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Critical review of competitiveness indicators for energy projects

Martin Colla[a], Anastasia Ioannou[b*], Gioia Falcone[b]

[a]Cranfield University, School of Water, Energy and the Environment, Cranfield, Bedfordshire, MK43 0AL United Kingdom

[b]University of Glasgow, School of Engineering, Glasgow, G12 8QQ, United Kingdom

*Corresponding author's email: anastasia.ioannou@glasgow.ac.uk

Abstract

The decarbonisation of the electricity sector can be a key contributor in the transition to sustainable energy systems. New low-carbon power production technologies are becoming available in the international market, contributing to building diversified portfolios of projects with very different features. Apart from technology-related features, the deployment of a power generation plant also depends on the availability of resources of the country/installation site, socio-economic implications, environmental impact and integration with the existing power grid. Decision makers should take all these factors into consideration when determining which project is more likely to move forward. Several studies have proposed the use of Key Performance Indicators (KPIs) to facilitate the decision-making process when selecting viable and sustainable energy projects. However, fewer studies exist that provide a detailed assessment of these KPIs. The scope of this paper is to critically review and investigate a set of multi-disciplinary KPIs, allowing a holistic comparison across different types of energy projects. The identified KPIs were classified as physical, economic, environmental and social. They were then analysed to assess their limitations, determine inter-connections and identify the need for additional indicators to capture risks and opportunities within a mixed energy market. This paper can be the basis for the development of an integrated framework, allowing a fairer assessment of competing energy projects by relevant stakeholders.

Word count: ~11,500 words

Keywords: competitiveness, Key Performance Indicators, critical review, environmental, social, economic, physical, energy projects

List of Abbreviations

Abbreviation	Description
ABEX	Abandonment Expenditure
AHP	Analytical Hierarchy Process
BCR	Benefits to Costs Ratio
CAPEX	Capital Expenditure

CBA	Cost Benefit Analysis
CCS	Carbon Capture and Storage
CED	Cumulative Energy Demand
CF	Capacity Factor
DALY	Disability Affected Life Years
DPB	Discounted Payback
EAPI	Energy Architecture Performance Index
EIA	Environmental Impact Assessment
EPR	Energy Payback Ratio
EPTB	Energy Payback Time
ERO(E)I	Energy Returned On (Energy) Invested
$EROI_{st}$	Standard EROI
$EROI_{pou}$	EROI at the “point of use”
$EROI_{ext}$	Extended EROI
EROC	Energy Returned On Carbon
FAHP	Fuzzy Analytic Hierarchy Process
GHG	Green House Gas
GPER	Gross Primary Energy Requirement
GWP	Global Warming Potential
IRR	Internal Rate of Return
KPI	Key Performance Indicator
LACE	Levelised Avoided Cost of Electricity
LCA	Life Cycle Analysis
LCOE	Levelised Cost of Electricity
LCOH	Levelised Cost of Heat
LCOS	Levelised Cost Of Storage
MCDA	Multi Criteria Decision Analysis
NEP	Net Energy Percentage
NER	Net Energy Ratio
NEY	Net Energy Yield
NPV	Net Present Value
O&M	Operation and Maintenance
OPEX	Operational Expenditure
PCA	Principal Component Analysis
R&D	Research and Development
RECAI	Renewable Energy Country Attractiveness Index
RES	Renewable Energy Sources
RET	Renewable Energy Technology
SDG	Sustainable Development Goal
SEE	System Energy Efficiency
SER	System Energy Returned
SPB	Simple Payback
TLCC	Total lifecycle Cost
TRL	Technology Readiness Level
WACC	Weighted Average Cost of Capital

1. Introduction

According to the 7th Sustainable Development Goal (SDG) of the 2030 Agenda for Sustainable Development [1], transition to sustainable energy systems requires a shift to affordable, reliable, sustainable and modern energy. The energy sector is currently undergoing a transition as a result of digitalisation, decarbonisation and decentralisation [2]. Global climate change policy, from the Kyoto protocol to the Paris Agreement (COP21), plays a pivotal role in this transition, pushing many countries to take actions to reduce the greenhouse gas (GHG) emissions [3,4]. In Europe, 27% of final energy consumed should originate from Renewable Energy Sources (RES) by 2030 [5] (in relation to 1990 levels), while the European Parliament has recently agreed to increase RES contribution to 32% [6].

The energy sector (including energy production, energy use by the industry, services and households, and transportation) accounts for more than 80% of total greenhouse gas emissions. The share of the electricity sector is approximately 38% of the total primary energy [7] and around 40% of the energy-related CO_2 emissions (equivalent to more than a quarter of global greenhouse gas emissions). Globally, more than 60% of electricity comes from fossil fuels, mainly coal and gas, so the decarbonisation of this sector can be a key contributor to reach a low carbon future [8]. To this end, increasing capacities of renewables and low carbon power generation plants are gradually added to the mix. These technologies are diverse in terms of their characteristics (efficiency, capacity factor, life time, flexibility, reliability [9] and level of maturity). Apart from the technology-specific characteristics, the deployment of a power generation plant also depends on other factors, e.g. the availability of resources of the country/installation site, socio-economic implications, environmental impact and the integration with the existing power grid. Decision makers should take all these parameters into consideration when determining which project is more likely to move forward.

For example, the integration of decentralised (and potentially intermittent) power plants requires the grid to be managed to ensure it has sufficient capacity and deliverability to satisfy the balance between electricity consumption and generation [2].

Considering the growing energy demand and the essential cuts in GHG emissions, the transition will necessitate significant investment. It is estimated that some US$48 trillion will be needed to cover the worldwide energy demand in 2035 [10], which could rise up to US$53 trillion to meet the environmental target of limiting global warming to 2°C [11]. Hence, investment decisions need to be well-informed to lead to a sustainable, reliable and cost-effective energy future.

Focusing on power generation projects, there is need for a set of indicators that can measure their holistic competitiveness performance and compare projects in a fair and transparent way to support investment decisions.

Although numerous studies use KPIs to assess power generation technologies, there are far fewer publications which focus on their critical review, specifying their scope, formulation, limitations and interconnections. A recent study [12] reviewed key environmental and energy performance indicators and categorised them in a life cycle style, covering: a) the manufacturing phase (e.g. Embodied energy for infrastructure of materials and for the building system and Net Energy Ratio), b) the operational phase (e.g. Life Cycle CO_2 Emissions and Electricity used from On-Site Generation) and c) the end-of-life phase (e.g. Energy Returned on Energy Invested and Battery Calendar Life). However, the focus of the study was on renewable energy systems integrated with storage solutions and did not account for economic and social factors.

To organise the plethora of KPIs (or the so called competitiveness indicators in the context of this paper) found in the literature for the evaluation and comparison of energy projects, this paper presents a structured overview of those currently in use, while also distinguishing which indicators are more appropriate/relevant for specific types of energy projects, e.g. whether some indicators are more relevant to power production projects or can be applied across all energy production projects. To this end, the scope, formulation, inputs and outputs of each indicator are examined in a transparent and critical manner. Their interconnections and limitations are further discussed, along with some focal points for future research. The set of Key Performance Indicators (KPIs) presented in this paper is not meant to be a prescribed or exhaustive list of indicators. The aim of this paper is to review and critically analyse a set of widely used, multi-disciplinary KPIs, as identified by a thorough literature review that could be considered when assessing an energy project. Not all indicators included in this review may be relevant to all energy projects, as different projects have different priorities; however, this list can be used as guidance on the various indicators covering the physical, economic, environmental and social aspects of energy projects.

The final competitiveness of power generation technologies will depend both on the characteristics of the technology at power plant level and the electricity local needs at grid scale level. To this end, this paper also presents key indicators concerning the electricity mix in terms of its resilience and environmental performance, among others.

The rest of the paper is set out as follows: Section 2 reviews indicators and decision support methods employed for the selection of energy production technologies from the literature. Section 3 classifies the competitiveness KPIs for the energy projects analysed in this paper. Section 4 proceeds with the analysis and comparison of competitiveness KPIs, outlining their mathematical expressions, inputs, outputs, interconnections and limitations; Section 5 discusses the specified indicators. Finally, the conclusions of this paper are summarised in Section 6.

2. Sustainability indicators and decision support methods for the selection of energy sources

Numerous studies have proposed sets of indicators for the assessment and comparison of power generation projects. However, indicators need to be carefully applied across different technologies, as their relevance depends on the specific characteristics of each technology. The Levelised Cost of Electricity (LCOE), for example, does not account for the possibility of co-generation of heat and power (e.g. from a geothermal power plant) and neither does it capture the utilisation rate of the project, which depends on the existing power generation mix and the load shape of the region [13]. The former case leads to the underestimation of the total energy produced by the technology (consequently to a higher LCOE), while the non-consideration of the utilisation rate overlooks the flexibility of the project to follow demand (dispatchable units); hence, LCOE may be misleading when comparing competing projects. In such cases, additional indicators, such as the Levelised Cost of Heat (LCOH) and Levelised Avoided Cost of Electricity (LACE) should be included in the analysis to account for the missing parameters, namely the amount of the heat produced and the ability to dispatch on-demand power, respectively. Furthermore, interconnections between indicators can cause difficulties; the Energy Payback Time (EPBT), for example, may be seen as a counterpart of the Simple Payback period (SPB), as they both express the amount of time that a project needs to operate to produce the equivalent amount of energy and the financial return that was required to develop it, respectively.

According to [14], prior to the implementation of a power generation project, the aspects that need to be investigated include: available resources, techno-economic factors and market potential. However, additional parameters such as environmental impact, technology-specific risks and social acceptance play a significant role in the implementation of a project.

