount of delivered energy (over the lifetime of the plant). As indicated in [16] the "Cumulative Energy Demand", used in renewable energy technology research quantifies all the energy consumed during the life cycle of a product. It includes operational energy consumptions, embodied energy consumptions and energy consumptions for the assembly of the components,

$$\mathrm{CED}=\frac{\text{Required Energy}+\text{Energy for extraction}+\text{Primary Energy}}{\text{Delivered Energy}}, \tag{4}$$

where

- the "Required Energy (kWh)" is the amount of energy for building up the necessary infrastructure, being related to its extraction, its processing and transport of the fuel/energy source and energy required for building up the necessary infrastructure (e.g. system/component/technology) related to the conversion of the energy;
- the "Energy for extraction (kWh)" represents the energy required for extraction, processing and transport of the fuel/energy source and energy required for maintenance of the conversion plant;
- the "Delivered energy (kWh)" represents the specified energy product from the energy plant and
- the "Primary energy (MJ)" (related to the energy product) is the amount of necessary energy for the generation of a specific amount (e.g. 1 kWh) of the delivered energy [36].

3.2. Environmental and energy performance indicators addressing the operational phase

For the operational phase, the indicators are classified into three main categories, where both energy and environmental performance indicators are included. The first category includes generic environmental KPIs as for example those of "Life Cycle CO_2 emissions", "Global Warming Potential" and have a value for both RES based and conventional fuels (e.g. fossil-based ones) energy systems. The second category includes environmental and energy performance indicators oriented mainly in the cases of RES based energy systems measuring the environmental impact savings compared to the corresponding of conventional systems (e.g. "Reduction of direct CO_2 emissions", "Avoided CO_2 emissions", "Delivered Energy", "Share of RES", "Electricity used from on-site generation"). The third category includes energy performance indicators with a value for both RES and conventional fuels energy based systems when integrated with storage solutions as those of ("Specific Energy Density", "Energy Storage Potential", "Net Delivered Electricity", "State of Health", "Storable Energy").

3.2.1. Environmental oriented indicators with a generic use

As concerns environmental impact assessment indicators with a generic use, the "Life-cycle CO_2 emissions (LCCE)" represents a theoretical measure, which indicates the amount of direct and indirect emissions (in kg $CO_{2,eq}$) for the production of a specific energy amount over a given period of time (t). The calculated emissions for a system/component/technology can correspond to all its stages potentially (construction, transportation, and energy production), dependent on the way it is used. This indicator calculates the operational (direct) $CO_{2,eq}$ emissions, as well as the transportation and infrastructure (indirect) $CO_{2,eq}$ emissions. The corresponding indicators are expressed in the following formula:

$$\mathrm{LCCE} = \sum_{i=1}^{TO} \text{Direct emissions } (i) + \sum_{i=1}^{TI} \text{Indirect emissions } (i), \tag{5}$$

where

- the "Direct emissions (kg $CO_{2,eq}$)" correspond to operational emissions during the operational phase depending on fuel properties and technology specifications;
- the "TO (years)" is the time of operational phase;
- the "Indirect emissions (kg $CO_{2,eq}$)" correspond to life cycle emissions not included in the examined operating scenario, such as those emissions corresponding to infrastructure (production and transportation of raw of materials, energy demands for the assembly of the different components etc) and
- the "TI (months)" is the time of infrastructure phase.

An environmental indicator that is commonly used in the open literature is the Global Warming Potential, including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Its functional unit, as afore-explained, is the 1 kg of $CO_{2,eq}$ emissions. This indicator measures the total emissions of the three main GHGs from energy production and use, which have a direct impact on climate change [37].

"Global Warming Potential (GWP)" is a very common used indicator calculating the equivalent CO_2 emissions in a time horizon of 100, 200 or 500 years. It actually compares the amount of heat trapped by a certain mass of the gas under examination, to the amount of heat trapped by a similar mass of carbon dioxide. Basic requirements for its calculation are the energy consumptions and CO_2 conversion rate (kg CO_2/kWh). The GWP is in link with other relevant indicators for the global warming potential, such as the indicators corresponding to "Life Cycle CO_2 emissions", the "Avoided CO_2 emissions", the "CO_2 equivalent Payback Time", and the "Cumulative Energy Demand". The GWP is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas:

$$\mathrm{GWP}\ (x) = \frac{\int_o^{TH} ax*[x(t)]dt}{\int_o^{TH} ar*[r(t)]dt}, \tag{6}$$

where

- the "TH" is the time horizon over which the calculation is considered (e.g. 20, 100, and 500 years);
- the "ax (Wm^{-2} kg^{-1})" is the radiative efficiency due to a unit increase in atmospheric abundance of the substance x;
- the "[x(t)]" is the time-dependent decay in abundance of the substance following an instantaneous release of it at time t = 0;
- the "ar" is the CO_2 radiative efficiency and
- the "r(t)" is the time-decaying function of pulses of the injected CO_2

The calculation of this indicator (in kg $CO_{2,eq}$) is carried out in line with the selected standardized impact methodology provided in Table 1.

3.2.2. Environmental and energy indicators with an orientation in RES based systems. The example of a photovoltaic system

The power from sun intercepted by the earth is about 1.8×10^{11} MW, which is many times larger than the present quantity of all whole energy consumption, worldwide. Several studies during the 70′s debate about the energy required producing a PV system and if that amount of energy is greater than the whole energy generated by the system over its lifetime. A photovoltaic system is sustainable only if the energy produced during its operating life compensates the total energy costs that can be estimated through the life cycle assessment (LCA) methodology.

The most commonly used materials from which PV panels are manufactured are mono-crystalline and poly-crystalline silicon [38]. Crystalline silicon modules are the most extensively studied PV types, since they are the most largely used. Mono-crystalline silicon or single-crystalline silicon type of PVs represent the most energy intensive and efficient PV technology. Poly-crystalline photovoltaic cells/panels have an efficiency of 15% and Silicon crystalline modules exhibit lifetimes in the range of 20–30 years. Commercial PV materials commonly used for photovoltaic systems include monocrystalline, polycrystalline and amorphous silicon and thin film technologies [40] and [40]. Because different PV technologies have different energy conversion efficiencies, the choice of a specific PV technology affects the results of their environmental assessment. Thin film-amorphous silicon technology as examined from [41] in the stage of materials construction has the highest energy requirements and thus the highest resulting emissions (measured in tonnes $CO_{2,eq}$.) among all. The study of [30] determines parameters, such as (a) the level of solar radiation, (b) the position of the modules, (c) the modules manufacturing energy intensity followed by its corresponding fuel mix, and (d) the solar radiation conversion efficiency of the module, which play a role in the estimation of the environmental performance of PV technologies, especially for the case of multi-crystalline and thin film (amorphous) modules. A methodology approach that has been proposed and carries out the environmental assessment of this type of RES technology, associated with a list of representative environmental indicators, such as the "Life Cycle CO_2 emissions (LCCE)", and the CO_2 emissions is that by [42]. As a reference in their study the examine the case of a 3.5 MW_p multi-crystalline PV installation in Springerville (Arizona) and indicate that PV plants potentially may approach near-zero GHG emission values with the development of advanced PV manufacturing technologies and installation concepts, thus simultaneously achieving significant reductions in their life-cycle energy, GHG emissions and associated costs of field PV plants. These reductions can be achieved with advances in PV manufacturing technologies, the large-scale manufacture of standardized BOS components and the development of more effective installation techniques. Fig. 4 depicts a simple scheme depicting the consecutively link between the materials used, the PV individual components (e.g. invertors) they are made of, the construction and installation of a PV system (e.g. way of individual components assembly) and their link with the corresponding operational (electricity production) and end-of-life phases (decommissioning).

