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A Survey on the LCOE

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Abstract

Metrics play an important role in decision making processes. Without them the right option can not be chosen and the progress can not be measured. For choosing the best economical option among the various kinds of electricity generating technologies, cost analysis supported by effective financial metrics should be done. Metrics should quantify sustainability as much as possible in order to justify their cost or benefit measures in the long run. This is possible, when metrics include three basic dimensions of the sustainability. Namely environmental, economical, and social dimensions. On the other hand, including these dimensions brings externalities and uncertainties into calculations. In addition to these dimensions, time and space are other important dimensions that an ideal metric should consider. Renewable energy production systems are important for sustainable development. But the intermittent nature of renewables, introduces difficulties in justifying their long run benefits, requiring extensive knowledge on the various kinds of metrics and on their properties. For this purpose, a short survey on the various types of metrics for electricity generation cost will be discussed in this paper. While the main focus will be on the LCOE metric, other types of metrics will be presented and qualitative and quantitative comparisons on them will be given. Different views from literature will be evaluated about the LCOE. Critical analysis will be done for the LCOE metric to list the strong and weak points of it.

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1 Introduction and Background

Metrics not only provide ways to make sustainable decisions but also among the options, show which one is the best. Effective metrics can integrate qualitative and quantitative aspects of the system along with time and space dimensions, helping the decision making process for important investments and projects. In fact any metric that is aspiring to become standard yard stick for the sustainability issues, has to include three fundamental dimensions of the sustainability, namely economical, environmental and social dimensions. Extensive review of such metrics that are used in general assessment methods for the sustainability can be found in [7], [16], [18], and in [27]. Difficulties in quantifying such dimensions may become big challenge because of many reasons. Complexity and chaotic nature of such systems, introduce challenges in finding proper models for analysis. Especially quantification of the uncertainties and inclusion of externalities are two main difficult aspects related to such systems. Another reason is related to the maturity of the scientific effort in this area. Sustainability and Renewable Energy topics can be regarded as new branches of the scientific interest [5] [14] [28]. After the industrial revolution mankind became more and more dependent on the energy. Yet immense quantities of energy demand, created immense side effects on the nature. Escalation of environmental problems signaled mankind to take action [30], which was not manifested before the 20^{th} century. In front of the difficulties caused by the irreversible changes, mitigation efforts, especially use of better energy production alternatives are favored and applied. Yet without the effective metrics, the ”right direction” can not be found. In this sense metrics play important role in the solution of the sustainability problems. Comparison capability of the metrics must also be taken into consideration in the case of energy production technologies with different natures. One good example is the intermittent and dispatchable nature of the energy production technologies. Specific discussions on this issue for LCOE metric can be found in [13]

Throughout this paper ”metrics” and ”index” can be used interchangeably. ”Financial indices” that are mentioned in the literature are special types of metrics, in which various factor are considered and the benefits or costs are expressed numerically. They are vital tools in Engineering Economics. Levelized cost of energy (LCOE), Net Present Value (NPV), Internal Return Rate (IRR), Break Even Point (BEP), Simple Payback Period (SPP), Benefit Cost Ratio (BCP), and EROI (Energy Return on Energy Invested) are such indices that can help in finding sustainable choices [4] [14, p. 81-133] [15]. The degree that an index provides flexibility in including the externalities, determines its effectiveness in differentiating sustainable options.

In the following sections, a short general survey on different metrics that are used for comparing various power generating technologies, will be given. In the section 2, the assumed system for the operation of the metrics will be explained, and the overview of the metrics will be given. This section also, presents short discussion on the use of metrics in LCA (Life Cycle Analysis) process as an example application for the metrics. In the section 3, the paper will focus on the LCOE method. Advantages and disadvantages of the LCOE will be surveyed by presenting different opinions from researchers. In the section 4, the importance of the metrics in the process of choosing sustainable paths will be discussed and classification of the metrics depending on various aspects, and comparison will be presented. Finally in the section 5, conclusions of the survey will be listed and recommendations will be proposed.