Several studies have presented critical parameters to be considered towards a sustainable choice of energy projects [15–18]. Authors in [15] introduced a method for evaluating the sustainability performance of energy technologies, using Principal Component Analysis (PCA). Various energy technology systems were subsequently evaluated based on the composite sustainability index built on a number of technical, economic, environmental, social and institutional indicators. A review of decision support methods applied in renewable energy investments was presented in [16], distinguishing lifecycle analysis, cost-benefit analysis and multicriteria decision aid methods and collecting potential evaluation criteria. Focusing on MCDM techniques, authors in [17] reviewed various MCDA techniques and outlined various performance indicators that can be used to achieve sustainability goals in developing nations, particularly in rural locations. In [18], environmental, economic and social aspects of shale gas are integrated to evaluate its overall sustainability and compared it to other electricity options for present and future scenarios, up to 2030. To this end, sixteen indicators were considered, including abiotic depletion of elements, abiotic depletion of fossil fuels, acidification potential, eutrophication potential, global warming potential, ozone depletion potential, levelised costs of electricity, direct employment, worker injuries and public support index. Outcomes of the NEEDS project [19] categorised the sustainability indicators as environmental, economic and social for the assessment of electricity supply options; each category was divided into sub-categories and into measurable indicators, ending up with 40 indicators in total.

The above-cited papers use several multi-disciplinary KPIs in the context of developing sustainability assessment methodologies. However, to the authors' knowledge, there have been no studies focusing on the collection of multi-disciplinary sustainability indicators for energy production projects, critically analysing their similarities, differences, limitations and technologies they may apply to.

Table 1 summarises recent studies assessing the sustainability of selected power and heat production technologies, along with their scope, indicators, methods and key outputs. Different indicators have been used across these studies, with the majority originating from the economic, social and environmental pillars of sustainable development, while fewer investigated more novel concepts, such as the exergetic sustainability [20] and resilience of energy sources [21].

The high-level sustainability assessment of selected power generation technologies on the basis of key indicators (including economic, environmental, social and technological aspects) is one of the methods commonly used in the literature [21–26]. In [16], the authors performed a review of the decision support methods that have received the greatest attention in the assessment of sustainable energy projects, with the top three being: Life Cycle Analysis (LCA), Cost Benefit Analysis (CBA) and Multi Criteria Decision Analysis (MCDA).

Indeed, numerous authors have rated alternative energy technology options against a set of sustainability criteria by employing MCDA [27–30], CBA [31], scenario analysis [22,32] and LCA [33,34] of energy technologies and energy systems. Main outcomes of the above works include the scoring and ranking of different technologies in terms of their sustainability KPIs, the sensitivity of the results to changing the weights of KPIs at technology level, as well as the ranking of scenarios (considering different electricity mixes and policy targets) at energy system level.

Table 1 Review of relevant studies on sustainability indicators and decision support methods for the assessment of energy production technologies

Ref.	Scope	Indicators	Selected technologies	Method(s)	Main outputs
[12]	To review a set of KPIs for renewable energy systems coupled with battery solutions.	Energy performance: Embodied energy, gross primary energy requirement, Net Energy Ratio, Cumulative Energy Demand, energy payback time, Energy storage potential, Energy stored on invested, Share of RES, Electricity used from On-site Generation, Specific Energy Density, Net delivered electricity, Battery cycle life Environmental: Life-cycle CO2 emissions, Global warming potential, reduction of the direct CO2 emissions, avoided CO2 emissions, CO2 equivalent payback time.	Renewable energy technologies integrated with storage solutions.	Literature review	Listing of environmental and energy performance indicators.
[35]	To review indicators to compare electricity production technologies	Energy Payback Ratio (EPR), Net Energy Ratio (NER), Cumulative Energy Demand (CED).	Hydropower, wind, biomass, fossil fuels	Sustainability assessment	Comparison of indicators and technologies
[36]	To assess the sustainability of selected technologies.	Unit energy cost, carbon dioxide emissions, availability, efficiency, fresh water consumption, land use and social affects.	Hydrogen fuel cells, hydro, wind, solar, geothermal, coal, natural gas and nuclear power plant.	MCDA	Ranking of selected energy technologies.
[20]	To assess sustainability of selected fossil and renewable energy sources in aspects of economic, environmental and exergetic sustainability.	Economic: present worth ratio and Net Present Value (NPV); Environmental: human health, ecosystems and resources; Exergetic: Total Cumulative Exergy Loss, exergy of product, exergy of emissions, internal exergy loss, abatement exergy loss and exergy loss land use.	Coal-fired power plant, coal-fired power plant including carbon capture and storage, biomass-fired power plant, offshore wind farm and photovoltaic park.	Sustainability assessment	Scoring of technologies in terms of economic, environmental and exergetic sustainability with and without subsidies.
[32]	To assess the sustainability of the selected technologies under six different scenarios.	Technical: energy generation efficiency, energy supply reliability, resource potential, water consumption; Economic: investment cost, job creation, cost of electricity, O&M cost; Environmental: CO_2 emissions, NO_x emissions, SO_2 emissions; Social: safety risks, social acceptability.	Coal, natural gas, wind, concentrated solar power, photovoltaics, biomass and nuclear.	MCDA: Analytical Hierarchy Process (AHP), weighted sum method, scenario analysis	Ranking of the selected technologies under six different scenarios.
[22]	To assess/identify the most sustainable energy options at both a technology and systems level.	Environmental: global warming, resource depletion, acidification, eutrophication, freshwater toxicity, human toxicity, marine toxicity, ozone depletion, summer smog and terrestrial toxicity; Economic: capital costs, annualised costs, levelised costs; Social: security and diversity of supply, public acceptability, health and safety and intergenerational issues.	Biomass, coal, coal Carbon Capture and Storage (CCS), gas, gas CCS, geothermal, heavy fuel oil, hydro, nuclear, ocean, solar thermal, solar PV and wind	Scenario analysis, LCA, life cycle costing, and social sustainability assessment	Ranking of the scenarios obtained using different preferences for the sustainability criteria.
[37]	To evaluate renewable energy resources in terms of sustainability criteria.	Economic: incentives and subventions, generation costs per unit, investment costs, economic potential; Technological: primary energy saving, technological maturity, sustainability and predictability of sources; Environmental: carbon dioxide emission, other emissions, other environmental impacts; Social: employment generation, reaction of local, nongovernmental organizations.	Biomass, geothermal, hydropower, solar, wind.	MCDA	Ranking of technologies in terms of sustainability performance and sensitivity analysis of criteria weights.
[27]	To assess the extent selected energy technologies contribute to social welfare and sustainable development.	Economic: GDP, trade balance, competitiveness and innovativeness of economy, unemployment rate, energy security of enterprise and public sector, balanced development of regions, land requirement; Social: eliminating social inequality, shaping new energy culture, energy security of households; Environmental: carbon emissions, amount of waste generation, resource efficiency of the economy, interference in the landscape, risk of failure/accident.	Wind on-shore/off-shore, solar, biomass and biogas, nuclear.	MCDA (Fuzzy Analytic Hierarchy Process (FAHP))	Ranking of technologies in the context of their impact on social well-being.
[30]	To evaluate different renewable energy options based on sustainability criteria.	Technical: capacity, technological maturity, reliability, safety; Economic: investment cost, O&M cost, service life, payback period; Environmental: impact on ecosystem, CO_2 emissions Social: social benefits, social acceptability, political acceptance.	Solar, wind, hydropower, geothermal, biomass.	MCDA: AHP	Scoring of criteria and ranking of technologies.
[38]	To assess electricity generation technologies based on sustainability criteria.	Institutional-political: compliance with international obligations, legal regulation of activities, technology's autonomy, government support, political organizations, influence on sustainable development of energy Economic: economic efficiency, competitiveness, production cost, value of technological complex Social: Influence on social welfare, Influence on sustainable development of society, public accept./opinion Technological: technology's rated capacity, reliability, innovativeness, durability Environmental: Contribution of renewable energy resources, effect on climate change and pollution cuts, treatment of waste, compliance with local natural conditions.	Nuclear, gas, biomass, geothermal, hydropower and wind.	MCDA: AHP and ARAS	Ranking of technologies and sensitivity analysis of the criteria weights.
[33]	To evaluate the current electricity production options.	Environmental: resource depletion, climate change emissions, water and soil; Economic: lifecycle costs Social: provision of employment, worker safety and energy security.	Lignite, hard coal, gas, large reservoir, small reservoir, run-of-river, wind and geothermal.	LCA and MCDA	Ranking of technologies and sensitivity analysis of the criteria weights.
[39]	To evaluate electricity production options.	Technical: technology maturity, efficiency, reliability, deployment time, expert human resource, resource reserves, safety of energy system, electricity supply availability, ease of decentralization, safety in covering peak demand and network stability; Economic: R&D cost, capital cost, O&M cost, energy cost, operational life, cost of grid connection, fuel cost, market maturity, site advantage, availability of funds, national economic development; Environmental: land requirement, emission reduction, impact on environment, need for waste disposal, disturbance of ecological balance; Socio-political: employment, social/political acceptance, human health impact, feasibility, compatibility with the national energy policy, national energy security/ independency, leading position as energy supplier.	Solar photovoltaic, concentrated solar power, wind, biomass, and geothermal.	MCDA: AHP	Ranking of renewable energy technologies under sustainability criteria.
[40]	To assess the sustainability of selected electricity and heat generation technologies.	GHG emissions, land demand, energy efficiency, other harmful ecological impacts, increase in costs, new jobs, local income.	CSP-tower, CSP-parabolic trough, small/large scale hydro, geothermal power plant, wind power plant, agricultural biogas, solar PV, biomass, gasifier, geothermal district heat-large/small, biomass non-grid heat-pellet/chips, solar thermal heating & HWS, biomass district heat-small/large.	Sustainability assessment	Ranking of power and heat production technologies in terms of sustainability criteria.
[21]	To assess low-carbon energy technologies in Europe against a set of sustainability and resilience criteria.	Sustainability: levelised costs, employment, noise pollution, waste, damage to ecosystems, land use requirement, fuel use, GHG emissions, aesthetic impact, mortality and morbidity, accident fatalities, level of public resistance/opposition, market size (domestic and potential exports); Resilience: Energy cost stability/sensitivity to fuel price fluctuation, climate resilience, stability of energy generation, peak load response, technological maturity, innovative ability.	IGCC coal, IGCC w/CCS, GTCC gas, GTCC w/CCS, nuclear, hydro, wind on/offshore, PV, biogas CHP.	Sustainability assessment	Scoring of technologies in terms of sustainability and resilience criteria.

