clean technologies

Systematic Review

A Literature Review on Existing Methods and Indicators for Evaluating the Efficiency of Power-to-X Processes

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Abstract: The challenges posed by climate change have prompted significant growth in efficiency evaluation and optimization research, especially in recent years. This has spawned a variety of heterogeneous methods and approaches to the assessment of technical processes. These methods and approaches are rarely comparable and are usually only applicable to specific sectors. This paper provides an overview of the literature on efficiency assessment methods and KPIs, leading to a more manageable selection of an appropriate method with special regard to energy system integration technologies. In addition to reviewing the literature systematically, this paper examines existing methods and indicators' applicability to and significance for efficiency optimization. In this context, a holistic approach to process design, evaluation, and improvement is given with particular regard to power-to-X systems. Within the framework of the study, three overarching goals could be defined as levels of efficiency evaluation of power-to-X systems: 1. identification of the process (steps) with the most significant optimization potential, 2. identification of the process phases with the greatest optimization potential (timewise considered), and 3. derivation of specific recommendations for action for the improvement of a process. For each of these levels, the most suitable evaluation methods were identified. While various methods, such as life cycle assessment and physical optimum, are particularly suitable for Level 1 and Level 2, for Level 3, even the best-identified methods have to be extended on a case-by-case basis. To address this challenge, a new approach to a holistic evaluation of power-to-X systems was developed based on the study's findings.

Keywords: efficiency evaluation; process evaluation; KPI; evaluation methods; power-to-X; energy systems integration

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1. Introduction

The main goal of an efficiency evaluation is to analyze a process's efficiency relative to alternative approaches and pathways. Thus, it serves as a decision-making aid for operators, developers, and customers. The primary objective of technical applications is to identify optimization capabilities and derive specific recommended actions [1–5].

Various evaluation methods have been developed over time as process efficiency has grown in importance, partly because of climate change. This has resulted in a large number of evaluation indicators, so-called benchmarks or key performance indicators (KPI), some of which are specific to certain industries, sectors, processes, or companies [1,5–8].

Since so many benchmarks exist, identifying the best possible efficiency evaluation strategy is a significant challenge. The lack of standard efficiency evaluations causes difficulties, especially when assessing integrated technologies, such as power-to-X (P2X). P2X is the collective term for all sector coupling technologies. The primary goal is to convert green electrical energy into products from different sectors such as fuels (mobility), chemical feedstocks such as hydrogen, methane, or methanol, as well as alternative energy sources for the flexible conversion of renewable energy into heat and electricity. P2X, thus, offers the potential to decarbonize even those sectors that cannot be electrified.

P2X offers a variety of utilization paths that are not comparable with each other based on existing sector-specific evaluation indicators, and thus, can hardly be evaluated comprehensively. Based on existing indicators, the efficiency of biological hydrogen production, for example, cannot be compared with the efficiency of water electrolysis, even though both processes result in the same product. For this reason, P2X is very versatile, and individual processes vary in complexity in terms of implementation and evaluation.

Various review articles on efficiency assessment already provide an overview of the multitude of existing methods and metrics. For example, M. Colla et al. [5] compare different efficiency assessment methods for energy projects. P. Wenzel et al. [9] focus on efficiency assessment in power plant engineering, specifically cooling towers. E. Domínguez et al. [2] identify different key performance indicators and provide an important approach for classification. In this paper, we summarize the results of previous review articles without setting a direct limit of applicability. In contrast to existing papers, this article does not limit its application to the energy or management sectors, and thus, includes physical, ecological, and economic indicators.

This literature review examines performance indicators and benchmarks' past and present status. The benchmarks are classified and exploited regarding their applicability and significance for different phases and goals of the efficiency evaluation. The suitability of the identified benchmarks and indicators for a comprehensive assessment of P2X systems is determined.

In the Section 1, a systematic literature review was conducted. The Section 2 contains a detailed description of the libraries, search terms, and criteria used. A list of all key figures identified during the research is provided. Section 3 defines the criteria for evaluating the suitability of the identified methods and benchmarks for evaluating P2X systems. A scoring system is defined for the evaluation of the metrics to verify the suitability of the respective metrics in a transparent and comprehensible manner. Based on these criteria, the evaluation of the metrics is carried out in Section 4 with the help of an evaluation matrix. For this purpose, three different levels are defined, depending on the objective of the efficiency evaluation, in which the criteria are weighted according to the evaluation objective. In addition, uncertainties and the transferability of the method used for other efficiency assessment objectives are addressed. Section 5 presents the evaluation results in a heat map showing the most appropriate metrics for each level. The basics of the most appropriate efficiency evaluation methods are summarized in Section 6. In addition, the results and uncertainties of the evaluation are discussed. The shortcomings and interactions of different assessment approaches are discussed, and a possible approach for a holistic assessment is proposed.

2. Materials and Methods

A systematic literature review was conducted to provide a comprehensive overview of the current status of evaluation methods and indicators.

2.1. Keywords and Bibliography

The keywords were selected based on the research task and validated during the review of the search results. Their relevance to the intended purpose was considered. Keywords that predominantly led to articles that compared different technologies' efficiency based on a defined metric (e.g., the addition of "power-to-X" or "energy systems integration") were eliminated based on the exclusion criteria.