2 System Description and Overview of Metrics

Before going into the discussions on the metrics, the envisioned system and its attributes, its nature should be explained. Some of metrics mentioned previously may be applicable on different systems. For this the system boundaries will be generic enough to include all the metrics listed above. Almost all of the scientific measures can be associated with, at least, one of the three dimensions (environmental, economical, social) of the sustainability. In addition to these dimensions, time and space can be listed among the dimensions of these metrics. Some metrics based on the past, some of them may be evaluated only in present and some others only for future. When time is considered, the other issue is the point that the metrics can be applied. Some metrics are powerful and can be applied during the construction, operation and maintenance phases of the power plant, yet for some metrics only the operation stage matters. In the following paragraphs, assumptions about the envisioned system attributes will be presented and general usage of these metrics will be described.

2.1 System Nature for the metrics

The system that is envisioned for the metrics mentioned above is the electricity production system (power plant). Various taxonomies can be given for the power plants depending on the technology used, fuel type, the prime mover, the nature of the energy output. Some examples of the classification can be given as Traditional vs Renewable, Conventional vs Non-conventional, and Dispatchable vs Non-Dispatchable. Extensive discussions on the power plant technologies and types can be found in [9]. Classification and technical information on different power plants can be found in [32]. In the figure 2.1.1 the system is shown schematically, which is taken from [14, p. 104]. The flow of energy and the flow of finances are included to explain cost of energy concept clearly. Explanations about parameters in the figure 2.1.1 is given in table 2.1.1 below.

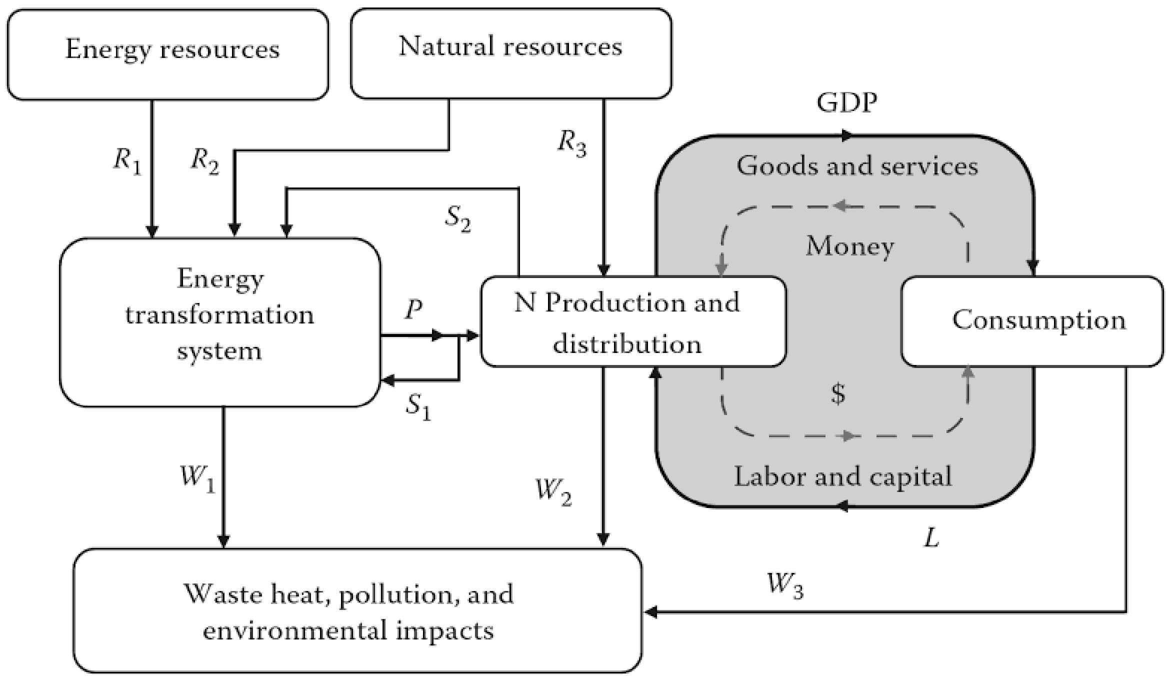


Figure 2.1.1: System overview and the flow of energy, resources, goods and money. (Source: [14, p. 104])

Table 2.1.1: List of parameters of the system in the figure 2.1.1. (Source: [14, p. 104])

Symbol	Meaning
GDP	Cost of Product and Services (Unit or dollar)
P	Consumer energy produced for sale
R_i	Flows of primary energy and natural resources
S_1	Energy needed to run the system (fuel/electricity)
S_2	Energy (equipment and materials) needed to extract and process energy
N	Net energy to the Economy
L	Labor and investment taxes
W_i	Waste flows

2.2 LCA and the metrics

Life Cycle Analysis (LCA) [1] is a powerful assessment tool for evaluating environmental impact of the processes, products and activities, from ”cradle to grave”. Detailed reviews on the LCA tool can be found in [11], [21], and in [25]. Metrics play important role in the LCA assessment process. LCA collects various metrics and translates them into environmental impact measure.