3. Classification of KPIs to assess competitiveness of power generation projects

KPIs measure, assess and quantify the performance of a project in terms of the scope, targets and objectives it was employed to satisfy [41]. Hence, they further assist in setting measurable objectives, monitor (lack of) progress and developments and indicate improvements, supporting the decision-making process. Typically, indicators are not just statistical data or metrics; instead, they are based on elaborated data with the aim to convey messages regarding the performance of the project and highlight important relationships that are not evident through basic statistics and can assist a fair comparison between technologies [19]. Each indicator comes with a number of assumptions and limitations.

In this work, KPIs assisting the comparison among competitive power generation projects are classified into four main categories: physical, environmental, economic, social and power generation mix. Although the focus of this paper lies on power generation projects, indicators are presented in their general form, potentially involving parameters relevant to all energy uses and specific reference is made on how these parameters would differ for power production projects (where appropriate).

- *Physical indicators* inform about the net energy yield of a project. They can express absolute values (such as the total energy produced by the project), relative values (e.g. the ratio of energy produced to energy consumed), or time-related values (e.g. the energy payback time). If the total energy required to extract, deliver and consume the raw source is higher than the actual usable energy produced via the project, then the project is likely to yield negative cash flows. Nevertheless, in some cases, projects can run at a loss (negative Net Present Value), but get support by the government to continue operation to ensure provision of electricity to the public as a basic commodity.
- *Environmental indicators* give information on the impact of a project on the environment (soil, water, atmosphere, climate, natural resources). They seek to quantify how the implementation of a project can affect the ecosystems, by specifying the amount of GHG emissions, along with the requirement of resources and of land use.
- *Economic indicators* follow an approach similar to that of physical indicators, adding to the energy-related quantities, the amount of resources, workforce and financial aspects associated with a given project. The economic attractiveness of an energy project is key to investors.

- *Social indicators* consist of parameters that capture the impact of the project on human activities. Social sustainability is one of the three pillars for sustainable development. A project is unlikely to proceed unless it satisfies social criteria, such as economic self-sufficiency, equity, health and social cohesion [42].

4. Analysis of competitiveness KPIs

4.1 Physical indicators

4.1.1 Overview of physical indicators

Physical indicators assess the amount of energy required throughout the whole life of a project (i.e. the manufacturing, operation and decommission phases) in relation to the usable energy produced by the project. The following physical indicators have been identified in the literature:

- Gross Primary Energy Requirement (GPER). The total amount of energy required for the production, transportation, operation and decommission of a project [12]. It is useful to analyse it alongside the total amount of energy produced and delivered by the project.
- Energy Payback Time period (EPBT). The time period after which the project will have produced the same amount of energy required to implement, run and decommission it.
- Net Energy Yield (NEY). The gross energy produced by the project minus the energy required to harvest the energy source, or else the net total amount of usable energy produced by a project.
- Energy Returned On (Energy) Invested (ERO(E)I). The ratio that presents the relative performance of a project to produce usable energy (energy produced compared with the energy required).
- System Energy Efficiency (SEE) and System Energy Returned (SER). Both indicators quantify the resource exploitation efficiency of the project. SER calculates the energy yield resulting from the energy investment in non-renewable resources and SEE the overall amount of primary energy required by a system.

4.1.2 Formulation of physical indicators

4.1.2.1 Gross Primary Energy Requirement (GPER)

The GPER expresses the requirement in primary energy over the life span (manufacturing, assembly, operation and decommissioning) of the project to provide a product/technology/service to the point of interest. This also includes the range of natural resources (e.g. fossil fuels) that has not been undertaken any anthropogenic conversion. GPER can be expressed by the following equation [12]:

$$\mathrm{GPER} = PE_{assemply} + PE_{operation} + PE_{decommissioning} \tag{1}$$

where, the GPER (J) of a product/technology/service delivered is the sum of the Primary Energy required to assembly the different components towards producing a single project/technology/service ($PE_{assemply}$), the Primary Operation Energy from direct (mainly from fuels) and indirect energy inputs (embodied energy) (J) during the operation of the system ($PE_{operation}$) and the Primary Decommissioning Energy ($PE_{decommissioning}$).

4.1.2.2 Energy Payback Time (EPBT)

This indicator expresses the time that a project needs to operate to produce the equivalent amount of energy that was required to implement it (manufacturing, construction, decommissioning, Operation and Maintenance (O&M) [43].

$$\mathrm{EPBT\ (y)} = \frac{\mathrm{E_r}}{\mathrm{ANEP}} \tag{2}$$

where, E_r (J or Watt hour (Wh)) is the direct and indirect energy required for the project and ANEP ((J or Wh)/y) is the Annual Net Energy Production.

This result should be interpreted together with the total life-time duration of the project to illustrate how many years the project is supposed to provide “free” energy, excluding the O&M energy cost [44]. It is one of the main indicators of energy performance, along with the Energy Returned On (energy) Invested (EROI) [43].

4.1.2.3 Net Energy Yield (NEY) and Energy Returned On (energy) Invested (ERO(E)I)

The Net Energy Yield (NEY) represents the difference between the energy resource harvested and usable for society (over its life-time) and the energy required to extract and provide this energy [45]. Similarly, the EROI is the ratio of the amount of energy harvested to the total amount of energy required to provide it [46]. Both use the life cycle analysis to define their equations’ parameters [47]. Figure 1 illustrates the concept of these two indicators. The ratio between the final blue bar (representing the energy generation for consumer’s use) and the purple bar (the energy consumed for construction, operation and decommission of the project) represents the EROI, while the difference between them gives the green bar (reflecting the net energy yield), which represents the NEY.

$$\mathrm{EROI} = \frac{\mathrm{E_d}}{\mathrm{E_r}} \tag{3}$$

$$\mathrm{NEY} = \mathrm{E_d} - \mathrm{E_r} \tag{4}$$

where, E_d (Wh or J) represents the energy returned to society, E_r (Wh or J) is the direct and indirect energy required to provide E_d (extract, deliver and transform and use depending on the limits of the study).

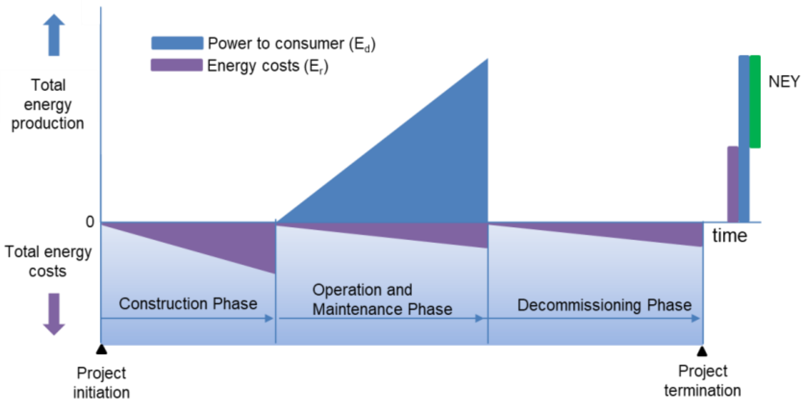

Figure 1 Energy production and costs over the energy project life-time (Source: based on [48])

There are several definitions of the EROI depending on the set boundaries of the system [45,46,49]:

- Standard EROI ($EROI_{st}$) considers $\mathrm{E_r}$ equal to the energy directly used to extract the fuel plus the indirect energy used for the gear manufacturing, needed for the extraction.
- EROI at the "point of use" ($EROI_{pou}$) adds to the denominator the energy required to transform, refine, enhance and transport the energy/fuel extracted.
- Extended EROI ($EROI_{ext}$) considers, additionally, in the denominator, the energy necessary to use the energy delivered (i.e. the infrastructure needed to provide the intended energy service).

The boundary limitation of the EROI for electricity generation projects needs to be adapted, accordingly. The authors in [50] proposed a methodology to ensure a fair EROI comparison for electricity projects. The energy returned to society is the final electricity provided to consumers. The energy required is the sum of the energy (direct and indirect) used for the power plant construction, O&M and end-of-life, and the energy (direct and indirect) used to extract, refine and deliver the fuel. Similar to the $EROI_{ext}$, the energy required for grid connection could also be added to the denominator. Additionally, the EROI of individual technologies could be multiplied by the overall electricity grid efficiency to be representative of the final electricity delivered [51].

This indicator analysis is useful because it expresses the physics beyond the project and provides a view of the project that markets struggle to draw [49]. Basically, if the EROI is higher than 1:1 it means that more energy would be usable than required. The NEY is linked with the EROI as illustrated in Equation 4 [52].

$$\mathrm{NEY} = \mathrm{E_d} * \left(1 - \frac{1}{\mathrm{EROI}}\right) \tag{5}$$

where, the terms in the brackets could be re-arranged as $\frac{E_d - \mathrm{E_r}}{E_d}$, showing the Net Energy Percentage (NEP), i.e. the efficiency of the project to produce net energy. Figure 2 illustrates graphically the relationship between NEP and EROI.

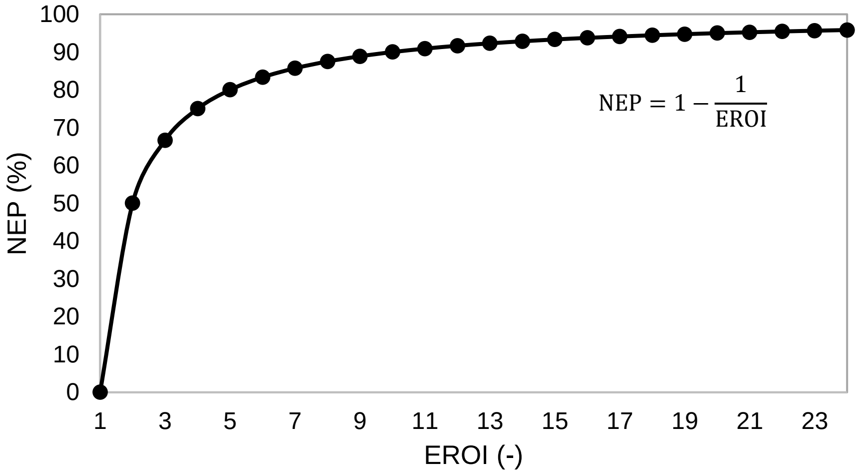

Figure 2 NEP and EROI's mathematical relationship

A modern society with an EROI slightly higher than 1:1 is one that cannot support the current life style of developed countries. A positive correlation between the EROI and living standards or the development of social welfare was found in [53], while the importance of the EROI to shape a country's future economy and quality of life was also highlighted by [49]. Moreover, a ceiling value of EROI (20:1) was observed, above which the improvement provided to the society is not increased. In [54], the authors estimated that the USA needs, on average, a minimum EROI of 11:1 to ensure the country's growth. Similarly, having an EROI below 5 is not recommended from a physical point of view, as the NEP is significantly decreased below this point (as shown in Figure 2), the so-called the "energy cliff" [52].