As concerns the RES installation compared to the existing conventional infrastructure, their RES penetration into the grid system should be determined. Therefore, the "Share of RES (SR) (%)" energy performance indicator calculates the RES penetration in the energy mixture. Rated powers of generators connected to the power system (HV, MV and LV networks), classified in generators from RES and other sources must be available in order to calculate the RES penetration.

$$\mathrm{SR} = \frac{\text{Sum of the rated power of RES plants}}{\text{Sum of the rated power of all generators}}, \tag{7}$$

where

- the "Sum of the rated power of RES plants (kW)" is the total RES penetration participating in the energy system using renewable sources
- the "Sum of the rated power of all generators (kW)" is the amount of power from assisting generators.

The "Reduction of the direct CO_2 emissions (RDE)" is an environmental indicator based on the aforementioned definition of RES share and indicates the reduction (kg CO_2) of direct (operational) CO_2 emissions. CO_2 direct emissions is the amount of the direct emissions (in kg) owed to the production of a specific amount of energy over a given time period. The arithmetic formula of this indicator is:

$$\mathrm{RDE} = \sum_{i=1}^{TH} (\text{Share of RES(i)}) \cdot CO_2 \text{ rate} \cdot \text{Delivered Energy (i)}, \tag{8}$$

where

- the "TH (years)" is the operational time horizon of the system;
- the "Share of RES (%)" indicates RES penetration percentage in the energy mixture;
- the "CO_2 rate" is the impact factor (kg CO_2/kWh $_{el}$) for fossil fuels. It is a function of the efficiency of the system and of the fuel's properties. Indicative examples of that rate are 0.36 kg CO_2/kWh $_{el}$ for lignite, 0.34 kg CO_2/kWh $_{el}$ for hard coal, 0.27 kg CO_2/kWh $_{el}$ for diesel and 0.2 kg CO_2/kWh $_{el}$ for natural gas [43] and
- the "Delivered Energy (kWh)" of a power plant is the amount of energy generated by the conversion of primary energy sources.

"CO_2 avoided emissions (AVE)", expressed in kg $CO_{2,eq}$, is an environmental indicator which refers to avoided GHG emissions that, otherwise would be emitted, if another method has been applied. In the following formula, the alternative option refers to RES application

$$\mathrm{AVE} = \text{Life Cycle } CO_2 \text{ Emissions} - \text{Indirect Emissions of RES}, \tag{9}$$

where

- the "Life Cycle CO_2 Emissions (kg $CO_{2,eq}$)" represents the total life cycle emissions from a conventional system;
- the "Indirect emissions (kg $CO_{2,eq}$)" is the amount of emissions from a renewable system.

In what concerns the assessment of process technologies in energy terms, indicators such as "Delivered Energy" and "Electricity used from on-site generation" are provided, since they are applied for the calculation of the respective environmental impact indicators.

Specifically, "Delivered Energy (DE)" of a power plant is the amount

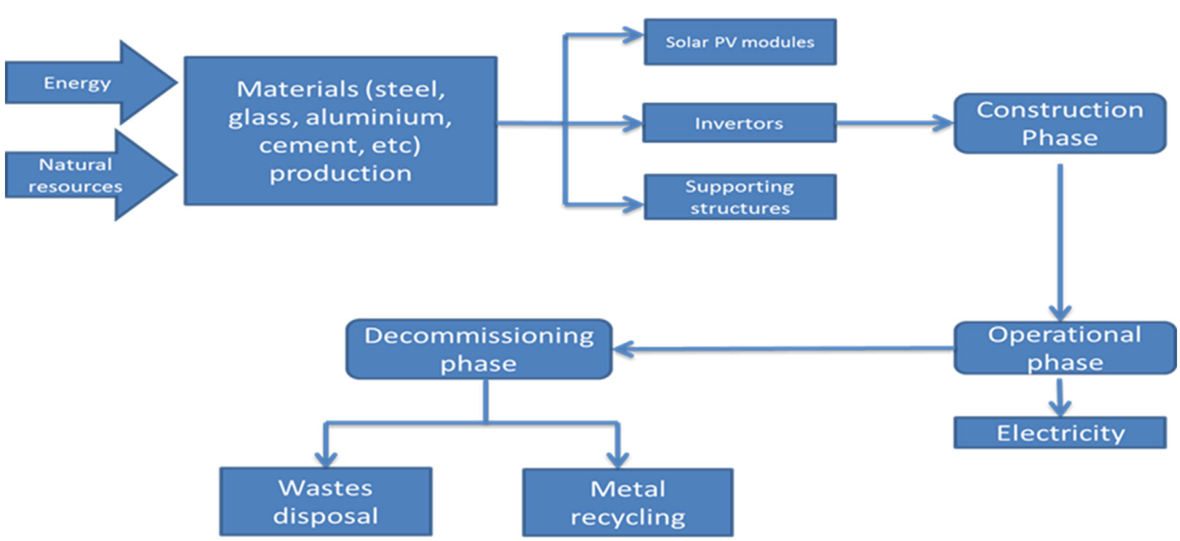

Fig. 4. Cradle-to-grave configuration scheme of PV components.

of energy (kWh) generated by the conversion of primary energy sources (renewable or not) and is supplied to the transformation and distribution grid through systems boundaries with purpose to ending up for residential use. The formula of this indicator is:

$$DE = \text{Efficiency of the power plant system} * \text{Primary energy}, \quad (10)$$

where

- the "Efficiency of a power plant" is the ratio (%) that indicates the conversion of thermal content of fuel into electrical energy;
- the "Primary energy (kWh)" is the total amount of thermal energy contained in raw fuels (direct thermal content) and others sources, which can be found in nature and have not undergone transformation or conversion process.

The amount of energy produced on-site needs to be recorded and examined in order to be balanced with the power acquired from the grid. "Electricity used from On-site Generation (EOSG)" calculates the electricity produced by RES to the electricity produced on-site plus the electricity from the grid network [44]. Energy production measurements, technical specifications of the system and grid, legislative framework issues are required for its definition.

$$EOSG = \frac{\text{Electricity produced by RES}}{\text{Elecrticity produced on site} + \text{Electricity from network}}, \quad (11)$$

where

- the "Electricity produced by RES system (RES penetration)" is measured in (kWh);
- the "Electricity produced on-site (kWh)" is the produced energy from of-grid sources and is connected to the system and
- the "Electricity consumed from network (kWh)" is the amount of electricity taken directly from the public network

Taking into consideration the comparative assessment results obtained by [16], indicative GHG emissions for different PV case studies across multiple countries are presented in Table 4. The Module Efficiency on a solar panel refers to the percentage of sunlight that hits the panel and converts into electricity.