However some caveats should be given about LCA. One major drawback is the fact that, LCA can not provide “ad hoc” results. In other words quantification of impacts in the case of LCA is global, general . Whereas EIA can be used to consider unique properties of the impact given “location and time”. Related to that drawback, in the literature there are discussions on the comparability power of the results given by the LCA method. Basically with LCA it is not possible to compare “environmental preferability” of two products (functionally same) by LCA. This is because LCA does not cover all relevant (product specific) environmental aspects [10].

Another major drawback is the “uncertainties” that come from the assumptions that are made during the LCA analysis. This may prevent precise results. Also the quality of the “inventory database” directly effects the sensitivity of the results given by the LCA analysis.

Although LCA is used for products, it can also used for services. Waste management is one of the services in which LCA is carried out. For short term effects of waste management, direct measurements can be given. But for long term processes direct measurements may not be given. For example in the case of landfill the emissions to water may take many years. Quantifying such long-term (>100 years) impacts from land-filling introduces problems for LCA analysis [19]. Also “Recycling” type circular services can not be easily handled by LCA, as it is difficult to fix appropriate “time frame” for the assessment.

2.3 Metrics

Most metrics try to determine the income-expenditure relationship of the system in their core functionality. They differ in the type of expenditures they include and in time frame they use for calculation. While some metrics can include externalities explicitly, others need customized versions for externalities. Simple Payback Period (SPP), Net Present Value (NPV), Internal Return Rate (IRR), Break Even

[1] Details about the standards related to LCA can be found in `http://www.iso.org/iso/catalogue_detail?csnumber=37456` (ISO 14040:2006) and in `https://www.iso.org/obp/ui/#iso:std:iso:14044:ed-1:v1:en` (ISO 14044:2006)

Point (BEP), Benefit Cost Ratio (BCR), EROI (Energy Return on Energy Invested) Levelized cost of energy (LCOE), are such metrics that can help in finding sustainable choices [4] [14, p. 81-133] [15]. The degree that an index provides flexibility in including the externalities, determines its effectiveness in differentiating sustainable options. In this section several of the widely used metrics will be explained. For this formulas and explanations of these common cost metrics are given below. Extensive review and additional hybrid metrics (combination of the basic metrics that are explained below) can be found in [12, p. 187-218] and in [14].

- Simple Payback Period (SPP) can be given by the following formula 2.3.1

$$SPP = \frac{C_0}{B_i \times C_i} \tag{2.3.1}$$

  Where

  - SPP [years], is the number of the year the system will payback the cost
  - C_0 [$], is the total cost of initial construction and installation
  - B_i [kWh/year], is the amount of energy saved per year or net energy produced per year
  - C_i [$/kWh], is the unit cost of the energy

  This method does not include inflation rate, fuel costs, and the time value of the money. If the system can pay itself in its life time than SPP labels the system economically feasible.

- Net Present Value (NPV) on the other hand includes discount rate and inflation rate (together nominal discount rate), calculating time value of the money. System is economically feasible, when its NPV is positive or above the ”threshold” value set by the investor.

$$NPV = \sum_{t=0}^{T} \frac{B_t - C_t}{(1+i)^t} \tag{2.3.2}$$

  Where

  - NPV [$], is the Net Present Value, in other words present discounted benefits minus present discounted costs
  - T [years], is the time horizon for the project or system
  - B_t [$], undiscounted benefits
  - C_t [$], undiscounted costs
  - i, real discount rate or can be nominal discount rate (real discount rate + inflation rate)

- IRR is the i value in formula 2.3.2 that sets NPV value to zero. In other words it is the discount rate for the ”break even” situation.

- In general BEP analysis can be done for any parameter by setting NPV to zero or simply setting the ”profit” to zero.