German translations and, where necessary, synonyms of English keywords were also used. The following set of keywords was employed for the search:

- Effizienz AND Kennzahl
- efficiency AND KPI OR key performance indicator

- Effizienz AND benchmark
- efficiency AND benchmark
- efficiency AND evaluation AND method
- efficiency AND evaluation AND tool

The keyword combinations were selected to include the respective tags as an "and" function. Since the syntax for this function varies from database to database, it was modified accordingly.

Since there were no restrictions on the considered sectors, thematic classifications (e.g., chemical engineering) were not applied. This yielded over two million search results from the SpringerLink and ScienceDirect databases, far more than could be examined in a single review.

The search was limited, however, to reviewing articles in the ScienceDirect and SpringerLink databases to provide a comprehensive overview of established evaluation methods. The filter "Review Article" was applied to ScienceDirect for this purpose. The term search was limited to title, abstract, and keywords only. The search in the SpringerLink database specified that an article's heading or keywords had to contain the term "review". It was, thus, possible to ensure that KPIs, which already have such considerable relevance that they have been listed or investigated in the form of reviews, were included in this overview.

To exclude approaches unsuited for the technical evaluation of the efficiency of P2X processes, only the following categories were searched in the SpringerLink database:

- Engineering
- Life Sciences
- Chemistry
- Environment
- Earth Sciences
- Physics
- Economics
- Energy

Categories such as medicine and public health and psychology and philosophy were therefore not searched in the database. No other filters were applied to the ScienceDirect database.

Using the aforementioned search settings, 15,077 results were obtained from 23 April 2022 to 6 August 2022, which were then saved and evaluated locally based on the inclusion and exclusion criteria.

2.2. Inclusion and Exclusion Criteria

Based on the keyword search, those hits were considered to contain reviews on evaluation methods and KPIs in general, or present novel KPIs.

Papers that reviewed different processes' efficiency using a single method or indicator or presented methods inapplicable to technical P2X processes judging from the abstract (e.g., health application indicators) were excluded.

2.3. Analysis of the Review Articles

The 15,077 results obtained from the keyword search were analyzed based on the inclusion and exclusion criteria as pictured in the flowchart in Figure 1. Once the direct hits had been reviewed, a forward-backward investigation was conducted to identify potentially relevant literature references in the articles examined. The analysis of the resulting set and the title, abstract, and full-text review procedure was repeated, creating a loop that was iterated a total of four times.

The search delivered a final set of sixty-five articles. Forty-eight of these articles are literature reviews or critical reviews. Seventeen other articles present the application of defined indicators without being based on a review.