4.1.2.4 System Energy Efficiency (SEE) and System Energy Returned (SER)

The SER differentiates renewable from non-renewable sources and it assesses the efficiency of the technologies to use the inherent energy of the non-renewable feedstock. However, the comparison also mixes two different aspects: energy returned and sustainability. Indicative values of SER for coal power plants are between 0.1 and 0.4 and for hydroelectric power plants between 63.2 and 83.3 [55]. Evaluating the use-efficiency of a renewable resource (with SEE) is a less critical point, but it can be useful depending on the abundance and the availability flow rate of this energy source. The relationships of SEE and SER are summarised as follows:

$$\mathrm{SEE} = \frac{\mathrm{E_d}}{(\mathrm{E_r} + \mathrm{E_f})_{\mathrm{tot}}} \tag{6}$$

$$\mathrm{SER} = \frac{\mathrm{E_d}}{(\mathrm{E_r} + \mathrm{E_f})_{\mathrm{NR}}} \tag{7}$$

where, E_f (J) is the energy content of the feedstock, and the suffices “NR” and “tot” stands for “non-renewable” and “total”, respectively. The inverse of SER represents the intensity of depletion of the stock of non-renewable resources, while that of SEE is the overall energy resources stock per energy unit returned to society.

4.1.3 Limitations

The EPBT analysis assumes that the annual energy production is constant throughout the life-time period of the power plant. This assumption could lead to over-estimating the energy produced by a particular project considering the performance degradation of technologies through their life-time [56]. The EROI evaluates the quality of the source of energy by calculating the ratio of energy returned to energy invested in that source, along its life-cycle [50]. The ratio does not consider the inherent energy of the feedstock, so it does not evaluate the efficiency of the resources exploitation. However, it could be relevant to do so, at least for the non-renewable energy sources. Additionally, the EROI does not distinguish among renewable and non-renewable energy projects, as opposed to SEE and SER which can fill this gap. However, the comparison is more complicated because it mixes two different aspects (energy returned and sustainability), and thus the final results cannot be directly comparable. The advantage of the EROI lies in its straightforward interpretation: if it is higher than 1:1, more energy will be returned to society than invested. Hence, to clearly present these two different, but substantial aspects, it might be more suitable to use the extended version of EROI, in conjunction with the proportion of non-renewable energy used and its efficiency.

The authors in [52] proposed a modified version of EROI, namely the Energy Returned On Carbon (EROC), to incorporate the environmental performance of the project. EROC is defined as the ratio between the net energy percentage and the carbon emission factor and it shows the net energy produced per unit of gCO_2 equivalent ($gCO_{2\text{-eq}}$) emitted. The EROC is an interesting concept, but it is more relevant to consider it as an improvement of the GHG emission factor. The indicator points out a pertinent idea: highlighting the total $gCO_{2\text{-eq}}$ emitted for the actual net energy produced (through including the NEP) and not the gross energy.

As far as power generation projects are concerned, attention should be paid to the assumptions used for each indicator's calculation and the limits of the study considered. Above studied physical indicators do not capture the flexibility of the power plant to address changes in the peak demand and network congestion (e.g. typical flexibility indicators of energy technologies are the ramping rate and the start-up time [57]). EROI allows the comparison across projects providing the same service, which is a dispatchable unit. The technologies that generate electricity that is not directly usable by the grid, could be coupled with storage technologies, and the pairing could be characterised with a new EROI [58]. Another relevant option is to compare the performance of technologies at a larger scale to evaluate the global service given by the grid (EROI of the total electricity system) and to analyse the contribution of the project considered to the global service quality. Despite their advantages and utility, none of the physical indicators are sufficient on their own to determine the overall competitiveness of a power generation project [49]. Additional aspects (e.g. environmental and economic) must be considered to ensure a holistic assessment.

4.2 Environmental indicators

4.2.1 Overview of environmental indicators

Environmental indicators utilise parameters characterising the impact of an energy project on the land, the atmosphere, the resources availability, the humans and the ecosystem. They are necessary but not sufficient criteria for the implementation of a project. In this work, the following key environmental indicators are investigated:

- Greenhouse gas emissions and fine particles. The emissions of GHGs in $gCO_{2\text{-eq}}$/(Wh or J) and fine particles in g/(Wh or J) that impact the climate and/or the health in a direct or indirect way.

- Land-use requirement and change. The land-use intensity is measured by the amount of land needed per amount of energy produced [59]. With the current growing population and economic development, land management is a critical aspect (e.g. for food, accommodation, industries, services and energy) [60]. In addition to the amount of land required, the land-use change, the degradation and the nature of the land should be considered. The ecosystem services that the land provides and the impacts from the implementation of the project, are all important parameters to take into account to ensure a complete and sustainable analysis of an energy project [61].

- Resources sustainability. This parameter is important in raising awareness of the resource depletion, waste production and recyclability. It is important to assess whether the implementation of the project at a large scale is possible or if it will create resource supply issues that might induce a decrease in the general performance of a technology, for example, due to lower physical and economic performance.

4.2.2 Formulation of environmental indicators

4.2.2.1 Greenhouse gas emissions and fine particles

The emission analysis should be global and consider the whole life-cycle to be relevant and complete: from the manufacturing to the decommissioning. Additionally, similarly to the physical indicators, the emissions can be reported for the net energy. For example, as mentioned above, the EROC represents the amount of GHGs and fine particles emitted through the production of one net Wh. For the GHGs, the emissions per Wh or J produced are calculated in $gCO_{2\text{-eq}}$ by considering the Global Warming Potential (GWP) of the different greenhouse gases emitted (CO_2, CH_4 and N_2O mainly) [12]. Global warming potential (GWP) represents the effect of different GHGs to climate change, taking as reference the GWP of CO_2. The general relationship for calculating the GWP (expressed in $\frac{\mathrm{gCO_{2-eq}}}{(\mathrm{J\ or\ Wh})}$) of an energy project is the following:

$$GWP = \sum_{k}^{K} GWP_k \cdot B_k \tag{8}$$

where, K is the total number of GHGs emitted from the project, $\mathrm{GWP_k}$ is the global warming potential of GHG, k and $\mathrm{B_k}$ represents the emissions of the GHG, k, per unit of energy produced (expressed in $\frac{\mathrm{g}}{(\mathrm{J\ or\ Wh})}$).

4.2.2.2 Land-use changes and requirement

The amount of land required per unit of energy produced (net energy) in m^2/(Wh or J) can be quantified. The analysis can consider the land used for the energy production plant, but also for the fuel extraction when appropriate. Fritsche et al. proposed an interesting comparative approach for determining the “land footprint” of different energy sources considering direct and indirect impacts [59]. Results of this analysis classified biomass, solar, hydropower and coal as the most land intensive electricity sources (in descending order).

The impact of land use (ILU expressed in $\frac{m^2 \cdot y}{(J\ or\ Wh)}$) of a plant is calculated as follows:

$$ILU = LA \cdot t_{LA} \tag{9}$$

where, LA ($\frac{m^2}{(J\ or\ Wh)}$) is the total land area required for the construction and operation of the project per unit of energy produced and t_{LA} is the amount of time that the land area is occupied by the project (y).

In addition to the amount of land required, the degradation and the nature of the land should also be considered. The ecosystem services that the land gives and the impacts from implementing the project are important parameters to take into account in order to ensure a complete and sustainable analysis [61].

4.2.2.3 Resources sustainability

Poliakoff and Tang [62] and Poliakoff et al. [63] focused on the depletion of elements resulting from the supply of energy generation technologies. Fossil fuel plants use non-renewable feedstocks to produce energy and, consequently, are resource-intensive energy technologies. Similarly to the SER indicators, the part of non-renewable energy indirectly required (for manufacturing, installation, maintenance etc.) should also be taken into consideration.

Certain renewable energy technologies, such as wind turbines and solar PV panels, may require rare earth metals and critical resources (such as neodymium, tellurium and ruthenium) in large quantities [64,65]. Graedel et al. developed a methodology to evaluate the criticality of the metals needed around three main aspects: “environmental implications, supply risk, and vulnerability to supply restriction” [66]. It is important to assess if the implementation of the project at a large scale is possible or will create a resource supply issue. Several studies have been conducted to assess the elements’ availability and the exploitable reserve according to their use [67]. With the depletion of critical elements (as a result of their large exploitation), more energy will be required for their extraction, decreasing the overall EROI of the project [64].

The recyclability of the project is also important for the assessment of its value at the end of its life and the capacity of recovering its materials. Currently, recycling the materials of energy technologies remains a challenge due to the multi-element composition, together with the complexity of the recycling process in terms of energy intensity and cost. Nevertheless, recycling is recognised as a key driver to ensure the sustainable development of energy production projects and more specifically for power generation plants [68].

Further parameters to be considered for the competitiveness analysis of energy projects include waste production during the decommissioning of the project. Brown et al. proposed an approach for estimating the waste production during operation and decommission for key electricity technologies [69]. They concluded that the waste resulting from coal and nuclear power plants is the largest and most toxic, requiring appropriate measures. This impacts on the overall cost (potentially included in the LCOE) and environmental performance of these technologies [70].

4.2.3 Limitations

Environmental indicators give substantial data about energy projects and have a critical effect on their implementation. However, these indicators must be analysed at global scale, namely the whole electricity grid (e.g. national), and not just at the power plant’s borders. The GHG emission indicator, for example, should be used with caution. Some low-carbon technologies are non-dispatchable, inducing abrupt changes to the electricity production, and so dispatchable units must be installed to maintain the reliability of the grid. If these dispatchable units are gas or coal power plants (with higher GHG emissions per Wh), the overall effect of adding low-carbon technologies on the carbon footprint of the electricity mix needs to be investigated at the grid scale. Hence, the carbon footprint indicator has to be analysed together with the impact of the project on the reliability of the mix [71]. The land-use parameter will depend on the conditions and the quality of the land available/required, with the associated potential issues for land access.