Studies that are more recent have revealed that current PV systems are in fact net energy producers, but they are an expensive alternative when compared to conventional technologies. The information collected based on an extensive survey of available open literature shows that the PV output power fluctuation under the effect of solar irradiance intermittency is the most important problem of PV grid integration [50]. The results of [51] show that cell temperature has a significant effect on the PV parameters and it controls the quality and performance of the solar cell. The significant effect of the temperature on the PV performance enhanced from the study of [52] which report that the output power of silicon based PV systems decrease with increasing PV module temperature. Environmental factors (external), PV system factors (internal), PV system installation factors (operational), PV system cost factors (economic) and other type of miscellaneous factors, have a considerable contribution on the system performance [38]. Although the PV technology is one of the most dominant RES solutions being currently applied and examined, it is associated with not negligible environmental concerns. The production of PV cells is accompanied by a high rate of emissions during their manufacturing, which consequently results in a significant negative impact on the environment. In fact, many renewable energy technologies do have an impact on water, ground, wildlife, landscape, especially during their manufacturing stage and as a result, the mere evaluation of CO_2 emissions results can be considered as limitative, for their in general positive impact. This rate of emissions during the manufacturing phase of a photovoltaic module can be measured from indicators such as "LCCE", "GWP" described above, from which it is possible to define the time for a PV to save the exact same amount of emissions as those produced during its manufacturing phase. In general, all PV technologies generate far less life-cycle air emissions per kWh than conventional fossil-fuel based electricity generation technologies, over their whole life cycle.

A photovoltaic power generation system consists of multiple components like cells, mechanical and electrical connections, mountings, and means of regulating and/or modifying the electrical output. These systems are rated in peak kilowatts (kW_p), which is an amount of electrical power that a system is expected to deliver when the sun is directly overhead on a clear day [50]. Generally, the power rating of residential PV systems is 1–20 kW and the peak power of commercial or industrial PV systems normally varies from in the range of kWs to MWs [53]. In the previous paragraphs, several operational indicators were defined in order to be able to measure the energy production of the system (e.g. "DE", "EOSG"), the penetration of the photovoltaic into the electricity grid (e.g. "SR"), the energy consumption to deliver the amount of energy (e.g. "NER", "CED").

3.2.3. Environmental and energy performance indicators with an orientation in storage based systems. The example of a battery storage technology

There is considerable interest in the use of electrical storage technology for the case of low-carbon power systems. At the domestic level, the use of batteries in grid-connected photovoltaic systems has been proposed for the purposes of minimizing grid exports, improving consumer economics by exploiting retail electricity tariffs with variable pricing, and increasing self-consumption with feed-in tariffs.

A key requirement for the linear operation of Distributed Energy Resources (DER) is the storing excess power from RES, in order to meet peak demands. Therefore, storage and release of electrical energy are critical aspects that need to be considered in the evaluation of RES based energy production processes, towards the uninterrupted and non-fluctuating supply with increasing penetration of intermittent renewable power sources [54]. A representative system for electrical storage is batteries, which are built in different sizes with capacity ranging from less than 100 W to several megawatts. Their round-trip energy storage efficiency is in the range of 60–80% depending on the operational cycle and the electrochemistry type [55]. Table 5 gathers operational parameters from different battery technologies affecting their capability of energy storage. According to [56], the most prominent battery technologies for household applications are lead-acid (LA) batteries, high temperature batteries (e.g. NaS or NaNiCl) flow batteries and lithium-ion batteries (LiBs).

The disposal is the most important factor to determine the total environmental impact of a battery system over its entire life cycle as performed by [57]. The most effective way to reduce the environmental impact of battery systems is to increase the recycling rates, the battery performance, and, to lower the content of hazardous material. Primary energy use and the emission of CO_2 are most significant during battery manufacturing, since significant SO_x and NO_x emissions arise in the

Table 4
GHG results of mono-Si PV systems.

Location	Irradiation ($kWh/m^2/yr$)	Module Efficiency (%)	Lifetime (years)	GHG emissions ($kg\ CO_{2,eq}/kWh$)	Reference
UK	1253	12	20	–	[45]
Japan	1427	12.2	20	61	[7]
South-European	1700	13.7	30	41	[46]
Switzerland	1117	14	30	–	[47]
South-European	1700	14	30	30	[48]
China	1702	–	–	50	[49]
Lebanon	1867	13.1	25	89	[16]

Table 5
Battery technologies and characteristics.

Reference	Battery Technology	Specific Energy (Wh/kg)/Power Density (W/kg)	Cycle life	Round-trip Efficiency
[59]	Sodium-sulfur (Nas)	150–240 Wh/kg	4500–5000 cycles at 80% DoD	75–90%
	Vanadium Redox flow Battery	10–70 kWh/m^3	several thousand cycles	85%
[60]		16–33 kWh/m^3	> 12,000 at 100% DoD	75–80%
[55]	Lead Acid (PbO2) battery (conventional battery)	30 Wh/kg–150 W/kg	1000 cycles	85–90%
[60]		30–50 Wh/kg	500–1000 cycles	65–80%
[60]	Lithium ion (Li-ion) battery	200 Wh/kg	3000Cycles at 80% DOD	95%
[60]	Nickel Cadmium (NiCd) battery	50–75 Wh/kg	2000–2500 cycles	85%

extraction and refining of raw materials [58].

According to [61,55,60], the most representative key parameters for the energy assessment of storage systems, which in turn can be coupled with representative environmental indicators are the following, i.e. (i) "Technical maturity and specific energy", (ii) "Stored energy and round-trip efficiency", (iii) "Life time and cycle life" and (iv) "Power rating and discharge time".

Specifically, concerning technical maturity in terms of energy intensity of the installed energy storage system, the "Specific Energy Density (SED)" can indicate the amount of energy stored in a given system or region of space per unit of mass (Wh/kg). The "Specific Energy Density" is the product of the specific capacity and the operating voltage in one full discharge cycle.

$$SED = \frac{I * \int_0^{tcp} V(t)dt}{3600 * M_w}, \quad (12)$$

where

- the "V(t)" is the average operating voltage of the cell during the discharge cycle;
- the "I" (Ah) is the constant current drain;
- the "M_w "(kg) is the weight of the cell and
- the "t_{cp} "(h) is the time required for the terminal voltage to reach its cut off value

The stored energy as a crucial technical parameter for the environmental assessment can be quantified through indicators such as "Energy Storage Potential (ESP)" and "Net Delivered Energy (NDE)". The estimation of the energy capacity of a storage technology made of a material is carried out, through a specific energy performance indicator called "Energy Storage Potential (ESP)" expressed in Wh [62]. Its arithmetic formula is:

$$ESP = \frac{\rho * M}{m_f}, \quad (13)$$

where

- the "ρ (Wh/kg)" is the theoretical energy density of the anode and cathode materials;
- the "M (kg)" is mass of material available that constitute only the storage medium and
- the "m_f (%) " is the mass fraction of the electrochemically active materials

For the case of energy from on-site generation alongside with energy storage, the "Net Delivered Dectricity (NDE)" (kWh) is an energy performance indicator calculating the amount of energy originating from a dispatchable system. Thus, is the sum of electricity delivered directly and electricity stored [63], e.g.

$$NDE = E_{tot} * (1 - f_{stor}) + \frac{E_{tot} * f_{stor}}{ER}, \quad (14)$$

where

the "E_{tot} (kWh)" is the total primary electricity generation;

- the "f_{stor} (%)" is the fraction of primary electricity generation stored and
- the "ER (%)" is energy ratio indicates the efficiency of the storage system representing the conversion efficiency during the storage and re-generation cycle.