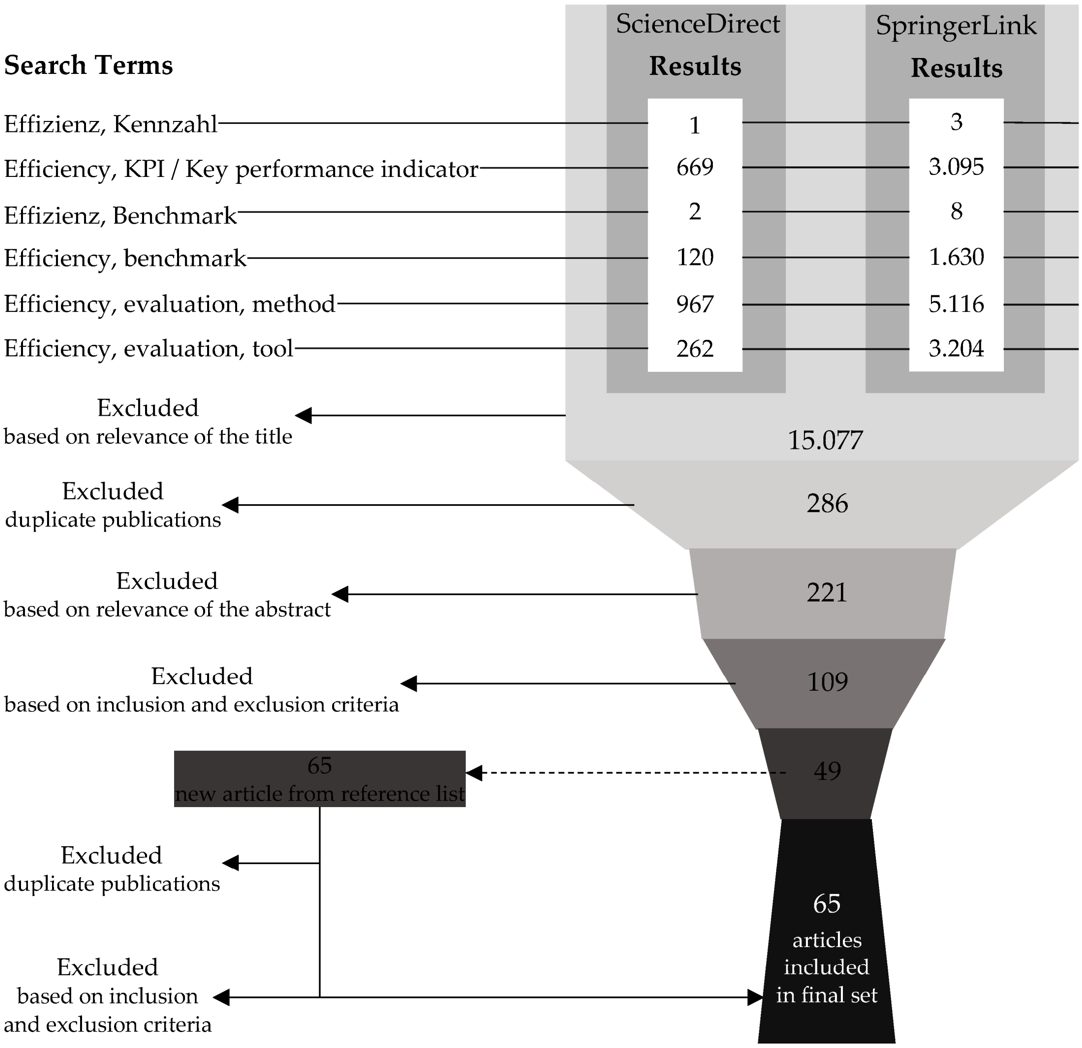

Figure 1. Methodology of the systematic literature search on review articles on efficiency evaluation and indicators.

2.4. Summary of Findings

The systematic literature search identified a total of 65 particularly relevant review articles on various energy assessment approaches. Figure 2 shows the percentage of the number of articles in the main journals. Journals from which a single article was considered are summarized under "Others" and include the following journals:

- Advances in Biochemical Engineering/Biotechnology
- Agricultural Water Management
- Chemical Engineering and Processing
- International Journal of Life Cycle Assessment
- Journal of Global Entrepreneurship Research
- Journal of Computer Standards and Interfaces
- Journal of Energy Storage
- Journal of Productivity Analysis
- Meditari Accountancy Research
- Water Ressources and Industry

The review articles identified by the systematic literature search are presented in Table 1, specifying the authors, the specific field of indicator application reviewed, the year of publication, and the type of review conducted.

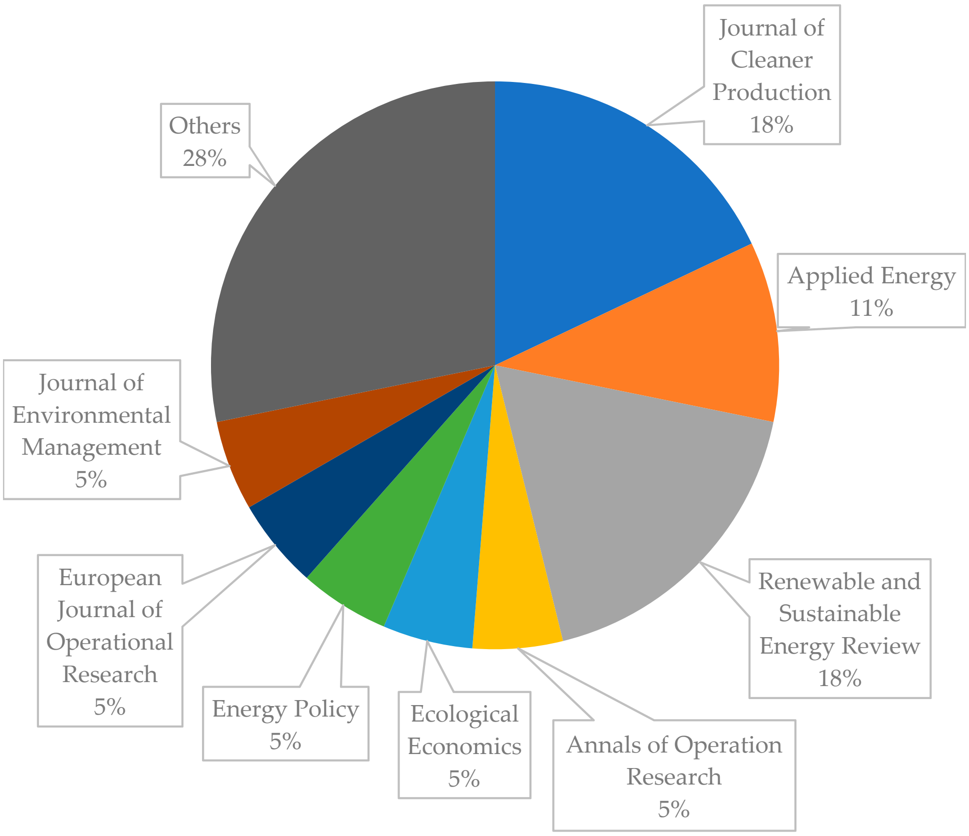

Figure 2. Overview of the relative number of relevant articles in different journals.

Table 1. Listing of review papers identified and examined in the research, sorted by publication date.