The accurate estimation of the resources stock, utilisation and future prediction is an arduous task, because it depends on multiple parameters: political, technological, physical and social. The environmental considerations should not be limited to the parameters discussed above, as there are further technology and site dependent parameters, e.g. noise pollution induced by the project, which may be important to take into consideration. An Environmental Impact Assessment (EIA) is commonly required before the approval of a project’s implementation, to capture its potential critical environment impacts and mitigation methods [72].

Similarly to the other categories of KPIs, these indicators are necessary, but not sufficient to determine the global competitiveness of a project. The economic and social criteria also need to be satisfied for the project to move forward.

4.3 Social indicators

4.3.1 Overview of social indicators

Relevant social indicators for energy production technologies are: job creation (direct and indirect), human health impact, safety risks and social acceptability [19,73,74]. A short description of each indicator is provided below:

- Jobs creation (direct and indirect employment). This indicator demonstrates the potential for direct and indirect jobs to be created as a result of the energy project deployment, during the construction, Operation and Maintenance (O&M), and decommissioning.
- Human health impact. This indicator is related to the increased rate of sickness or morbidity due to normal operation of the electricity generation project and its associated supply chain.
- Safety risks. Hazards can be assessed in terms of accident fatalities per unit of energy produced in different fuel chains. They represents a vital issue to society, and people's life including safety measures for employees on site that must be guaranteed.
- Social acceptability. This indicator qualitatively points out the anticipated public opinion towards the implementation of the project. Lack of social acceptability is likely to impact the duration of commissioning a power plant project.

4.3.2 Formulation of social indicators

Social indicators are usually expressed through statistical data (e.g. number of jobs-years per GWh), expressions involving multiple parameters, or semi-quantitatively, by rating a specific project in terms of the social indicator on an ordinal scale.

4.3.2.1 Jobs creation (direct and indirect)

Jobs creation demonstrates the potential for creation of jobs associated with the project, from construction to decommissioning, including O&M. Direct employment refers to the jobs created directly by core activities of the power generation plant without accounting for the intermediate inputs (such as the supply of materials and financial services) necessary to manufacture the equipment, construct and operate the plant, which are covered by upstream industries supplying and supporting the core activities (indirect employment) [75]. The jobs creation indicator is measured in jobs-years per Wh or Joule [76], according to the following expression:

$$JC = \frac{\sum_{i=1}^{I}(JC_i \cdot t_i)}{P_{tot}} \tag{10}$$

where, JC represents the number of jobs created over the lifecycle of the project (jobs-y/Wh or jobs-y/J), JC_i is the number of jobs created during the life cycle stage i (years), t_i is the duration of employment in stage i (years), P_{tot} is the total energy generated over the asset life of the plant and I is the total number of lifecycle phases.

4.3.2.2 Human health impact

The impact of human health can be measured by the number of years of life affected by disabilities (Disability Affected Life Years, or DALY) combining mortality and morbidity into a single measure [77]. The calculation of DALY is based on the sum of Years of the Life Lost (YLL) to premature death of a population and the Years Lived with Disability (YLD):

$$DALY = YLL + YLD \tag{11}$$

$$YLL = N \cdot L \tag{12}$$

$$YLD = (I \cdot LD) \cdot W = P \cdot W \tag{13}$$

where, N is the number of deaths in the population and L is the population's average remaining life expectancy, in years, at the age of death, *I* is the number of incident cases of a particular condition in the population, *LD* is the average length (duration) of disability from a particular condition, *P* is the prevalence of the condition, and *W* is the disability weight associated with the condition.

4.3.2.3 Safety risks

Safety risks are usually measured in terms of fatalities resulting from accidents per unit of produced energy [22,39]; hence, this indicator is based on historical data. Accidents may occur during the construction, installation, O&M and decommissioning phase of the project. In some cases, they may have catastrophic consequences for the residents near the plant. Apparently, the safety risk of an energy production plant is an issue that significantly affects the plant’s social acceptability; hence preventive measures should be applied [32].

4.3.2.4 Social acceptability

Public acceptance is a substantial aspect to consider for an energy project because it directly influences its implementation [78]. This parameter can be qualitatively assessed with an ordinal scale, indicating the anticipated level of satisfaction of the public and their opinions toward each energy technology.

Within the UK, the low public acceptance for an energy project, leading to social controversy, is deemed as a major obstacle to achieve the GHG emissions reduction target [79]. The authors in [80] divided this concept into three acceptance categories (integrating all stakeholders): the market, the community and the socio-political acceptance. The author of [81] stated that the public acceptance for energy technology is influenced by three main factors’ classes: personal, psychological and contextual. Hence, the public acceptance varies for each specific project and area of implementation. A good public information campaign can help communities to understand correctly the different challenges of the project. Hence, it can improve public acceptance and remove this barrier to project implementation [81]. A typical example of projects characterised by low social acceptability constitutes the nuclear power production plants, due to the negative perception created by the Chernobyl accident.

4.4 Economic indicators

4.4.1 Overview of economic indicators

Economic indicators integrate parameters such as costs (C_o), revenues (C_i), power output and discount rate (r) of the featured project. The differences lay in the way the indicators are expressed, for example: a rate, a ratio, a number of years, a difference, etc. They indicate utility for developing the economic scenario and provide results in different angles. In this paper, the following economic indicators are further analysed:

- Weighted Average Cost of Capital (WACC) represents the cost that a company must pay to raise the capital required for the implementation of the project. Basically, this indicator gives a view on the financial aspect by giving the average rate of return that a company must generate to satisfy its investors (shareholders and debtholders). Hence, it is usually used as the corporate hurdle discount rate in the project cash flow calculations [82,83].
- Total Life-Cycle Cost (TLCC) represents the total expenditure over the whole project's life and discounts this amount to a present value [84]. It can include taxes if needed, and the equation must be adjusted according to the relevant tax system in operation.
- Net Present Value (NPV). Discounted Cash Flow (DCF) analysis is based on assessing the costs and revenues over the lifetime of the investment and discounting expected future cash flows to estimate the present value of the asset.
- Benefits to Costs Ratio (BCR) is an indicator composed of the ratio between the discounted benefits and costs over a period of time [85]. It could be said that BCR is the corresponding economic indicator of the EROI.
- Simple Payback (SPB) and Discounted Payback (DPB) periods, where SPB represents the time period (in number of years) required to break even from undertaking the initial expenditure without discounting, and the DPB reflects the time to breakeven by discounting future cash flows.

- Internal Rate of Return (IRR) is a common metric used in capital budgeting to evaluate the profitability of potential investments and it is defined as the discount rate that sets NPV of an investment equal to zero.
- Levelised Cost of Electricity (LCOE) is an indicator that is widely used to compare specifically electricity generation technologies in term of their cost competitiveness [86]. Basically, this indicator gives the minimum price for the electricity produced to achieve a zero economic yield (break-even price or NPV=0).
- Levelised Avoided Cost of Electricity (LACE) is focused on electricity production technologies and it represents the value of the plant to the grid, by accounting for the costs that would be incurred to provide the electricity displaced by a new generation project. Avoided cost provides an estimate of the potential revenues from sales of electricity generated by the candidate project.

4.4.2 Formulation of economic indicators

4.4.2.1 Weighted Average Cost of Capital (WACC)

WACC is determined by the source of capital as well as the estimation of the financial risks associated with the investment. Projects gather their capital by raising funds through debt and equity. These sources of financing demonstrate individual risk-return profiles; hence their costs also fluctuate. The cost of capital for a company will correspond to the weighted average of cost of the equity and debt in its corporate financial structure, with weights determined by the amount of each financing source. The WACC is calculated by the following expression [87,88]:

$$WACC = r_{eq} * \frac{E_c}{V} + r_d * \frac{D}{V} * (1 - T) \tag{14}$$

where, E_c is the market value of equity, D is the market value of debt, $V = E_c + D$, r_{eqc} denotes the return on equity, r_d the interest rate on debt and T is the corporate tax rate. The risk of the project significantly influences the amount of return on investment required by the investor. External capital is cheaper and, thus, it is often desirable to obtain the highest possible amount of debt; however, the cost of debt depends on the specific investment risk, so that the higher the investment risk, the lower the amount that risk-averse banks are usually willing to lend.

4.4.2.2 Total Life-Cycle Cost (TLCC)

The TLCC can be used to appraise the difference in costs over the asset's life span (from the predevelopment and consenting to the decommissioning phase) and the time these occur between alternative projects. The costs are discounted to a base year adopting the present value approach, as follows [89]:

$$\mathrm{TLCC} = \Sigma_{\mathrm{t=1}}^{\mathrm{LT}} \frac{\mathrm{C_{tot,t}}}{(1+\mathrm{r})^{\mathrm{t}}} \tag{15}$$

Costs must be discounted at the real discount rate. Real discount rate integrates the inflation adjustment according to Fisher Equation [90]:

$$r = \frac{1 + r_{nom}}{1 + R_{infl}} - 1 \approx r_{nom} - R_{infl} \tag{16}$$

where,r is the real discount rate, r_{nom} is the nominal discount rate and R_{infl} represents the inflation rate. The TLCC does not provide a sufficient indicator to assess the performance of an investment as it does not involve the revenues, but it does help to evaluate the size of the total investment required [89]. For projects with the same benefits, where the benefits are fixed, it can be used to highlight the most interesting solution [91].

4.4.2.3 Net Present Value (NPV)

The discounted cash flow (DCF) valuation approach provides a basis for assessing the cash flows of a project. The total lifetime cash flows are discounted to the present or to a defined base year [92]. The NPV analysis brings together the TLCC and the total life time revenues (both discounted to base year) [91]:

$$NPV\ (\$) = -CF_0 + \sum_{t=1}^{N} \frac{CF_t}{(1+r)^t} \tag{17}$$

where, N is the lifetime duration of the investment, CF_0 is the cash flow in year 0, CF_t are the free cash flows of period t, namely the difference between costs and revenues including taxes, depreciation, etc.