- Based on the parameters of the formula 2.3.2, BCR can be given with the following formula 2.3.3:

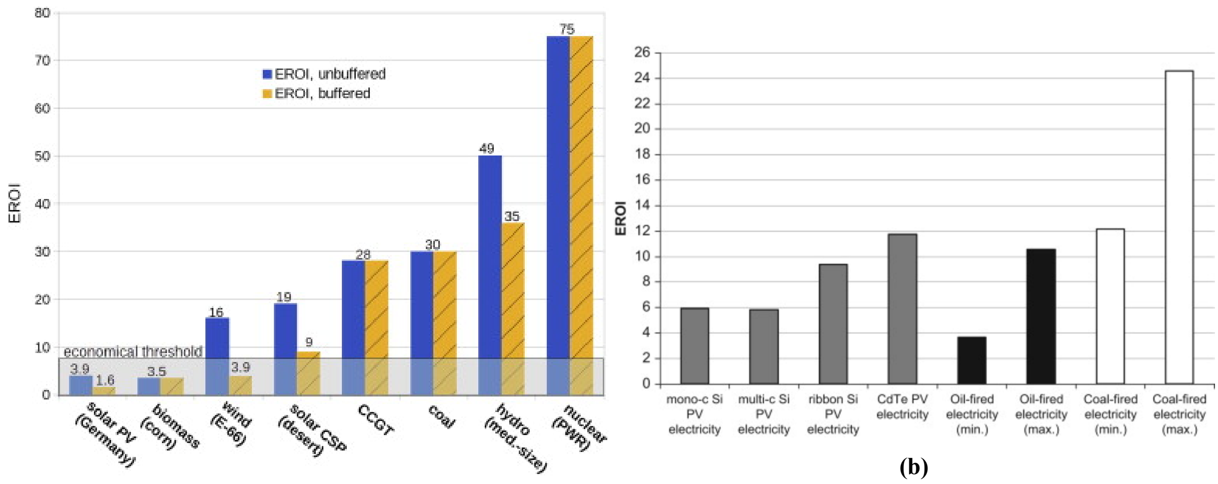
$$BCR = \frac{\sum_{t=0}^{T} \frac{B_t}{(1+i)^t}}{\sum_{t=0}^{T} \frac{C_t}{(1+i)^t}} \tag{2.3.3}$$

  According to the formula 2.3.3, the condition for economical feasibility of the project or the system happens when *BCR* is greater than 1.

- EROI (Energy Return on Energy Invested) is a bit controversial measure as it can be seen in the discussions of the [22], [24], [34], and [35]. To overcome these controversies, this paper follows the system model proposed in [14, p. 104] as it is shown in the figure 2.1.1 above. According to the figure 2.1.1 and the table 2.1.1 EROI formula (2.3.4) can be given as:

$$EROI = \frac{P}{S_1 + S_2} \tag{2.3.4}$$

  EROI is unitless as it is the ratio of two energy magnitudes. It can be adjusted to a certain year or to a life time of the system. Sample values of EROI for different technologies can be found in [34](figure 2.3.1a) and in [23](figure 2.3.1b) as it is shown in the figure 2.3.1 below. It can be seen in the figure 2.3.1a and in the figure 2.3.1b EROI values for renewables are low. This can mislead companies that base their investment analysis on the EROI solely, as there is no time factor included in the formula(2.3.4) of the EROI.



(a) (b)

Figure 2.3.1: Comparative values of EROI for different energy production technologies. (Source: [34] for (a) and , [23] for (b))

- Levelized cost of energy (LCOE) is metric that widely used in studies to compare different energy generation technologies. It calculates the present value of the all costs associated to the system (operation, maintenance, initial, fuel) per unit power generation (discounted to present). So it can be regarded as a rendition of NPV. But, as the calculation is with respect to unit cost or with respect to cost of unit power generation, it gives values that are ”comparable” (common basis) for various electricity generation technologies. According to the figure 2.1.1 and parameters given in the table 2.1.1 LCOE can be calculated by the following formula (2.3.5) from [14]:

$$LCOE = \frac{(\sum S + \sum R + W_1)}{P} \tag{2.3.5}$$

Whereas the generic formula for LCOE can be given as [14]:

$$LCOE = \frac{\sum_{t=1}^{N} \frac{C_t}{(1+i)^t}}{\sum_{t=1}^{N} \frac{Q_t}{(1+i)^t}} \tag{2.3.6}$$