Field of Application	Type	Year	Authors
Energy systems	Literature	2022	P. Wenzel et al. [9]
Farming sustainability	Critical	2021	P. Chopin et al. [10]
Energy systems	Literature	2021	T. E. T. Dantas et al. [11]
Technical performance	Critical	2021	H. Dyckhoff et al. [12]
Sustainability	Critical	2021	G. K. Amoako et al. [13]
Energy systems	Literature	2021	F. Kullmann et al. [14]
Building	Literature	2021	S. Su et al. [15]
industrial biotechnology	Critical	2020	M. Fröhling et al. [1]
KPIs in general	Critical	2020	M. Colla et al. [5]
Road infrastructures	Literature	2020	G. B. Suprayoga et al. [16]
Isogeometric analysis	Critical	2020	J. Gao et al. [17]
Building	Critical	2019	I. H. Denwigwe et al. [7]
Production	Literature	2019	R. Menghi et al. [8]
Water consumption	Literature	2019	J. Willet et al. [18]
Energy systems	Critical	2019	P. Tallapragada et al. [19]
KPIs in general	Literature	2018	E. Domínguez et al. [2]
Sustainable energy systems	Literature	2018	D.S. Kourkoumpas et al. [20]
Green supply chains	Critical	2018	A. Banasik et al. [21]
Social and socioeconomic impacts	Literature	2018	S. Sureau et al. [22]
Sustainable energy systems	Literature	2017	M. Martín-Gamboa et al. [23]
High energy consuming industry	Critical	2017	M.J. Li et al. [24]
Water consumption	Critical	2017	H. Pereira et al. [4]
Process industries	Literature	2017	H. Pikhola et al. [25]
Energy systems	Literature	2017	T. Horschig et al. [26]
Energy systems	Critical	2017	V. Andiappan [27]

Table 1. *Cont.*

Field of Application	Type	Year	Authors
Building	Critical	2016	A. Kylili et al. [28]
KPIs in general	Critical	2016	K. Letrache et al. [29]
Sustainable energy systems	Literature	2016	E. Strantzali et al. [30]
Process industries	Critical	2016	B. K. Kanabar et al. [31]
Sustainability	Critical	2015	G. Harangozo et al. [3]
Sustainability	Literature	2015	K. Angelakoglou et al. [32]
Sustainability	Critical	2015	K. H. Dakpo et al. [33]
Forest management	Critical	2015	B. Uhde et al. [34]
Water consumption	Literature	2014	M.R.N. Vilanova et al. [35]
Energy systems	Literature	2014	E. Santoyo-Castelazo et al. [36]
Sustainability	Critical	2014	C. Song et al. [37]
Process industries	Critical	2014	Z. Yingjie [38]
Sustainability	Critical	2013	F. M. Johnson et al. [39]
Energy systems	Critical	2013	M. R. Rosen [40]
Sustainability	Critical	2012	A. Gasparatos et al. [41]
Farming sustainability	Critical	2012	T. Lebacq et al. [42]
Building	Critical	2011	W. Chung [43]
Sustainability	Critical	2010	A. Gasparatos [44]
Sustainability	Critical	2007	B. Ness et al. [45]
Water consumption	Critical	2007	S. Hajkowicz et al. [46]
Sustainability	Critical	2004	G. Finnveden et al. [47]
Process industries	Critical	1997	G. J. M. Phylipsen et al. [48]
Sustainability	Literature	1996	D. Tyteca [49]
Technical performance	Literature	1995	A. Neely et al. [50]

2.5. Further Research

The review search identified well-established efficiency evaluation methods and indicators examined in several review papers.

Additional efficiency evaluation tools discovered by the authors at conferences and other sources (e.g., social networks such as ResearchGate) were included to complete the overview of existing evaluation methods. Due to the aforementioned high number of search results, these methods are not based on a systematic review. Therefore, the methods identified from this are included in the comprehensive overview and indicated by a gray color.

2.6. Identified Efficiency Evaluation Indicators

Table 2 lists all metrics and evaluation methods identified by the systematic literature review and further work that meets the defined inclusion criteria.

For initial consideration, these were classified into physical (blue), environmental (green), and economic (red) metrics and approaches, referencing Colla et al. (2020) [5].

Physical indicators provide information on the net energy yield of the evaluated process. They can express absolute values (e.g., the total energy provided by the process), relative values (e.g., the ratio of the energy supplied to the converted energy), or time-related values (e.g., the energy payback period).

Environmental or sustainability indicators deliver information on a process's impact on the environment (soil, water, atmosphere, climate, and natural resources). They quantify an implemented process's impact on ecosystems in terms of greenhouse gas emissions or the demand for resources or land used.

Economic indicators include parameters of the process evaluated, such as costs, revenues, service charges, and discount rates. These indicators chiefly differ in their mathematical expression (e.g., rate, ratio, period, or difference).

Table 2. Identified efficiency evaluation indicators (nomenclature, subdivided into ecological—green, economic—red, and physical—blue, grey fond color indicates they have been identified in Section 2.5).