The NPV and the TLCC do not allow a fair comparison between projects with different features, such as different power output, capacity factor or lifespan duration. For projects with different lifetimes, it is possible to annualise these indicators to turn them into equivalent yearly cash flow series. For this purpose, the capital recovery factor (CRF) is used to multiply the NPV or the TLCC [89].

$$\mathrm{CRF} = \frac{\mathrm{r}}{(1 - (1+\mathrm{r})^{-\mathrm{t}})} \tag{18}$$

The NPV for an energy project is sensitive to the electricity price forecast, which influences the future cash inflow, and to the assumed discount rate, which is often taken to be the WACC of the investing company [92]. NPV can be used to compare different projects that are mutually exclusive, to choose the one with the highest NPV providing that the company is able to provide the investment required [89]. The NPV results must be accompanied with an accurate rate of return for investors and risk exposure management.

4.4.2.4 Benefits to Costs Ratio (BCR)

BCR examines whether the benefits of the project are higher than the costs. It tends to be used for projects associated with public interest and social benefits [89]. It is defined as the ratio of the total discounted benefits of the project over its life span to the total discounted costs.

$$\mathrm{BCR}\,(-) = \frac{\Sigma_{\mathrm{t=1}}^{\mathrm{LT}} \frac{\mathrm{B_{tot,t}}}{(1+\mathrm{r})^{\mathrm{t}}}}{\Sigma_{\mathrm{t=1}}^{\mathrm{LT}} \frac{\mathrm{C_{tot,t}}}{(1+\mathrm{r})^{\mathrm{t}}}} \qquad (19)$$

4.4.2.5 Simple Payback (SPB) and Discounted Payback (DPB) period

The simple and discounted payback period indicators specify the length of time required for the cumulative revenues to be equal to the cumulative costs, i.e. the required length time for an investment to reach its breakeven point [89,91]. The payback period can consider the Simple Payback time (SPB) or the discounted Payback time (DPB). For capital intensive projects (such as renewable energy technologies), the DPB is generally expected to be higher (longer payback period) than SPB as revenues are discounted from the future while the capital cost undergoes lower or no discounting [91].

SPB (years): $$\Sigma_{\mathrm{t=1}}^{\mathrm{SPB}} \mathrm{B_{tot,t}} = \Sigma_{\mathrm{t=1}}^{\mathrm{SPB}} \mathrm{C_{tot,t}} \qquad (20)$$

DPB (years): $$\Sigma_{\mathrm{t=1}}^{\mathrm{DPB}} \frac{\mathrm{B_{tot,t}}}{(1+\mathrm{r})^{\mathrm{t}}} = \Sigma_{\mathrm{t=1}}^{\mathrm{DPB}} \frac{\mathrm{C_{tot,t}}}{(1+\mathrm{r})^{\mathrm{t}}} \qquad (21)$$

These indicators inform the investor about the amount of time the investment is at risk. It is often used with the financial risk exposure. However, there is no consideration about the cash flow after the payback time, hence it is not a sufficient indicator to determine the overall profitability of the project [89].

4.4.2.6 Internal Rate of Return (IRR)

The internal rate of return (IRR) gives the maximum rate of return (%) economically viable for an assumed cashflow model, according to the following expression:

$$\mathrm{IRR}\,(\%) = \Sigma_{t=1}^{LT} \frac{\mathrm{B_{tot,t}} - \mathrm{C_{tot,t}}}{(1+\mathrm{IRR})^{\mathrm{t}}} = 0 \qquad (22)$$

This percentage should then be compared with the WACC or directly with the interest on bank loan and/or with the return on investment required by the shareholders. If the IRR is higher than the WACC of the key investor, the project is deemed profitable, and it will generate money for the project owner. If the IRR is lower than the WACC, it is unlikely to attract investors [89]. This indicator is not sufficient on its own to choose projects as it does not include absolute term about revenues and does not integrate the difference in project lifespans. Additionally, it assumes that the future revenues are re-invested at the same rate than IRR which is not likely to be representative of the reality [89]. More simply, the growth rate and the average annual growth rate could be used to assess how the initial investment has been valued through the life-time of the project [93].

4.4.2.7 Levelised Cost of Electricity (LCOE)

LCOE considers the TLCC divided by the total discounted electricity production during the whole life-time of the asset (discounted to the present value). The discounting of the physical electricity production is not intuitive, but it is the economic value of the production that is discounted. The LCOE assumes the discount rate and the electricity production as constant over the lifetime of the project [70,86].

$$\mathrm{LCOE}\ (\$/\mathrm{Wh}) = \frac{\sum_{t=1}^{LT} \frac{C_{tot,t}}{(1+r)^t}}{\sum_{t=1}^{LT} \frac{ANEP_t}{(1+r)^t}} \tag{23}$$

where, $C_{tot,t}$ is the total cost in the year t (\$), $ANEP_t$ is the net electricity production in the year t (Wh) and r is the is the real discount rate.

However, the LCOE method does not evaluate the revenues or the actual profitability of the project as it depends on the electricity price on the market and on the policy in place [94]. The tax and incentives can be included in the LCOE calculations. LCOE is largely used due to its “raw simplicity” [95] and because it allows an economic comparison of technologies with different power output, life-time, capacity factor [89].

4.4.2.8 Levelised Avoided Cost of Electricity (LACE)

The EIA has created the indicator known as the Levelised Avoided Cost of Electricity (LACE) in order to complete the LCOE results [96]. While the LCOE gives information on the “revenues requirements”, the LACE focuses on “the revenues available” for a given project or technology [96]. To calculate the LACE, numerous data are needed, which renders this indicator specific to the local conditions [97].

$$\mathrm{LACE}\left(\frac{\$}{\mathrm{Wh}}\right) = \frac{\Sigma_{y=1}^{Y}\left(\text{marginal generation price}_y * \text{dispatched hours}_y\right) + \text{cap payment} * \text{cap credit}}{\text{annual expected generation hours}} \quad (24)$$

The parameters used in above equation are summarised in the Nomenclature included in the Appendix.

This indicator assesses the actual value of the electricity produced in the current electricity mix in place. LACE is highly dependent on the region, the electricity mix in place, the fuel costs and the electricity demand [96]. For example, in regions with a power capacity mix using higher cost fuel and lower efficiency power plants (compared to the new power plant to be installed), LACE is expected to be higher, as the new project in the region would displace existing inefficient generation units [98]. As its name suggests, the LACE represents the costs avoided due to the technologies considered, i.e. the costs needed to meet the demand with the current grid without implementing the project. Hence, when the LACE is higher than the LCOE (potentially including support scheme), the estimated net value is positive and thus the project should be profitable according to this analysis.

4.4.3 Limitations

The numerous indicators reviewed are characterised by limitations that are presented in this section. Some are in common for all the economic indicators, while others are specific to individual indicators.

Firstly, the economic indicators present one single result, which is advantageous when one needs to compare projects, but this simplicity comes with a loss in accuracy. By mixing different information, economic indicators make the interpretation broader for the decision makers. For instance, the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) are not differentiable in the LCOE, but it is often instructive to separate them as, for instance, CAPEX can be the main barrier for the implementation of the project in developing countries even if it has a relatively low LCOE [99].

Furthermore, the definition of LCOE implies there is only one unique decision maker, whereas the interests of other stakeholders can be different and they may not focus on the same aspects of the project [99].

Additionally, the economic indicators depend on many assumptions that are debatable depending on the conditions considered (Capacity Factor (CF), discount rate, policies, life-time, etc.). In many instances, the assumptions are considered constant through the project life-time while they may vary with time (PO, CF, discount rate, O&M costs etc.). Attention must be paid to the difference between theoretical and effective capacity factor. For example, a project (e.g. coal power plant) might have a high theoretical CF, but due to the merit order (i.e. the priority order of power production technologies according to their marginal cost to run), its effective CF in the electricity mix might be lower. Authors in [100] outlined the different methodologies and assumptions used in several studies for cost assessments and concluded that the CF impacts significantly on the results. To avoid misleading interpretation of economic results, the assumptions, the method and the limitations of the estimates should be clearly stated.

Secondly, the LCOE does not give any information about “when, how and where” for the electricity production [70]. Instead, it only considers the power plant on its own without considering the grid in which it is implemented, the presence of a market, and the role that this production will have in the energy mix (base or peak load). This can be considered a major drawback as it directly influences the project integration to the grid and the market and thus the actual profitability [99]. Joskow [101] showed that if wind turbines produced during off-peak hours, even with a low LCOE, the project could present a negative economic profit. The introduction of non-dispatchable and intermittent technologies in the energy mix makes the interpretation of the LCOE more complicated as they do not deliver strictly the same service [102]. Therefore, it was suggested by IEA [103] that a part of the costs of the dispatchable technologies used to offset the abrupt production changes of the variable renewable energy technologies should be attributed to them. In that purpose, Taylor [102] coupled the wind turbines with gas or coal power plant to evaluate the global LCOE and found that the resulting LCOE was at least double the estimate for wind turbines alone. Alternatively, coupling storage technologies is another solution, but the corresponding costs must be analysed too. For that purpose, Lazard [104] has developed a new indicator similar to the LCOE, but for storage, which is called the Levelised Cost Of Storage (LCOS). Another way of comparing projects more fairly is to calculate the avoidance of costs linked with the project (fuel costs mainly).

The indicators that estimate the revenues, consider the time factor of the production, as they need to estimate the electricity price for the specific energy produced. However, this information is embedded and is therefore not directly interpretable. The estimates of revenues rely on assumptions and probabilities for the production and the market behaviour. They should be known adequately well to ensure a correct interpretation and accuracy of the forecast. In the NPV calculation example in [89], the selling price of electricity is assumed to be constant, but this is unlikely to represent the reality of the electricity market as discussed for the LACE calculations, with the seasonal and daily price changes. The constant price could be calculated as an average of the different market prices through the year.