However, according to [64], the storable energy is reduced by aging, with this reduction depending on calendar and cycling degradation. In order to calculate the storable energy, it is necessary to define first the factor of "State of health (SOH)", which is a time dependent factor used for the evaluation of the actual state of a battery in comparison to its state in the beginning of its life time, e.g.

$$SOH = 1 - Degradation_{\ TOTAL} \quad (15)$$

In specific, the formula of the "Storable Energy (SE)" is

$$SE = SEN * (0.8 + 0.2 * SOH), \quad (16)$$

where

- SE_N (kWh) is the nominal storable energy

After identifying the four major pillars, (i) "Technical maturity and specific energy", (ii) "Stored energy and round-trip efficiency", (iii) "Life time and cycle life" and (iv) "Power rating and discharge time", meaningful KPIs are tracked for each of these pillars, for the evaluation of the battery energy performance. The repository of these KPIs is gathered in Table 6.

The estimation of battery systems environmental profile should preferably be done in a systematic way, pointing emphasis in actions that have the greatest influence such as the energy performance of the proposed system. In previous section emphasis was put to identify the major structural pillars in where the assessment take's place and the crucial indicators for that assessment was calculated.

Since batteries exhibit most of their life cycle impacts during their manufacturing and possibly disposal phases [65], including the primary energy use of the module, the proposed KPIs are oriented to indirect emissions. Tabular data for the GHG emissions per kg of produced battery presented in Table 7 and Table 8 according to the findings of [66,67] respectively pointing that the most environmental intensive batteries in terms of their production is the lithium ion and the nickel metal hydride.

Table 6
Allocation of the proposed KPIs at the selected battery assessment pillars.

Battery energy performance assessment pillars	Key performance indicators
Technical maturity and specific energy	"Specific Energy Density (SED)"
Stored energy and round-trip efficiency	"Energy Storage Potential (ESP)" "Storable Energy (SE)"
Life time and cycle life	"State of health (SOH)"
Power rating and discharge time	"Net delivered electricity (NDE)"

Table 7
Characterized GHG emissions per kg of produced battery and MJ of capacity.

Type of Battery	GHG emissions ($kgCO_{2,eq}$/kg of battery)	GHG emissions ($kgCO_{2,eq}$/MJ)
Lead Acid	0.9	5–7
Lithium-ion (NMP solvent)	12.5	17–27
Lithium-ion (water solvent)	4.4	–
Nickel cadmium	2.1	10–15
Nickel metal hydride	5.3	16–20
Sodium sulphur	1.2	2

3.3. Environmental and energy performance indicators addressing End-of-life phase

Finally, the end-of-life phase includes indicators that refer to the whole lifetime of the examined system and measures the energy and emission savings that can be achieved by any RES system application in the place of fossil-based ones. Eight representative indicators are defined.

The development of RES application is depending on the ratio between energy invested on the renewable system and the delivered energy that it is expected to substitute in the place of fossil-based energy sources, over a year of operation. This ratio indicates whether a RES investment is profitable or not. Within this framework, the "Energy Payback Time (EPBT)" (years) indicates the time during which, the RES system (e.g. PV) will produce the same energy used for its construction

$$EPBT = \frac{\text{Primary Energy Invested in PV System}}{\text{Delivered Energy substitued for PV per year}}, \tag{17}$$

where

- the "Primary energy invested in PV System (MJ)" is the energy that consumed during the manufacturing phase (e.g. raw of materials, assembly of the components) of the PV module and
- the "Delivered Energy substituted for PV (kWh)" is the PV energy production per year

The first indicator named as "Energy Return on (energy) Investment (EROI)" takes into consideration the system/component/technology whole life and estimates the ratio of the amount of usable energy (the exergy) delivered from a particular energy resource to the amount of exergy used to obtain that energy resource. This is an energy performance indicator. A high-energy return on energy investment (EROI) of an energy production process is crucial to its long-term viability. Following the definition of NER, it is quite easy to observe the link between NER and EROI in the fact that NER although is a measure that refers in the operational phase of a system, EROI tends to refer to NER at the end of life phase. EROI is defined as:

$$EROI=\frac{\text{Energy Delivered}}{\text{Primary energy required to deliver that energy}}, \tag{18}$$

Table 9
Representative EROI values for fuel resources, per country.

Resource	Country	EROI (X:1)
Oil and gas production	Global	18
Oil and gas (domestic)	U.S.A	11
Oil and gas (imported)	U.S.A	12
Natural gas	U.S.A	67
Natural gas	Canada	20
Coal (mine-mouth)	China	27
Hydropower	n/a	> 100
Wind Turbines	n/a	18
Photovoltaic	n/a	6 to 12
Ethanol (biomass)	n/a	0.8 to 10
Corn-based ethanol	U.S.A	0.8 to 1.6
Bio-diesel	U.S.A	1.3

where

- the "Energy Delivered (kWh)" is the energy delivered by the whole system and
- the "Primary energy required to deliver that energy (MJ)" is the primary energy require to obtain that source of energy.

The energy inputs considered in the EROI should be measured consistently, so that this definition can be valuable. The energy input component of the EROI can be calculated in terms of electrical or thermal energy. According to [72], the EROI values for various fuel resources listed in Table 9. Furthermore, typical EROI values for different PV modules are available in Table 10.

As concerns, the lifetime and cycle life of a storage system, "Battery calendar life" and "Battery cycle life" are the two indicators used to evaluate the operational time horizon of the storage system respectively, which in return are linked to the evaluation of such type of processes in environmental terms.

"Battery Calendar Life (BCL)" indicates battery life in number of years before a predefined degradation of its performance, is made and this is measured between the battery's commissioning and its replacement (at the net of possible stops for maintenance, out-of-services, etc.), e.g.

$$BCL = \text{Year of commissioning} - \text{Year of replacement} \tag{19}$$

When evaluating batteries cycle life, there are three important factors that should be taken into account, e.g. those of (a) Depth of Discharge (DOD), (b) discharge and charge rates and (c) ambient operating temperature. DOD expresses how much of the stored energy in a device has been used, e.g., 0% DOD means that a battery is fully charged while 100% DOD means that a battery is fully discharged. DOD has an important role in battery degradation. If the battery cycles with a high DOD the cells will degrade rapidly but if the DOD is designed not to exceed 0.6, the battery lifetime is considerably high. Hence, high DOD cycling results in a shorter cycle life [59,56].