Abbreviation	Method/Indicator	Classification	
AE	Allocative efficiency	economic	[4]
BN	Bereitstellungsnutzungsgrad (deployment rate)	physical	[51]
BAT	Best available technology	physical	[48,52]
BPM	Best practical means	physical	[48]
BPO	Best practice observed	physical	[48]
CFac	Capacity factor	physical	[19]
CF	Carbon footprint	environmental	[3,53]
CBA	Cost-benefit analysis	economic	[30,44,47]
CRR	Cost recovery ratio	economic	[19]
CED	Cumulated energy demand	physical	[19,20,51,54]
DEA	Data envelope analysis	physical economic	[43,49,55–57]
DA	Drittmengenabgrenzung (third party delamination)	economic	[58]
EA	Exergy analysis	physical	[31,40]
EF	Environmental footprint	environmental	[47]
EE	Economic efficiency	environmental	[4]
EE-I	EE index	environmental	[37,59]
EPCpC	Electric power consumption per capita	economic	[19]
EEM	Embodied energy of materials	physical	[20]
EAG	Energieautarkiegrad (degree of energy self-sufficiency)	physical	[60]
ELK	Energieleistungskennzahl (energy performance indicator)	physical	[61]
EEG	Energy efficiency gap	physical	[62]
EPR	Energy payback ratio	physical	[19,54]
EPBT	Energy payback time	physical	[5,20]
EPBT	Energy payback time period	physical	[5]
ERO€I	Energy returned on (energy) invested	physical	[5]
EnV	Environmental footprint	environmental	[3]
EIA	Environmental impact assessment	environmental	[44,47]
EPD	Environmental product declaration	environmental	[7]
EEIO	Environmental-extended input-output analysis	environmental	[7]
EEE	Equipment energy effectiveness	physical	[63]
GPI	Genuine progress indicator (Wirtschaftsindikator)	environmental	[3]
GWP	Global warming potential	environmental	[20]
GGA	Greenhouse gas accounting	environmental	[7]
GER	Gross energy requirement	physical	[20]
GPER	Gross primary energy requirement	physical	[5]
GG	Gütegrad (efficiency rating)	physical	[64]
HPI	Happy planet index	environmental	[3]
HIC	Hierarchal indicator comparison	environmental	[37]
HDI	Human development index	environmental	[3]
ISEW	Index of sustainable economic welfare	environmental	[3]
IOA	Input-output analysis	physical	[47]
ITCE	Irrigation water technical cost efficiency	economic	[4]
IWUE	Irrigation water use efficiency	economic	[4]
IW	Isentroper wirkungsgrad (isentropic efficiency)	physical	[65]
LACE	Levelized avoided cost of electricity	economic	[5]
LCOE	Levelized cost of electricity	economic	[5]
LCOH	Levelized cost of heat	economic	[5]
LCA[1]	Life cycle analysis	environmental	[1,5,7,20,23,30,36,47,49,66,67]
LC	Life cycle approaches (LCA, LCSA, DLCA, etc.)	environmental	[15,22,23]

Table 2. *Cont.*

Abbreviation	Method/Indicator	Classification	
LF	Load factor	physical	[19]
MFA	Material flow analysis	physical	[14,47]
MCDA	Multiple-criteria decision analysis (In this consideration, different approaches of the method were summarized.)	environmental	[12,21,23,29,30,34,36,68]
NER	Net energy ratio	physical	[54]
NEY	Net energy yield	physical	[5]
OECD	Environmental performance reviews	environmental	[3]
OR	Operating ratio	physical	[19]
OEO	Operational energy optimum	physical	[69]
OLS	Ordinary least square	environmental	[43]
OEEI	Overall equipment efficiency indicator	environmental	[70]
OTE	Overall technical efficiency	physical	[4]
PC	Pius-Check	environmental	[71]
PEO	Plant energy optimum	physical	[69]
PhO	Physikalisches Optimum (physical optimum)	physical	[72]
PPI	Pollution performance index	environmental	[49]
PBN	Potenzielles Best-Niveau (potential best level)	physical	[73]
PCA	Principal component analysis	physical	[5,74]
PTE	Pure technical efficiency	physical	[4]
REC	Resource efficiency cockpit	physical environmental	[6]
REF	Resource efficiency flowchart	physical environmental	[6]
SIC	Simple indicator comparison	environmental	[37]
SPB	Simple payback period	economic	[5]
SEbP	Spezifischer Energieverbrauch des besten Produktionsprozesses (Best in Class)	physical	[75]
SESdT	Spezifischer Energieverbrauch nach dem SdT (Best according to State of the Art)	physical	[75]
SFA	Stochastic frontier analysis	physical economic	[37,43]
SEA	Strategic environmental assessment	environmental	[44]
SEI	Subjektiver existierender Idealzustand (Subjectively Existing Ideal State)	physical	[73]
SEE	System Energy Efficiency	physical	[5,76]
SEEA	System of Economic and Environmental Accounting	economic environmental	[47]
TSE	Taylor Series Expansion	environmental	[37]
TE	Technical Efficiency	physical	[4]
TEff	Teileffizienz (Shared Efficiency)	physical	[64]
TEO	Theoretical Energy Optimum	physical	[69]
TbEM	Theoretisch berechneter Energie und Materialeinsatz (Theoretically Calculated Energy and Material Input)	physical	[73]
TW	Thermischer Wirkungsgrad (Thermal Efficiency)	physical	[77,78]
TFEE	Total-factor energy efficiency	physical	[79]
TD	Trend Decomposition	physical	[70]
WF	Water Footprint	environmental	[3,53]
WUE	Water Use Efficiency	environmental	[4]

2.7. Critical Evaluation of the Themethodological Approach of the Systematic Literature Review

The systematic literature search was designed to be as transparent as possible in order for the study to be reproducible according to scientific standards. Of course, the selection of libraries, keywords, and inclusion and exclusion criteria directly influenced the results of this search. A change in the search criteria would probably have resulted in a different set of articles being considered.