Where

- $LCOE$ [$/kWh]
- N [years], is the period of analysis as years
- C_t [$], is cash flow in the year t. Equals to tax savings + incentives - operating costs - debts + energy value in the project
- Q_t [kWh], is the electricity generated by the system in year t
- i, real discount rate or can be nominal discount rate (real discount rate + inflation rate)

In the formula 2.3.6 numerator is called Total Life Cycle Cost (TLCC). Also if the Q_t is constant for all years then the formula 2.3.6 can be rewritten as:

$$LCOE = \frac{TLCC}{\sum_{t=1}^{N} \frac{Q_t}{(1+i)^t}} \tag{2.3.7}$$

By taking the Q_t (constant) out of the summation then formula 2.3.7 becomes as follows 2.3.8:

$$LCOE = \left(\frac{TLCC}{Q}\right) \times CRF \tag{2.3.8}$$

Where

- $TLCC$ [$], is the Total Life Cycle Cost
- Q [kWh], is energy savings
- CRF is called Capital Recovery Factor. It is the sum of the series in formula 2.3.7 and can be expressed in the following formula 2.3.9:

$$CRF = \left[\frac{i \times (1+i)^t}{(1+i)^t - 1}\right] \tag{2.3.9}$$

LCOE gives idea about the break even unit price for the sale of the electricity produced. ”Grid parity” or ”socket parity” is the term used to specify the ”cost-effectiveness” situation for the renewable, occurs when the price from renewable is less than or equal to the price of the purchased electricity from the grid [6].

In the following section, the paper will focus on LCOE metric and the discussions on LCOE will be presented.

3 Critical Analysis of Literature

In the previous section several metrics were explained and their formulas are presented. In this section current research about LCOE will be discussed and the criticism will be given. Works that proposed contrary views will be listed and their opinions will be presented. After that compromising views will be presented. While some researchers present deficiencies of the LCOE metric, some others focus only on the strengths of the LCOE. Yet there are also works in which improvements are proposed for the deficiencies.

The main trade off for the most of the Renewable Energy production technologies is between their ”intermittent nature” and their ”zero fuel price”. In other words while renewables provide cheap energy, they can not be used at all times. Which in turn makes it very difficult to do the financial analysis on the profitability of the renewable energy use. To overcome such difficulties long term analysis by using effective metrics is required. For the LCOE, most of the discussions are centered on this issue, namely whether LCOE is powerful enough to include such factors or not. Although LCOE is a method that is capable to make comparisons on various alternative energy sources, some researchers have contrary opinions [13] and some other researchers proposed ”correction factors”, claiming that the ”plain” LCOE ignores the intermittent (bad effects to cost [2]) nature of various Renewable Energy technologies [26, 29].

The general tendency for the renewables is to use them on top of the ”base load” because of their intermittent nature. On the other hand, one of the solutions that is proposed for overcoming ”intermittency” of renewables is the use of ”electric energy storage” facility. Pumped-hydro, compressed air and chemical battery energy storage technologies are examples of such facilities that are frequently used. In [1] detailed technical review on the storage technologies and their costs can be found. Analysis for the effects of storage technologies on LCOE can be found in [20]. These researches show one of the advantages of the LCOE, namely its flexible nature. In other words limitations are not ”inherent” for the LCOE but depends on the ability of the researchers to integrate various cost and benefit parameters into the equation. Example research on this issue can be given as [33], in which interesting application of LCOE is given for generating LCOE maps for ”tidal stream energy” as a new geospatial tool.

In [3] several shortcomings of LCOE is mentioned. The paper first lists the additional cost associated for integrating renewables into the grid because of their intermittent and non-dispatchable nature, as being a problem in comparisons with dispatchable technologies. Ignoring environmental and economical externalities is listed as the second shortcoming of the LCOE. For the third shortcoming, paper mentions LCOE being limited as it considers new source development but not existing source generation. Although authors state that customized LCOE formulas had been proposed, they do not consider these alternative metrics being widely adopted.