In addition, "Battery Cycle Life (BCYL)" reflects the battery life in terms of number of cycles at 80% DoD before a predefined degradation of its performance. This includes the number of equivalent cycles at

Table 8
LCA studies on batteries.

Battery Typology	System boundaries	GHG emissions ($kgCO_{2,eq}$/kg of battery)	Reference
$LiFePO_4$	Manufacturing	22	[68]
Nickel cobalt manganese Li-ion	Manufacturing	22	[68]
Li-ion	Manufacturing	12	
$LiMnO_4$	Manufacturing and end-of-life	6	[69]
$LiFePO_4$ (NMP solvent)	Manufacturing and end-of-life	41.04	[70]
$LiFePO_4$ (water solvent)	Manufacturing and end-of-life	31.71	[70]
Nickel–metal hydride	Manufacturing, operation and end-of-life	54.6	[71]
Li-ion	Manufacturing, operation and end-of-life	40.5	[71]

Table 10
Typical EROI values for PV modules [73].

PV module	EROI
Mono-Csi (rooftop)	5.9
Multi-c Si (rooftop)	5.9
Ribbon Si (rooftop)	9.4
CdTe (ground)	11.8

80% DoD measured between the battery's commissioning and its replacement,

$$\text{BCYL} = \text{Number of equivalent cycles at 80\% DoD measured between the battery's commissioning and its replacement} \tag{20}$$

According to power rating and degradation of any storage system, battery degradation is an energy performance indicator, which can estimate the reduction of its power quality over a given period of time. Hence, the energy storage capability is reduced by aging. In what concerns the battery storage system, the 'Battery Total Degradation (BDT)" is the sum of calendar and cycling degradation [64],

$$\text{BDT} = \text{Degradation}_{\text{CALENDAR}} + \text{Degradation}_{\text{CYCLING}} \tag{21}$$

A number of Battery degradation models can be developed for the quantification of this indicator, using data obtained from dynamic operating conditions estimating calendar as well as cycling aging. The Degradation $_{\text{CALENDAR}}$ is a value that depends on the state of charge, which is the remaining battery capacity that is available for discharge as a percentage of the maximum battery capacity, ambient temperature and time. In specific, a calendar degradation empirical model for iron phosphate cells under dynamic validation of the operating conditions is provided based on the following formula, as a function of the determination of the calendar loss of capacity:

$$Q_{\text{loss}} = \alpha_1 * \exp(\beta_1 * \text{T}-1) * \alpha_2 * \exp(\beta_2 * \text{SoC}) * t^{0.5}, \tag{22}$$

where

- the "Q_{loss} (%)" is the calendar loss of capacity;
- the "α_1, β_1, α_2, β_2" are fitting parameters for specific conditions;
- the "State of Charge (SoC)" is the remaining battery capacity, which is available for discharge as a percentage of the maximum battery capacity;
- the "T (K)" is storage temperature and
- the "t (days)" is the storage time

As concerns the Degradation $_{\text{CYCLING}}$, which indicates the fade of capacity, an empirical model expressed for different range of DoD values under varying operating conditions is the following:

$$Q_{\text{loss}} = (\gamma_1 * \text{DOD} + \gamma_2 * \text{DOD} + \gamma_3) * k * \text{Ah}^{0.87}, \; 10\% < \text{DOD} < 50\%$$

Or

$$Q_{\text{loss}} = \alpha_3 * \exp(\beta_3 * \text{DOD}) + \alpha_4 * \exp(\beta_4 * \text{DOD}) * k * \text{Ah}^{0.65}, \quad \text{DOD} < 10\% \text{ and DOD} > 50\%, \tag{23}$$

where

- the "Q_{loss} (%)" is the cycling capacity loss;
- the "Depth of discharging (DoD)" is an indicator which calculates the state of charge of a battery and measured in Ah or in percentage (0% means full charged battery-100% the battery is empty);
- the "Ah" is the total charge processed through the battery and
- the "α_3, β_3, α_4, β_4, γ_1, γ_2, γ_3"are fitting parameters and the "k" is a correction factor parameter for dynamic operating conditions and is equal to 1 if DoD is constant

A very crucial environmental indicator for evaluation of RES and storage systems is "CO_2 equivalent Payback Time (CO_2PBT)". It calculates the time (years) required for the RES system (e.g. PV) to save the exact amount of $CO_{2,eq}$ emitted during its entire life time (starting from its manufacturing). The $CO_{2,eq}$ PBT is mainly dependent on the amount of kWh produced by the system, and the grid $CO_{2,eq}$/kWh emission factor.

This indicator is in relation with the capacity factor and the load of the RES and both of them are functions of the operation time. The indicator is calculated according to the following formula,

$$f(t) = \sum_{t=1}^{TO} \text{Reduction of the operational } CO_{2,eq} \text{ emissions}(t), \quad \text{when } f(t) = \text{Indirect emissions EEIM} \;\; t = CO_{2,eq} \text{ Payback Time.} \tag{24}$$

where

- the "Reduction of the operational $CO_{2,eq}$ emissions (kg$CO_{2,eq}$/year)" is the amount of reduced $CO_{2,eq}$ emissions from the replacement of a conventional system by a RES;
- the "Indirect emissions EEIM" is the emissions (kg$CO_{2,eq}$), which correspond to the embodied Energy for Infrastructure of Materials and for the building system and
- the "TO (years)" is the operation time of the system

An alternative calculation method for the estimation of the $CO_{2,eq}$ Payback Time obtained from the study of [16] according to the following formula

$$CO_2 \text{ PBT} = \frac{\text{Indirect emissions}}{\text{Emissions Factor} \cdot \text{Annually Produced Energy}}, \tag{25}$$

where

- the "Indirect emissions" (kg $CO_{2,eq}$) correspond to life cycle emissions not included in the examined operating scenario, such as those emissions corresponding to infrastructure (production and transportation of raw of materials, energy demands for the assembly of the different components etc);
- the "Emissions Factor" (kg $CO_{2,eq}$/kWh) is the emissions per unit of energy produced by grid and
- the "Produced Energy" (kWh/year) is the annually RES produced energy

Motivated by the EROI indicator, analyzed previously, a relevant formula, which can be presented and is meaningful for this type of solutions, is the "Energy stored on invested (ESOI)". Over their entire life, electrochemical storage technologies only store in between two and ten (2–10) times the amount of energy required to build them. ESOI is the ratio of electrical energy stored over the lifetime of a storage device to the amount of primary embodied energy required to build the device [62]:

$$\text{ESOI} = \frac{\text{Energy Stored}}{\text{Embodied Energy}}, \tag{26}$$

where

- the "Energy Stored (kWh)" is the amount of energy that can be stored in the battery system and
- the "Embodied Energy (kWh)" is the required energy to build up that system.

Typical ESOI values for various batteries technologies are summarized in Table 11. The addition of energy storage in a system has an influence on the overall EROI of a system, by decreasing the net energy

Table 11
Typical ESOI values for battery storage technologies.