Although the LACE considers different prices depending on the season and on the day time, it considers these marginal generation prices constant for all the years through the project life-time. An updated version could be to calculate the average LACE on the whole life-time. It would also allow to consider the annual degradation factor for the net production estimation. However, estimating the electricity price on the market in 20 years or more is a difficult task [105]. This drawback is general for all the indicators that estimate the total revenues of the project. Additionally, the LACE does connect the power production with the demand of electricity. It looks at the current price of electricity without considering the changes in the demand and production for the future or the project's effects on the electricity market. Winkler et al. [106] showed that adding new power production capacities to the grid influences the market depending on the characteristics of:

- Loads: time-shape and value.
- Current production parameters: end-of-life, PO, CF and its time repartition, electricity costs of production, the must-run requirement (the minimum use that is required to be able to enjoy the full power of the technology when needed).
- New projects: PO, CF and its time repartition, lifetime and electricity costs of production.

For example, implementing a variable energy technology adds uncertainties and abrupt changes to the production and thus it would rise the need for flexibility to ensure the reliability of the grid (e.g. with gas power station or storage technologies). Hence, a high share of variable energy technologies in the electricity mix will generally lead to a higher price volatility of the electricity [106,107].

Basically, the coupling of the LACE and LCOE indicators aims to depict the profitability for the individual project, by looking also at the current electricity market. However, it considers neither the absolute project physical coherence for the local needs, nor its impact on the electricity mix and market.

Moreover, the economic indicators do not usually consider the location of the project. Hence, grid connection, transport, distribution and marketing expenditures are ignored although they can represent up to 40% of the electricity cost [70]. For small scale and distributed (by opposition of central) power generation technologies, the grid connection costs might be consequent depending mostly on the localisation [103].

Additionally, the economic indicators exhibit limitations in integrating risks and uncertainties of the market in the analysis (apart from the interest rate). Risks could be of different kinds: construction, operation, fuel supply, safety, electricity supply and production, etc. However, the impact of these risks on the value of the project is often important and should be considered before its implementation; to this end, the value at risk of the project can be estimated to provide a more insightful assessment [108] than the LCOE [99].

Finally, the presented indicators are inefficient at integrating some expenditures such as the dismantling cost (due to the discounting and the long-term view). The Abandonment Expenditure (ABEX) might be small when discounted at the beginning of the project but still they need to be spent when needed and it is not insignificant amount [109]. But they also failed to correctly consider the impact of externalities (environmental or social). Yet, they can have a huge influence on the actual interest and relevance of a project. Roth and Ambs [110] indicated that including externalities (environmental and non-environmental) can lead to a LCOE which is three times higher for fossil fuel combustion technologies, similar results were obtained by [111].

However, it should be noted that giving an economic value to each of the externalities is based on specific assumptions that strongly influence the unique, final result. There is no perfect solution to economically valuate some externalities as the impact on the health, the depletion of the resources or the controllability. Furthermore, Renewable Energy Technologies (RETs) developed at a large scale, present major drawbacks that need to be evaluated as well to conduct a fair comparison. It is widely recognised that intermittent RETs with a penetration rate above 30% of the electricity production within the mix, induce imbalance and require a major adaptation of the power system [112]. The electricity grid needs resiliency and reliability from different levels depending on the demand in place. Each project implemented influences the performances of the overall system compensating or degrading the characteristics of the others. Thus, it is logical that when analysing energy projects, it should include the electricity market and the grid and mix in place.

4.5 Energy mix and market indicators

The energy mix and local energy market characteristics are substantial to assess the integration of the new energy project to the electricity mix. However, studying these sectors required a multifactorial analysis. Different papers propose methodologies and final indicators to rank country depending on their energy mix characteristics and performances. These indicators help to evaluate what is the impact of individual energy projects on the grid and (at a larger scale) on the national energy mix. Such indicators are, for example, the Choiseul index (by the Choiseul Institute [113]), the Trilemma index (by the World Energy Council [2]) and the Energy Architecture Performance Index (EAPI – by the World Economic Forum). The three indicators give a global view on the energy system in place and its reliability and competitiveness. They agree that the global energy system has to be evaluated under different angles, considering the global situation at the national scale. The three main groups of parameters to balance are: the general energy mix characteristics (security, independence etc.), the energy quality, availability and access and the environmental sustainability of the energy mix. The three indicators agree on the characteristics the energy mix of a country are required to have:

- High electrification rate, good quality, availability and affordability of the energy, low blackouts occurrences.
- Low GHG emissions from energy sector.
- High energy independence with an important share of renewable energy and a good diversity in the supply.
- Low energy intensity.

These indicators assist to evaluate the energy system at a scale larger than the energy project level, analysing how and why the implementation of a new electricity project would affect the energy mix performance. For example, the reliability and resilience of the grid will be influenced by the diversity of the supply, the characteristics of the production (dispatchable or no, time distribution of the production etc.), blackouts occurrences, the power quality (frequency, voltage).

5. Critical Discussion

Table 3 summarises the classified competitiveness indicators in terms of their inputs/outputs and the application technologies. Most indicators examined can be applied across multiple energy production projects from both primary and secondary sources for heating, cooling, electricity, co-production of heat and electricity units, among others. Nevertheless, SEE appears to be more relevant to energy projects using a depletable feedstock or feedstock with limited potential to be renewed in a specific period of time and SER is more relevant to renewable technologies. Finally, LCOE and LACE are focusing on electricity generation plants, with LCOE focusing on the break-even price for the produced electricity and LACE providing a measure of what it would cost to generate the electricity that would be displaced by a new project.

A correlation can be highlighted between the approach of developing physical and economic indicators. Some economic indicators can be seen as counterparts of physical indicators, such as the EPBT and the SPB period, the NEY and the NPV or the BCR and EROI. The LCOE and EROI also exhibit similarities as they are both ratios representing the total costs over the net electricity production and the net electricity production over the energy cost, respectively. Moreover, the economic indicators are not only influenced by the energy invested but also by the financial aspect, the workforce and resources costs or by the local policy. The local conditions have thus an important influence on the result. The company Ernst & Young (EY) created the Renewable Energy Country Attractiveness Index (RECAI) for ranking countries in terms of attractiveness for renewable energy projects for investors. This index methodology highlights the multidisciplinary factors that should be taken into account in the analysis. It integrates different categories of parameters specific to the local conditions: the general economic and financial climate, the energy market, the policy and political situation and the technology potential [114]. For their part, the physical indicators are simple to understand and interpret as they consider only the energy spent and returned. The economic indicators are more complex to use as they are sensitive to the financial and local conditions (integrating numerous assumptions which are often market dependent). Hence, the physical indicators often reveal, from an energy point of view, what the economic indicator may hide under “good performances” due to specific conditions (financial, policy, etc.).

The environmental indicators do not present the same methodology or the same purpose as they focus on the impact of the project on the environment and not on the energy performance or the economy. The System Energy Returned indicator tries to connect the environment and energy aspect but the interpretation of the result is difficult. To clearly present these two different, but substantial aspects, it might be more suitable to use the $EROI_{ext}$ in conjunction with the proportion of non-renewable energy used and the efficiency of its use. The environmental aspect needs an analysis at a larger scale than just the power plant border. For energy project, it can be more relevant to analyse the scenarios at the grid scale to see the actual performance for the service delivered. In the same way, the social indicators are necessary but not sufficient as they do not evaluate technical performance of the project but assess the indirect impacts for the social welfare. Due to this similitude, the environmental and social parameters are often grouped in one category: socio-environmental aspects. They can constitute the cause of the abandonment of a project, depending on the local conditions. All categories of indicators can be described as necessary but not sufficient to satisfy all pillars of sustainable development and to be competitive.

The national energy mix indicators do not follow the same approach as the rest of indicators as they are based on a mix of different weighted indicators. Although the energy mix indicators cannot be directly employed to compare competitiveness of individual projects, they indicate the impact of the new project on the balancing of the energy system. Energy system indicators incorporate the three aspects of sustainable development: economic, social and environmental, as well as the policy and financial context that can influence the overall performance of the system. Thus, these indicators can provide an overview of the whole energy systems following the implementation of the project.

Additionally, the analysis should consider the maturity of the technology and thus the perspective of improvement. Some technologies are not at the same maturity level (Technology Readiness Level – TRL) and hence might enjoy financial support to promote their development and improve their performance. In terms of technical competitiveness, it is not really a fair comparison to compare technologies with different TRLs. However, it happens in the actual market because it promotes the innovation [115]. Additionally, promoting emergent technologies and the Research and Development (R&D) are a substantial help in improving their economic or technical competitiveness [116]. These technologies can be supported by different support schemes: feed-in tariff, feed-in premium, quota obligations, investment support or auction and tender [117]. Hence, it is important to be aware of the TRL and the potential support scheme in place to consider uncertainties and opportunities linked with the maturity of the projects. The risk analysis is also substantial to have complete and well-informed results. A complete risk analysis should be undertaken before the project implementation to identify most critical risks (risk ranking) characterised by their probability of occurrence and the importance of their consequence and work towards their management and mitigation [118].

Table 2 Classification of indicators, their inputs/outputs and application technologies

Indicators	Inputs	Output	Applicable technologies
Physical			
EPBT [y]	• Energy required during the whole life-cycle [manufacturing, construction, implementation, operation & maintenance, decommission) [Wh or J] • Annual net energy production [Wh/y]	Time period that a project needs in order to produce the equivalent amount of energy that was required throughout its life-cycle	All energy production projects
NEY [Wh or J]	• Energy required during the whole life-cycle [Wh or J] • Energy produced during the whole life-cycle [Wh or J]	Net energy produced on the whole life-cycle	All energy production projects
EROI [-]	• Energy required during the whole life-cycle [Wh or J] • Energy produced during the whole life-cycle [Wh or J]	Ratio expressing how much energy is produced per unit of energy invested	All energy production projects
NEP [%]	• Energy required during the whole life-cycle [Wh or J] • Energy produced during the whole life-cycle [Wh or J]	Capacity of the project to produce net (usable) energy	All energy production projects
SEE [-]	• Energy required during the whole life-cycle [Wh or J] • Energy produced during the whole life-cycle [Wh or J] • Inherent energy of the feedstock used [Wh or J]	A rating of the performance in terms of production of energy and efficiency of production	More relevant to energy projects using a depletable feedstock or feedstock with limited potential to be renewed in a specific period of time (biomass)
SER [-]	• Non-renewable energy required during the whole life-cycle [Wh or J] • Total energy produced during the whole life-cycle [Wh or J] • Inherent energy of the feedstock used that is non-renewable [Wh or J]	A rating of the performance in terms of production of energy and efficiency of production	More relevant to non-renewable technologies
Environmental			
GHG emissions [tons $CO_{2\text{-eq}}$ /(Wh or J)]	• Total number of GHGs emitted from the project • Net energy/electricity produced (direct and indirect – LCA) [Wh or J] • Global warming potential of GHG [-] • GHG emissions per unit of energy produced [tons $CO_{2\text{-eq}}$]	GHG emissions equivalent per unit of energy/electricity produced, i.e. the Global warming potential of the project	All energy production projects – for electricity: need to assess the impact on the carbon footprint of the overall mix
Land-use [m^2/y(Wh or J)]	• Total land area required for the construction and operation of the project per unit of energy produced [$\frac{m^2}{J}$] • Amount of time that the land area is occupied by the project [y]	Area required for a unit of produced energy/electricity	All energy production projects
Resources sustainability	• Amount of critical elements • (Net) energy/electricity produced (direct and indirect – LCA) [Wh or J]	Amount of critical elements per unit of (net) energy/electricity generated	All energy production projects
Social			