In [31] LCOE is explained and its limitations are commented. In the report uncertainties about the LCOE calculations are stated. The report also suggests Levelized Avoided Cost of Electricity (LACE) as an additional indicator, to overcome the limitations of the plain LCOE method.

In [17], National Renewable Energy Laboratory (NREL) analyzes the impact of the financial structure on the cost of Solar Energy. In the report the difficulty of the uncertainties for the production and cost parameters is mentioned. Also many assumptions that can be made when calculating LCOE is discussed. Although this report is specific to Solar Energy, proposals are valuable in general for the LCOE.

In [6] the paper mentioned assumptions that are made by some researchers causing misconceptions about the LCOE method. Also in [8] authors provide set of assumptions that make LCOE powerful analysis tool. In both papers sensitivity analysis examples are given. Also in [8] authors stated the difficulties in determining the correct values for parameters associated with the cost and the electricity production. To overcome such uncertainties, the paper proposed Monte Carlo simulation method, in which various probability distribution models are chosen for the cost and for the production parameters. By combining Monte Carlo simulation method with LCOE, researchers extended the ability of the LCOE for doing analyses by considering uncertainties. In this way, the distributions of the output values from the LCOE method, can capture the uncertainties in the input parameters.

4 Independent Assessment

The paper stressed the importance of the metrics for sustainability and explained their functions in determining sustainable paths. The figure 4.1 shows the process of finding the best sustainable path for any sustainable development effort. As it can be seen the role of the metrics is vital. The research is always active in every part of the process. But eliminating possibilities that are not convenient is impossible without any quantification, in which comparisons can be done. Metrics are the tools that integrate many parameters, quantify possibilities, and propose quantified alternatives. For doing this, the metric should output ”comparable” measures. Decision process taking quantified alternatives as input, proposes the best path or paths to the development. The feedback line to the assessment step signifies the continuous measurements for monitoring the progress of the development. This means metrics are not single use tools but they are necessary throughout the life time of the process. With this vision, this

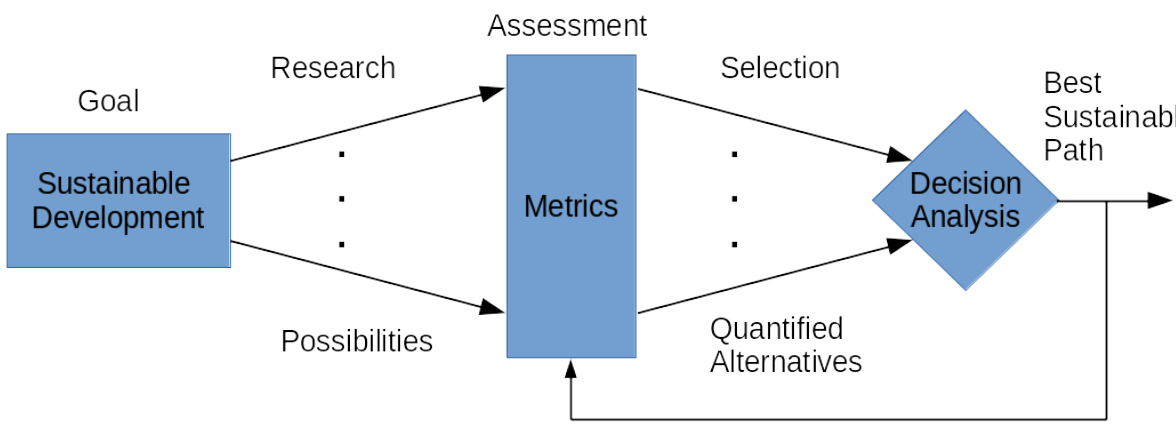


Figure 4.1: The process of finding sustainable path and the role of metrics

survey study is focused on the LCOE metric, which is the most effective measurement tool among the ones explained in the section 2.3. Firstly current research effort related to the use of LCOE and to the theory of LCOE is summarized. Papers criticizing the LCOE are presented along with the ideas from the papers that are offered modifications and improvements to the shortcomings of the LCOE.