Battery Technology	ESOI
Lead-acid battery	5
Lithium-ion battery	32
Vanadium redox battery	10
NaS battery	20
Zinc bromide battery	9

produced due to increasing conversion and storage losses, with the energy input requirements imposed by the construction of the energy storage system being increasing.

In Table 12, the correlations between the energy and environmental performance indicators corresponding to each of the infrastructure, operational and end-of-life phases are provided.

4. Interest of KPIs by different types of stakeholders

Centralized energy systems are being decarbonized becoming more environmental friendly, while energy production is transitioning towards distributed energy sources, facilitated by advances in underpinning power system management technologies. This trend is in harmonization with the accelerating changes in the energy landscape. Distributed energy sources are electric generation units (typically in the range of 3 kW–50 MW) isolated from the main electric distribution grid or near the end-user. Energy storage technologies produce no net energy but can provide electric power, whenever needed, over short periods of time working as distributed power sources. The integration of distributed energy resources (DERs) into the electric power grid creates technical challenges at both bulk power system and distribution system levels. The KPIs provided by this methodology can play a significant role in making electricity grids more promising for energy generator players, more efficiently sustainable for Transmission System Operators (TSOs) and Distribution System Operators (DSOs), and more practical and cheap for consumers (sometimes acting as producers simultaneously), including the RES distributed producers (e.g. prosumers). Fig. 5 illustrates the flow chart of the electricity among the different stakeholders starting from the phase of the electric energy (electric utility) production and its distribution through the transmission (TSOs) and distribution system (DSOs) operators, until its final consumption (consumer, prosumer). As a result, each stakeholder group can have different interest in the aforementioned KPIs; thus making this addressing and connection between the relevant stakeholders groups and the KPIs and interesting area of research and development, that needs to be examined. This paper tries for the first time to shed some light in this connection and individual interest of each of the most meaningful and limited KPIs by the stakeholders.

4.1. Electric utility

An electric utility is an electric power company dealing, in most of the cases, with the generation, distribution, and transmission of electricity for sale, in a regulated market. Utilities' capacity generators can be switched on or off upon the requirements of demand. Variable capacity RES generators are dependent on factors like wind or sunshine and are therefore only able to generate certain amounts at certain times [74]. Because of the multiple role an electric utility can support in the

Table 12
Indicator's (environmental and energy) metric parameter correlation.

	Indicators	Linked relation with other Indicators	Orientation
Manufacturing phase	Embodied Energy for infrastructure of materials	Life Cycle CO_2 emissions, Energy payback time, Cumulative energy demand, Gross primary energy requirement, Global Warming Potential	Generic
	Gross Primary Energy Requirement	Cumulative energy demand, Embodied energy for infrastructure of materials and for the building system	
	Net Energy Ratio	Cumulative Energy Demand, Embodied Energy for infrastructure of materials, Gross Primary Energy Requirement, Delivered Energy	
	Cumulative Energy Demand	Net Energy Ratio	
Operational Phase	Life Cycle CO_2 Emissions	Avoided CO_2 emissions, CO_2 equivalent Payback Time, Cumulative energy demand, Embodied energy for infrastructure of materials, Gross primary energy requirement, Global Warming Potential	Generic
	Global Warming Potential	Reduction of the direct CO_2 emissions, Life Cycle CO_2 emissions, Avoided CO_2 emissions, CO_2eq Payback Time, Cumulative Energy Demand	
	Avoided CO_2 Emissions	Life Cycle CO_2 emissions, $CO_{2,eq}$ Payback Time, Cumulative Energy Demand, Global Warming Potential	RES based systems
	Share of RES	Electricity used from on-site generation, Delivered Energy	
	Delivered Energy	Net Energy Ratio, Electricity used from on-site generation	
	Electricity used from On-Site Generation	Reduction of the direct CO_2 emissions, Avoided CO_2 emissions, Delivered Energy, Share of RES	
	Reduction of the direct CO_2 emissions	Life Cycle CO_2 emissions, $CO_{2,eq}$ Payback Time	
	Specific Energy Density	Energy Storage Potential, Battery cycle life, Battery calendar life	Battery installation
	Energy Storage Potential	Battery total degradation, Battery cycle life, Battery calendar life	
	Net Delivered Electricity	Energy storage potential, Battery total degradation, Battery calendar life, Battery cycle life, Delivered Energy, Electricity used from on-site generation	
	State of Health	Battery total degradation, Battery cycle life, Battery calendar life	
	Storable Energy	Battery total degradation, Battery cycle life, Battery calendar life	
End-of-life Phase	Energy Returned on Energy Invested	$CO_{2,eq}$ Payback Time, Cumulative Energy Demand, Embodied Energy for infrastructure of materials	RES based System/Battery installation
	$CO_{2,eq}$ Payback Time	Reduction of the direct CO_2 emissions, Embodied energy for infrastructure of materials, Global Warming Potential	RES based System/ Battery installation
	Energy Stored on Energy Invested	Energy storage potential, Battery total degradation, Embodied energy for infrastructure of materials	Battery installation
	Battery Degradation	Cumulative Energy Demand, Electricity used from on-site generation	
	Battery Calendar Life	Battery total degradation, Battery cycle life, Energy Storage Potential	
	Battery Cycle Life	Battery total degradation, Energy Storage Potential, Battery calendar life	
	Energy Payback Time	Embodied Energy for infrastructure of materials, Share of RES	RES based System/ Battery installation

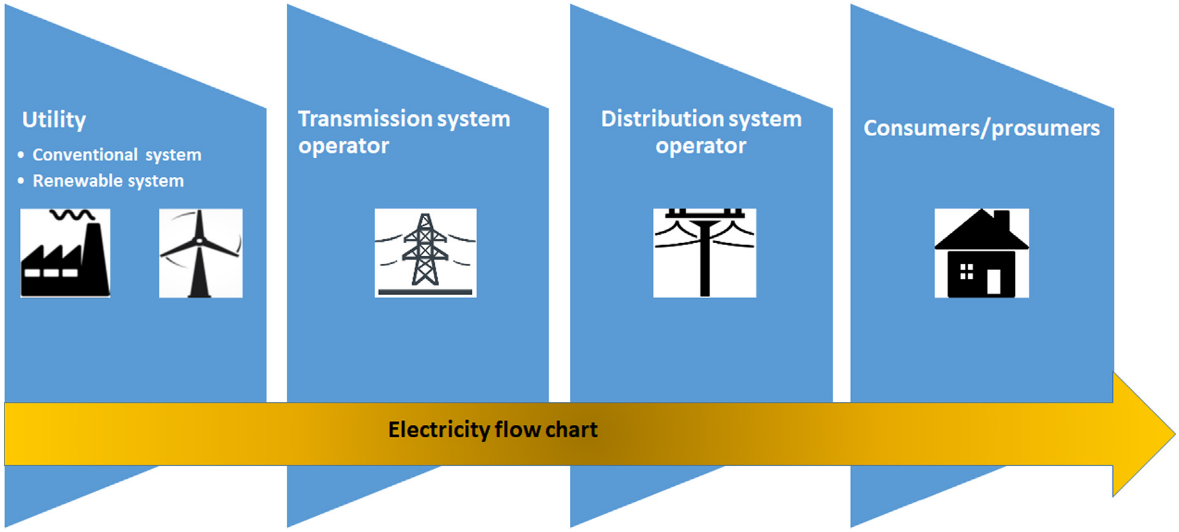

Fig. 5. Overview of the various stakeholders, playing a role in the electricity flowsheet.