Jobs creation [jobs-y/Wh or jobs-y/J]	• Number of jobs created during the life cycle of the project (direct and indirect) [-] • Duration of employment [y] • Total number of lifecycle stages [-] • (Net) energy/electricity produced [Wh or J]	Jobs per produced unit of energy/electricity	All energy production projects
Human health impact [number of years of healthy life lost]	• Number of deaths in the population [-] • Population's average remaining life expectancy [y] • Number of incident cases of a particular condition [-] • Average length (duration) of disability from a particular condition [y] • Prevalence of the condition • Disability weight associated with the condition	Number of years of life affected by disabilities	All energy production projects
Safety risks	• Number of fatalities from accidents • (Net) energy/electricity produced [Wh or J]	Fatalities resulting from accidents per unit of produced energy	All energy production projects
Social acceptability [%]	• Percentage of the residents in favour of the project [%]	Anticipated public opinion towards the implementation of the project	All energy production projects
Economic			
WACC [%]	• Repartition of the value of the project/company and the corresponding rates of return, including tax rate when relevant [-]	Average rate of return that a company must generate to satisfy its investors	All energy production projects
TLCC [$]	• Total costs on the life-cycle scale [$] • Discount rate [%]	Total costs discounted to the present/a given date	All energy production projects
NPV [$]	• Total costs (capital, fixed and variable operating costs) [$] • Total revenues [$] • Discount rate [%]	Total life-time cash flow discounted to the present or a given date	All energy production projects
BCR [-]	• Total costs [$] • Total revenues [$] • Discount rate [%]	Ratio that shows the efficiency of the project to generate benefits	All energy production projects
SPB [y]	• Total annual costs [$] • Total annual revenues [$]	Time period required in order that the cumulative revenues become equivalent to the cumulative investments – evaluate the time period during which the investment will be at risk	All energy production projects
DPB [y]	• Total annual costs [$] • Total annual revenues [$] • Discount rate [%]		All energy production projects
IRR [%]	• Total costs [$] • Total revenues [$]	Maximum rate of return (%) economically viable for the assumed cash flow model	All energy production projects

LCOE [$/Wh]	• Total costs [$] • Net energy production [Wh] • Discount rate [%]	Break-even price for the electricity produced	Power production technologies only - need to be completed by other indicators (LACE – LCOS) to consider the intermittent aspect of concerned technologies.
LACE [$/Wh]	• Marginal generation price [$/Wh] • Dispatched hours [h] • Capacity payment (cap payment) [$/W] • Capacity credit (cap credit) [-] • Annual generation hours [h]	Costs that would be incurred to provide the electricity displaced by a new generation project.	Power production technologies only

6. Conclusions

Shifting to affordable, reliable, sustainable and modern energy is one of the goals of the 2030 Agenda for Sustainable Development. When selecting among candidate power generation projects a common basis of comparison across technologies should be adopted. Apart from the technology-specific characteristics, decision makers should consider other factors, such as the availability of the resources of the country/installation site, the socio-economic implications, the environmental impact and the integration to the existing power grid, when deciding the deployment of a power generation plant.

This paper critically reviewed a set of KPIs for the assessment of competitiveness of individual power generation projects, classified as physical, environmental, social and economic. The advantages of each indicator were discussed, along with their interconnections and limitations, highlighting the significance of transparency and critical consideration of the underlying assumptions. Indices for energy mix performances were also reviewed and discussed as they can offer a holistic view, required for a coherent analysis. The list of indicators analysed in this paper is not exhaustive, but brings together key and replicable indicators, capable of quantifying the competitiveness and sustainability of power generation technologies.

Although the focus of this paper lies on power generation projects, the majority of KPIs reviewed can also be applied across different types of energy projects and uses, including heating, cooling and co-production of heat and electricity. However, there are exceptions to this observation, as some indicators are technology-specific, such as the SEE, which appears to be more relevant to energy projects using a depletable feedstock, and SER, which is more relevant to non-renewable technologies. LCOE and LACE both focus on electricity generation plants.

Some common limitations among indicators of different categories were detected. For example, EPBT and LCOE both assume constant annual energy production throughout the life span of the power plant, which could lead to over- or under-estimation of the energy produced considering the volatility of the power output of some electricity production technologies. Using LCOE alone to compare two competing technologies is not representative of the value of the plant’s output to the grid, as it does not consider the “how, when and where”. LACE has been cited as a complementary indicator for assessing the economic competitiveness by considering the avoided cost, i.e. what it would cost to generate the electricity that would be displaced by a new generation project [13].

Some indicators were found to express similar measures, such as LCOE and EROI, both expressed in the form of a ratio of the total costs over the net electricity production and the net electricity production over the energy cost, respectively. Similar conclusions were drawn from the observation of other indicators such as the EPBT. This KPI may be seen as a counterpart of the SPB, as they both state the duration of time the project needs to operate to produce the equivalent amount of energy and financial return that was required to implement it, respectively. When considering appropriate indicators to assess the sustainability of an energy project, a key issue to address is the availability of data. Access to data may vary depending on the stakeholder and the purpose of the analysis. For example, if it is a project developer seeking to assess a range of different energy projects, data from previous projects could be available to use, while for more detailed analysis, multidisciplinary stakeholder consultation elicitation may need to be employed.

Future research should also consider the maturity of the technology, potentially through the Technology Readiness Level (TRL), as it is a critical indicator to assess the competitiveness of a power generation project and it needs to be considered to allow a fair comparison among technologies with different TRLs. Other critical factors that may affect the implementation of a project are the macroeconomic benefits yielded, e.g. the localisation, the national content, the GDP growth along with the existence of an established supply chain.

The focus of this paper lies on the collection of several key and replicable indicators, assisting a holistic view on the competitiveness of alternative energy projects. Further research is underway to develop a structured evaluation framework based on the identified set of indicators, aiming at proposing the order in which they should be applied and corresponding threshold values for the selection of the most competitive technologies for sustainable energy systems.

Appendix

Nomenclature

Symbol	Description	Units
$ANEP$	Annual Net Energy Production	(J or Wh)/y
$annual\ expected\ generation\ hours$	The yearly number of hours of production of the project (the capacity factor multiplied by 8760 – the total number of hours in a year).	h
$\mathrm{B_{tot,t}}$	Total benefits of the project at year, t	\$
B_k	Emissions of the GHG, k, per unit of energy produced	$\frac{\mathrm{g}}{(\mathrm{J\ or\ Wh})}$
$cap\ credit$	The ability of the project considered to ensure the margin supply. It equals 1 if the unit is	-

	dispatchable while if it is intermittent, the capacity credit will be lower than 1 depending on the resource availability (locally or regionally) during the peak time-period.	
$cap\ payment$	The value to the system in order to meet the reliability reserve margin.	\$/W
CF_0	Cash flow at year 0	\$
$C_{tot,t}$	Total costs of the project at year, t	\$
D	Market value of debt	\$
$dispatched\ hours_y$	The number of hours in the period in which the electricity unit considered is "dispatchable", it basically depends on the capacity factor considered for the specific time section	h
E_c	Market value of equity	\$
E_d	Energy returned to society	J or Wh
E_f	Energy content of the feedstock	J
$\mathrm{E_r}$	Direct and indirect energy required for the implementation of the project	J or Wh
GWP_k	Global warming potential of GHG, k	$\frac{gCO_{2-eq}}{(J\ or\ Wh)}$
I	Total number of lifecycle phases	-
i	Stage of the project	-
JC_i	Number of jobs created during the life cycle stage i	-
K	Total number of GHGs emitted from the project	-
L	Population's average remaining life expectancy	years
LA	Total land area required for the construction and operation of the project per unit of energy produced	$\frac{m^2}{(J\ or\ Wh)}$
LD	Average length (duration) of disability from a particular condition	years
LT	Life time of the asset	years
$\begin{pmatrix} marginal\ generation \\ price \end{pmatrix}_y$	The cost of meeting the electricity demand depending on the time and season considered. According to [97] this price will be fixed by the most expensive electricity generation unit that needs to be used to satisfy the specific loads	\$/Wh
P	Prevalence of the condition	-
P_{tot}	Total power generated over the life of the plant	$J\ or\ Wh$
$PE_{assemply}$	Primary Energy required for the assembly of the energy technology	J
$PE_{decommissioning}$	Energy required for the assembly	J
$PE_{operation}$	Primary Operation Energy from direct and indirect energy inputs	J
r	Real discount rate	%
r_d	Interest rate on debt	%
r_{eq}	Return on equity	%
R_{infl}	Inflation rate	%
r_{nom}	Nominal discount rate	%
t_i	Duration of employment in stage i	years

t_{LA}	Amount of time that the land area occupied by the project	years
T	Corporate tax rate	%
V	Sum of equity and debt	$
W	Disability weight associated with the condition	-
Y	The number of time-periods in the year. Indeed, the LACE takes into account different periods of the year and of the day. Usually there are 9 divisions: 3 seasonal (winter-summer and spring/fall) and 3 daily (night, day and intermediary) [97]. The marginal generation price, the capacity factor (and hence the dispatched hours) are estimated separately for each of these 9 divisions.	-
YLL	Years of the Life Lost	years

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