Since a machine- or software-assisted evaluation would not have been functional, the search was limited to the two most critical online libraries. Therefore, there is no claim to the completeness of this article.

The documentation in Sections 2.1–2.6 ensures that the analysis is transparent and reproducible.

The review papers identified provide an excellent basis for highlighting the large number of existing evaluation methods and KPIs and for comparing them with one another.

3. Classification Criteria for Efficiency Evaluation Methods and Benchmarks Applied to Power-to-X Processes

To evaluate the efficiency assessment approaches identified during the literature review, the authors defined several criteria. The following criteria based on Angelakoglou et al. (2015) [32], Colla et al. (2020) [5], and Menghi et al. (2019) [8] were considered in the overall review:

3.1. Resources

Since an evaluation of energy efficiency alone is often insufficient for a comprehensive assessment of P2X processes in which energy conversion (often into material resources) plays a significant role, material resources must be included in addition to electricity and heat. Other than the possibility of defining a separate indicator for each of the considered resources (e.g., energy efficiency, water use efficiency), the cross-resource representation through the formation of technically comprehensible and invariable equivalents is particularly important.

3.2. Identification of Measures for Improvement

A comprehensive evaluation of P2X processes should focus on more than the current state. The capability to optimize a process must be determined based on an evaluation indicator, and it should be possible to derive recommended actions to improve process efficiency. Moreover, the defined optimum should be as independent of the state of the art as possible to avoid constantly adjusting the indicator as the state-of-the-art technology evolves. Recommended actions to improve a process can only be derived when the process evaluation is based on a detailed process model that maps process-specific properties beyond the trial balance.

3.3. Time's Significance in Efficiency Evaluations

Time usually plays a rather subordinate role in the development of KPIs. A comprehensive evaluation of P2X processes, however, requires indicators that can be measured at a certain point in time and over a certain period. This ensures that different process stages (e.g., commissioning) can be considered separately. Since most methods do not provide an explicit distinction, three criteria have been developed for this category. If a KPI can be determined at a defined point in time (3.1) and over a specified period (3.2), criterion 3.3 is essential for ensuring transparent differentiation.

3.4. Applicability to Power-to-X

This study aims to identify indicators that can be used for a comprehensive evaluation of complex P2X processes. Although the exclusion criteria were applied in the initial review to exclude indicators not applicable to P2X, cross-sector applicability and transferability criteria were examined more closely for the remaining indicators.

3.5. Ease of Use

Most users of efficiency evaluation indicators apply the most practical and cost-effective method. Although oversimplified methods do not adequately reflect a process's efficiency, overly complex methods are rarely used in industry. Evaluation methods and resulting indicators should therefore encompass different levels of application so that they can be used in both smaller and larger companies. Guidelines, supporting tools, and software effectively increase the applicability and usability of methods and metrics.

4. Analysis of the Identified Indicators and Methods

The analysis of all identified physical, economic, and environmental evaluation indicators is based on the yes/no criteria presented in Table 3.

Table 3. Criteria and relevant questions, which serve as the basis for evaluating the application of the analyzed metrics to power-to-X processes.

Criteria Category and Relevant Questions	**Checklist**
1. Resources	
1.1. Can different resources (e.g., energy, land area, material resources) be taken into account in the process evaluation based on the method in question?	✓/✗
1.2. Can the formation of equivalents represent the efficiency evaluation of different resources?	✓/✗
1.3. Are the defined equivalents ultimate (i.e., equivalents are independent of economy and state of technology)?	✓/✗
2. Improvement Measure Identification	
2.1. Is the indicator based on an idealized reference process (e.g., state of technology or physically reversible limit case)?	✓/✗
2.2. Is the reference process on which calculations are based independently of the state of technology?	✓/✗
2.3. Can a feasible optimization potential of the evaluated process be derived from the reference process?	✓/✗
2.4. Can the indicator be used to determine whether performing the evaluated process generally makes sense?	✓/✗
2.5. Can specific recommended actions be derived from the indicator?	✓/✗
3. Time's Significance in Efficiency Evaluation	
3.1. Can the KPI be measured at a defined time?	✓/✗
3.2. Can the KPI be measured over a specific period?	✓/✗
3.3. Is there a precise distinction between the two values?	✓/✗
4. Applicability to Power-to-X	
4.1. Is it possible to measure the KPI across sectors?	✓/✗
4.2. Do the KPIs retain their comparability across sectors?	✓/✗
5. Ease of Use	
5.1. Can non-expert users understand and develop the models on which the evaluation is based?	✓/✗
5.2. Can non-experts apply and interpret the underlying models?	✓/✗
5.3. Are there clear guidelines for implementation in connection with the indicators?	✓/✗
5.4. Are there supporting tools or software for implementation?	✓/✗

A score of one was assigned to each "yes" answer to the yes/no criteria questions.

The respective number of questions per criterion category results in a ranking of the categories. This was adjusted based on a utility analysis. A score was assigned to each yes/no criterion, resulting in a weighting factor. According to the weighting factors defined in Table 4, each metric examined was rated on a scale of 0–25, with the best method identified by the highest score. Of course, an individual adjustment of the criteria weighting is possible for the reader, e.g., on the basis of a utility value analysis.