field of energy system production and distribution, there is an extended list of energy and environmental performance indicators in the sphere of their interest. As concerns the electricity production, energy performance indicators such as "Delivered Energy (DE)", "Cumulative Energy Demand (CED)", "Share of RES (SR)", "Net Energy Ratio (NER)", "Gross Primary Energy Requirement (GPER)", "Electricity used from On-site Generation (EOSG)" and "Embodied Energy for Infrastructure of Materials (EEIM)" are considered to be of important KPIs for this group of stakeholders. In connection with the production of the electrical energy, the relevant environmental impacts can be most importantly quantified by the use of environmental KPIs, such as "Life Cycle CO_2 Emissions (LCCE)", "Global Warming Potential (GWP)", "Reduction of the Direct CO_2 emissions (RDE)" and "Avoided of CO_2 Emissions (AVE)". Electrical energy is stored during times when production, especially from intermittent power plants such as RES, exceeds consumption and returned to the grid when production falls below consumption. Moreover because of the distribution and transmission role of the electric utilities may have, their interest on storage products/technologies is as well important. Therefore, since the storage of the excess of electricity during low demand time periods is important, energy performance indicators such as "Battery Total Degradation (BTD)", "Energy Storage Potential (ESP)", "Battery Calendar Life (BCL) and Battery Cylindrical Life (BCYL)" and "Net Delivered Electricity (NDE)", "Specific Energy Density (SED)", "State of Health (SOH)", "Storable Energy (SE)" and "Energy Stored on Energy Invested (ESOI)" are included in the list of environmental KPIs being part of their interest. In the case of a RES system, the energy performance indicators of "Energy Payback Time (EPBT)", "Energy Return on (energy) Investment (EROI)" and the environmental KPIs of "CO_2 equivalent Payback Time (CO_2PBT)" can be applied accordingly for the power utilities.

4.2. Distribution system operators

A DSO (Distribution System Operator) or a DNO (Distribution Network Operator) is responsible for the management and operation of the distribution network of electricity, in the LV/MV (low/medium voltage) grid. The main aim of a DSO/DNO is the sustainability, reliability and flexibility of the system; i.e. the ability of the distribution grid to reciprocate to the consumer needs every single moment, or the ability to modify the load curve via peak shaving techniques. In many cases DSOs (DNOs) act as intermediaries between consumers/small producers and utilities, validating the operational credibility of the technological installations supporting alternative demand response schemes, to identify potential profile deviations and evaluate the impact of the benefits generated by the applied policies. DSOs (DNOs) as intermediaries among consumers/small producers and utility are interested more in the grid operational credibility, than the energy production itself. This is enumerated through energy consumption measurements as well as the delivered energy from the distribution network including the paybacks from RES and storage installations. As a result, environmental KPIs are most of the times not in their sphere of interest. However, the validation of the operational credibility concerning RES and storage installations for a DSO (DNO) is made through energy related indicators such as "Delivered Energy (DE)", "Electricity from on-Site Generation (EOSG)", "Cumulative Energy Demand (CED)", "Share of RES (SR)" and "Net Energy Ratio (NER)". These can assess in technical terms, the electricity produced from a RES installation (a PV module), so that they can evaluate the sustainability and the demand response of the grid. DSOs (DNOs) are mostly interested in the operational impact of any scenario to the grid conditions and are highly interested in investigating the environmental impact of new technologies in comparison to conventional systems replacing them. The installation of an integrated renewable and storage system is an interest for the DSOs in the field of energy paybacks, when compared to a conventional system. As a result, the KPIs of "Energy Returned on Energy Invested (EROI)" and "Energy Payback Time (EPBT)" can assess how much time is required for any RES based system, as for example the PV-battery system, to save the exact amount of energy required for the installation of this specific technology.

4.3. Transmission system operator

Transmission System Operators (TSO) transmits electrical power from generation plants over the electrical grid, at the level of HV (high voltage), to regional or local electricity distribution operators. Transmission grids operate on a sub-national or national level. They receive the power generated from the large power stations and transmit it to inlet points on the distribution networks or to the premises of some high energy demand consumers supplied with high voltage [75]. It is required from TSOs to dispatch generation, storage, and/or apply demand response techniques to match supply and demand at all times. Electric storage solutions can be used to assist transmission system operators in daily operation, aiming at avoiding electrical grid congestion. The transportation of the intermittent energy produced at remote locations can lead to a growing amount of congestions in the transmission grid [76]. Because of the TSOs duty to supply the distributors with electrical power from the utilities, they are responsible for the balance between the demand and response, at the highest level of the grid. Therefore, TSOs, except from relevant environmental KPIs, they are as well interested in energy indicators that measure networks energy consumption (“Cumulative Energy Demand (CED)”, “Net Energy Ratio (NER)”) and the delivered energy (“Delivered Energy (DE)”, “Share of RES (SR)”). Moreover, payback time related indicators for investments addressing the existing infrastructure or future installations such as storage are also crucial for the transmission system operators (“Energy Payback Time (EPBT)”, “Energy Return on (energy) Investment (EROI)”, “Energy Stored on (energy) Investment (ESOI)”. Battery storage is used from TSOs to improve the effectiveness, efficiency and cost-effectiveness of the existing electrical transmission systems and to reduce the need for transmission and distribution equipment (managing transmission congestion and deferring/avoiding the need for additional equipment). Therefore, “Energy storage potential (ESP)”, “Battery Total Degradation (BDT)”, “Battery Cycle Life (BCYL)”, “Battery Calendar Life (BCL)”, “Specific Energy Density (SED)”, “State of Health (SOH)”, “Storable Energy (SE)” “Net Delivered Energy (NDE)” are considered to be crucial indicators for the transmission system operators for the case of storage installation.