Throughout this work ”effectiveness” is used to denote the power of the metric in guiding the decision making process for sustainable paths. As the metric is used for sustainability, it is vital that parameters associated to the three fundamental dimensions of the sustainability must be included or must be easily integrated into the calculations. It is also proposed in the section 2.3 that inclusion of externalities and handling uncertainties are two important factors for the ”effectiveness”. This is the framework this survey paper suggests for assessing the ”effectiveness” of any metric that needs to be used for doing analysis in finding a ”sustainable path”. The criteria is summarized in the table 4.1 below, in which the list of metrics that are explained in the section 2.3, along with their basic properties are shown. For the ”inclusion of discount rate and inflation rate” attribute, SPP and EROI are labeled as ”Not Direct” and all then others as ”Yes”. This is due to the fact that in their formulas SPP (formula 2.3.1) and EROI (formula 2.3.4) do not include these parameters. But the effect of these parameters can be added through indirect calculations. In the ”inclusion of uncertainties” again SPP and EROI rated different than the others. This is due to the flexibility that other formulas offer through the inclusion of cost parameters based on changing rates and through the flexibility that they offer to be integrated into probability analysis methods, like Monte Carlo, as it is mentioned in [8]. For the ”inclusion of externalities” again the flexible cost parameters can include externalities as additional cost for the methods that are labeled as ”Possible”, which depends on the skill of the researcher. The attribute ”inclusion of time factor (Forecasting)” is basically the ”forecasting” or ”prediction” power of the metric. In the case of the metrics that are discussed in section 2.3, it is the consideration of the changing value of the cost and benefit. However for the attribute ”Degree of Comparability of the Output”, LCOE can provide better measure for comparing ”sustainability” of different electricity production technologies.

Table 4.1: Assessment of the ”effectiveness” for the metrics explained in the paper.

Metric	**SPP**	**NPV**	**IRR**	**BCR**	**EROI**	**LCOE**
Meaning	Simple Payback Period	Net Present Value	Internal Return Rate	Benefit Cost Ratio	Energy Return on Energy Invested	Levelized Cost of Energy
Output Unit	[Years]	[$]	Unitless	Unitless	Unitless	[$/kWh]
Output	Years to payback cost	Discounted profit	Disc. rate to breakeven	Ratio	Ratio	Cost per unit power
Inclusion of discount/inf. rate	Not Direct	Yes	Yes	Yes	Not Direct	Yes
Inclusion of uncertainties	Not Direct	Yes	Yes	Yes	Not Direct	Yes
Inclusion of externalities	Not Easy	Possible	Possible	Possible	Not Possible	Possible
Inclusion of Time factor (Forecasting)	Not Easy	Possible	Possible	Possible	Not Possible	Possible
Degree of Comparability (Output)	Weak	Weak	Weak	Not Possible	Weak	Strong

5 Conclusions and Recommendations

In this work survey is presented on the metrics used for assessing electricity generating costs, in the context of choosing the best sustainable choice. Different types of metrics are listed and their properties are explained in the section 2.3. The paper proposes LCOE as the most effective tool for such endeavor. For the justification of this claim, a framework is suggested to assess the effectiveness of metrics in the section 4 and the assessment is presented in the table 4.1. The main advantage of the LCOE is the fact that it proposes a ”common basis” for comparing the output of the different electricity generation technologies. However caveats should be added to this suggestion. The first one is the ”difficulty of predicting the future”. No method can precisely include the effect of the future events, that may affect costs and benefits. Yet on the other the only thing is to ”estimate approximately” the outcome. The second caveat is the ”objectivity” of the calculations. Even LCOE is flexible enough to integrate the uncertainties and externalities in the calculation, at the end the researcher has to choose one of the estimates proposed by many studies for these parameters. One good example can be given as the social cost of CO_2, in which different values might be suggested by different studies. Medical science based research may propose different value for the social cost of CO_2, compared to the environmental science based research. Another caveat, as it is mentioned in the section 1, is related to the complexity of the systems subjected to the analysis. Which brings out the issue of ”completeness” of the metrics. It is possible that the current metrics do not have complete coverage of the factors involved for the calculations.

LCOE may have some limitations, but among the existing metrics, it is the most effective. In addition to that, as it is mentioned in the section 3, some researchers suggested that LCOE has enough flexibility to be expanded for overcoming the limitations that are listed in the literature. The implication of such suggestions is that, the limitations listed may not be ”inherent” limitations of the LCOE. The researcher may fail to apply the metric properly. In this sense the right direction could be further research and better modeling.

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