The respective user decides which evaluation approach is selected. It depends on the objective pursued by the efficiency evaluation. In general, there are three evaluation levels, depending on the objective of the efficiency evaluation to be performed.

4.1. Levels of Efficiency Evaluation

The objective of the first level of efficiency evaluation is to identify inefficient processes, process steps, and process sequences. For this evaluation step, a purely balance sheet-based consideration is usually sufficient. Fundamental decisions, such as a purchase decision or a decision to improve a specific process step or replace an inefficient component, can be made based on this initial evaluation.

Table 4. Weighting factors for each of the defined yes/no criteria for the overall evaluation of indicators and the evaluation indicator's applicability to levels 1, 2, and 3 of efficiency evaluation.

		Resources			Improvement Actions					Time			Applicability			Ease of Use			
Criteria		**1.1**	**1.2**	**1.3**	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**3.1**	**3.2**	**3.3**	**4.1**	**4.2**	**4.3**	**5.1**	**5.2**	**5.3**	**5.4**
Level 1	Factor	3	2	2	0	0	0	5	0	0	3	0	2	2	1	1	2	1	1
Level 2	Factor	2	2	2	0	0	0	0	0	10	2	1	2	2	2	0	0	0	0
Level 3	Factor	1	2	2	0	0	0	0	20	0	0	0	0	0	0	0	0	0	0
Total	Factor	1	2	2	1	1	1	1	1	2	2	1	2	2	1	1	2	1	1

Inefficient process phases can be identified by evaluating a process's efficiency at different times. Various phases of a process step identified as inefficient at level one are examined at the second level of process evaluation to identify those with the theoretically greatest potential for optimization.

Inefficient processes and process phases can only be improved when the specific cause of inefficiency is identifiable. Especially when planning and designing new processes and process components, the transport processes within the process (e.g., mixing or mass transfer) must be considered. This can only be achieved by comparing the process to be evaluated with a complex system model, which maps the internal transport processes in addition to the overall balance.

4.2. Priority of Criteria Depending on the Evaluation Level

A point cluster was created for each of the three levels of the process evaluation. Criteria 1, 4, and 5 are given particular weight on the first level. On the second level, the evaluation must be possible over time and at a specific point in time (criterion 4). On the third level, recommendations for actions are identified. Within the framework of the study, this criterion was considered by dividing the process into the steps to be evaluated. The more detailed the consideration, the more precise the derivation of recommendations for action. The consideration should go beyond an input-output analysis and consider internal transport processes for explicit recommendations.

The criteria for the three levels of the efficiency evaluation were weighted, as shown in Table 4.

4.3. General Information on the Answering of the Yes/No Criteria

Not all yes/no criteria questions could be answered unambiguously. The procedure for borderline cases is described below.

Re Criteria 2.1:

Even if the idealized reference process results from the comparison with a reversible limit case (for example, in the case of efficiency), 2.1 was answered with "yes". The resulting reduced informative value of the indicator regarding the optimization potential of the evaluated process was covered by 2.3.

Re Criteria 2.3:

In applications that preclude direct determination of the indicator, it is often estimated by an indirect method (e.g., indirect efficiency for combustion plants). In this case, the optimization potential of the process is derivable. This can only be achieved by measuring existing losses, since a direct reference to a specific ideal reference process is not possible. However, since the efficiency is, in its original definition, a direct reference to the reversible limit case, which is not feasible in reality, the question was answered with "no" for this particular case.

Re Criteria 2.5:

It was assumed that explicit recommendations for action could only be derived if the process could be examined in sufficient detail. If the methodological procedure for determining the indicator does not include any investigation of internal transport processes, meaning that it does not go beyond a purely balance sheet-based consideration, the answer to 2.5 is " no".

Re Criteria 5.1:

The answer to this question is based on the authors' personal evaluation. It was checked whether the authors could apply the method to a specific process based on the available information after the research.

5. Results of the Classification for the Considered Categories

Each of the metrics analyzed has advantages and disadvantages for the efficiency evaluation of P2X processes. The evaluation criteria defined in Section 3 were applied to evaluate the metrics and are partially based on the experience and personal opinion of the authors (see Section 4.3). The respective score for each metric and level of evaluation is presented as a heat map in the last column of Tables 5–7. The more intense the gray of the HeatMap, the better the considered method is suited for the respective level of efficiency evaluation.

5.1. Physical Indicators

The following physical indicators were identified in the literature:

Table 5. Evaluation of physical efficiency evaluation metrics based on the yes/no criteria defined in Table 3 for the three levels of the efficiency evaluation, with a maximum score of 25 points.