4.4. Consumers and active users

The role of the consumer in the energy system can change from a passive user, simply using energy from the energy system to an active participant in the energy system, reacting to signals in the market and delivering energy services to the grid and market participants. Regarding distributed generation consumers’ profiles, they can generate and consume their own energy, or participate in community schemes by exchanging energy with others. This type of end-users are called prosumers. Regarding distributed storage consumers, they can store excess generation from their own generation or use energy smarter with time of use rates. Consumers are interested in the delivered electrical energy by the distribution system operator. Therefore, energy performance indicators such as “Delivered Energy (DE)”, belong in the sphere of their interest according to their needs. Consequently, environmental indicators such as “Global Warming Potential (GWP)”, “Life Cycle CO_2 Emissions (LCCE)”, “Reduction of the Direct CO_2 Emissions (RDE)” and “Avoided CO_2 Emissions (AVE)”, which assist on the environmental evaluation of an energy technology, are not applicable to their needs. However, the situation is different in the case of active users (prosumers), who produce electric energy from a RES based system in cooperation with storage solutions. In such cases, the environmental evaluation of the installed renewable technology and the reductions of emissions expressed by KPIs as “Life Cycle CO_2 emissions (LCCE)”, “Reduction of the Direct CO_2 Emissions (RDE)”, “Global Warming Potential (GWP)”, “Avoided CO_2 Emissions (AVE)”. Since active users involved actively in the coverage of their energy needs indicators such as “Embodied Energy for Infrastructure of Materials (EEIM)”, “Share of RES (SR)”, “Delivered Electricity (DE)”, “Electricity from on-site generation (EOSG)”. In the case of a RES system, the energy performance indicators of “Energy Payback Time (EPBT)”, “Energy Return on (energy) Investment (EROI)” and the environmental KPIs of “CO_2 equivalent Payback Time (CO_2PBT)” can be applied accordingly for the power utilities. Moreover, “Energy storage potential (ESP)”, “Battery Total Degradation (BDT)”, “Battery Cycle Life (BCYL)”, “Battery Calendar Life (BCL)”, “Specific Energy Density (SED)”, “State of Health (SOH)”, “Storable Energy (SE)”, “Net Delivered Energy (NDE)”, “Energy Stored on Energy Invested (ESOI)” are considered to be crucial indicators for the prosumers, especially for the case of storage installation. The selected aforementioned KPIs establishes a mechanism for continuous monitoring and control, providing useful information to each of the abovementioned group of stakeholders involved in integrated RES with storage systems. Table 13 summarizes the list of identified limited and of highest importance KPIs per stakeholders group.

5. Conclusions

An important challenge of our society is to reduce global GHG emissions. To this direction, the quantification of the environmental impact through the development of relevant environmental tools is considered necessary. In this light, the introduction and use of a limited number, but at the same time replicable and scalable environmental and energy performance indicators, capable of quantifying the characteristics of a RES based integrated with storage system is a prerequisite, before its environmental and energy assessment. In addition,

Table 13
List of KPIs per stakeholder group, as an express of interest.

	Stakeholders					
Key Performance Indicators	Utility	DSO	TSO	Active users (Prosumers)	Consumers	
					Residential End-users	Commercial End-users
Life Cycle CO_2 emissions	✓			✓		
Embodied Energy for infrastructure of materials	✓			✓		
Gross Primary Energy Requirement	✓					
Reduction of the direct CO_2 emissions	✓			✓		
Avoided CO_2eq emissions	✓			✓		
Energy Payback Time	✓	✓	✓	✓		
Energy Stored on Energy Invested	✓	✓	✓	✓		
Energy Storage Potential	✓		✓	✓		
Share of RES	✓	✓	✓	✓		
Net Energy Ratio	✓	✓	✓			
Cumulative Energy Demand	✓	✓	✓			
Global Warming Potential	✓			✓		
Delivered Energy	✓	✓	✓	✓	✓	✓
Electricity used from on-site generation	✓	✓		✓		
Battery Total Degradation	✓		✓	✓		
Battery Cycle Life	✓		✓	✓		
Specific Energy Density	✓		✓	✓		
State of Health	✓		✓	✓		
Storable Energy	✓		✓	✓		
Battery Calendar Life	✓		✓	✓		
Net Delivered Energy	✓		✓	✓		
Energy Returned on Energy Invested	✓	✓	✓	✓		
$CO_{2,eq}$ Payback Time	✓			✓		

the interest of the different stakeholders group in different KPIs, as a function of their area of interest, is as well of importance and should be taken into consideration. The current paper tries to make a first effort to present the KPIs of higher interest and their discretization per stakeholders' group primary interest. The suggested list of these KPIs are as well grouped as part of the product/technology individual steps of their whole life-cycle they address, i.e. referring to the individual phases of manufacturing, operation and end-of-life based on the boundaries set of each examined system.

Apart from standard KPIs, it is also made an effort to group some of them, into new proposed ones, as limited as possible but at the same time meaningful, replicable and at the same time easily adaptable to various configurations. This is done by on one hand capitalizing on the existing know-how databases for environmental and energy performance KPIs tracked in the open literature and through the consolidation of some of them into new proposing ones. Such representatively include the "Life Cycle CO_2 Emissions (LCCE)", "Reduction of the Direct CO_2 Emissions (RDE)" and "Avoided CO_2 Emissions (AVE)", "Electricity used from on-Site Generation (EOSG)", "Gross Primary Energy Requirement (GPER)", "Share of RES (SR)".

The whole list of proposed KPIs, being in position to evaluate a system in environmental and energy terms, is as well grouped in the following list of categories, i.e. those of (a) Energy KPIs related to the infrastructure of RES and storage systems ("Net Energy Ratio (NER)", "Cumulative Energy Demand (CED)", "Gross Primary Energy Requirement (GPER)"), (b) Energy KPIs related to the operational phase ("Delivered Energy (DE)", "Electricity used from On-site Generation (EOSG)"), (c) Environmental KPIs related to the operational phase ("Life Cycle CO_2 emissions (LCCE)", "Global Warming Potential (GWP)", "Avoided CO_2 emissions (AVE)", "Reduction of the Direct CO_2 emissions (RDE)") and (d) Energy and Carbon dioxide paybacks times related to the end of life phase ("Energy Returned on Energy Invested (EROI)", "Energy Payback Time (EPBT)", "Energy Stored on Energy Invested (ESOI)", "CO_2 equivalent Payback Time ($CO_{2,eq}$ PBT)"). This repository of selected KPIs addressing separately each one of them multiple needs and requirements of various types of stakeholders such as the Utility, the DSO (DNO), TSO and the prosumer/final consumers, is as well a key scope of this paper. This is owed to the fact, that the different profile characteristics of them, imposes different scope and orientation of assessment for them. As concerns an electrical utility, all the selected environmental and energy performance indicators are in the sphere of their interest, since energy generation, operation of the energy system and distribution of electrical energy are part of their business portfolio. Regarding DSOs (DNOs), because of their distinct role in the energy system, a list of only energy related KPIs corresponding only to the energy performance are relevant to them. DSOs (DNOs), most of the times are not expected to focus on KPIs related to environmental impact, due to the fact that their main responsibility is oriented to the balance of energy demand and supply in the energy system. Moving on the same page, TSOs as the energy operators responsible for the receipt of the power from the power stations and its transmission to inlet points on the distribution networks, they are as well mostly interested in energy KPIs. Finally, the active users as a special category of energy system stakeholders, they have an interest in environmental impacts. Consequently, they are interested in both of environmental and energy performance indicators related mainly with the operational phase, as well as the end-of-life phase of a product/technology. For the most common case of simple consumers, the most of interest indicator for them is the "Delivered Energy (DE)". However, the continuously upcoming entry on the market of RES and energy storage solutions indicates that these group of stakeholders should further develop the best fitting and of primary interest for them interpretation indexes (KPIs), expected to evaluate in a short-term period of time, the energy performance and the impacts on the environment of multiple innovative and updated energy systems and technologies, envisioned to sustainable replace old technologies (mostly based on fossil fuels) on a common basis.

6. Declaration of interest

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