Abbrev.	1.1	1.2	1.3	2.1	2.2	2.3	2.4	2.5	3.1	3.2	3.3	4.1	4.2	4.3	5.1	5.2	5.3	5.4	Total	Level 1	Level 2	Level 3
BAT	✓	✓	✗	✓	✗	✓	✓	✗	✓	✓	✗	✓	✓	✗	✓	✓	✗	✗	17	20	20	3
BN	✗	✓	✓	✓	✓	✗	✓	✗	✗	✓	✓	✗	✗	✓	✓	✓	✓	✗	15	17	9	4
BPM	✓	✓	✗	✓	✗	✓	✓	✗	✓	✓	✗	✓	✓	✗	✗	✓	✗	✗	16	19	20	3
BPO	✓	✓	✓	✓	✗	✓	✓	✗	✓	✓	✗	✓	✓	✗	✗	✓	✗	✗	18	21	22	5
CED	✗	✓	✓	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✗	✓	✓	✓	16	16	13	4
Cfac	✗	✗	✗	✓	✓	✓	✗	✗	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	12	9	7	0
DEA	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✗	✓	✗	✗	✗	✓	✓	✓	19	21	20	25
EA	✗	✓	✓	✓	✓	✓	✓	✗	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	21	21	22	4
EAG	✗	✗	✗	✓	✓	✗	✗	✗	✗	✓	✓	✓	✗	✓	✓	✓	✗	✗	11	9	7	0
EEE	✗	✗	✗	✓	✓	✗	✓	✗	✓	✓	✗	✓	✓	✓	✓	✓	✗	✗	15	16	18	0
EEG	✗	✓	✓	✓	✗	✓	✓	✗	✓	✓	✗	✓	✓	✗	✗	✓	✗	✗	17	18	20	4
EEM	✗	✓	✓	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓	✓	✗	✓	✗	✗	15	19	13	4
EnPI	✓	✓	✗	✓	✓	✗	✓	✗	✓	✓	✗	✓	✗	✗	✗	✗	✓	✗	13	16	18	3
EPBT	✗	✓	✓	✓	✓	✗	✓	✗	✗	✓	✓	✓	✓	✓	✗	✗	✓	✗	16	18	13	4
EPR	✗	✓	✓	✓	✓	✗	✓	✗	✗	✓	✓	✓	✓	✓	✗	✗	✓	✗	16	18	13	4
ERO€I	✗	✓	✓	✓	✓	✗	✓	✗	✗	✓	✓	✓	✓	✓	✗	✗	✓	✗	16	18	13	4
EUI	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✗	✗	✓	✓	✓	✓	✓	10	14	5	0
GER	✗	✓	✓	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✗	16	16	13	4
GG	✗	✗	✗	✓	✓	✗	✓	✗	✓	✓	✗	✗	✗	✓	✓	✓	✓	✗	12	13	14	0
GPER	✗	✗	✓	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✗	14	14	11	2
IOA	✓	✓	✓	✓	✓	✗	✓	✗	✗	✓	✗	✓	✓	✓	✓	✓	✓	✗	21	24	14	5
IW	✗	✓	✓	✓	✓	✗	✗	✗	✓	✓	✗	✗	✗	✓	✗	✗	✓	✗	12	9	18	4
LEED-Score	✓	✓	✗	✗	✗	✗	✓	✗	✗	✓	✓	✗	✗	✗	✗	✓	✓	✓	11	17	7	3
LF	✗	✗	✗	✓	✓	✗	✓	✗	✗	✓	✓	✗	✗	✓	✓	✓	✓	✗	11	13	5	0

Table 5. *Cont.*

Abbrev.	1.1	1.2	1.3	2.1	2.2	2.3	2.4	2.5	3.1	3.2	3.3	4.1	4.2	4.3	5.1	5.2	5.3	5.4	Total	Level 1	Level 2	Level 3
MFA	✗	✓	✓	✓	✓	✗	✓	✗	✓	✓	✗	✓	✓	✓	✓	✓	✗	✗	19	20	22	4
NER	✗	✓	✓	✓	✓	✗	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✗	19	21	13	4
NEY	✗	✓	✓	✓	✗	✗	✓	✗	✗	✓	✓	✓	✓	✗	✗	✓	✓	✓	18	21	11	4
NPI	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✗	✗	✓	✓	✓	✓	✓	10	14	5	0
OEO	✗	✓	✓	✓	✗	✓	✓	✗	✓	✓	✗	✓	✗	✗	✗	✓	✗	✗	15	16	18	4
OR	✗	✗	✗	✓	✓	✗	✓	✗	✓	✓	✗	✗	✗	✓	✓	✓	✗	✗	11	12	14	0
OTE	✗	✓	✓	✓	✗	✗	✓	✗	✗	✓	✗	✓	✗	✗	✗	✓	✓	✗	13	17	8	4
PBN	✓	✓	✓	✓	✗	✓	✓	✗	✓	✓	✗	✓	✓	✗	✗	✓	✗	✗	18	21	22	5
PC	✓	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗	✗	✓	✓	15	17	19	21
PCA	✓	✗	✗	✗	✗	✗	✓	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗	✗	8	13	16	1
PEO	✓	✓	✓	✓	✗	✓	✓	✗	✓	✓	✗	✓	✗	✗	✗	✓	✗	✗	16	19	20	5
PhO	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	24	24	25	25
REC	✓	✗	✗	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗	✗	11	13	16	1
REF	✓	✗	✗	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗	✗	11	13	16	1
RT-EE	✗	✗	✗	✓	✓	✗	✓	✗	✗	✓	✓	✗	✗	✗	✗	✓	✓	✗	9	11	3	0
SEbP	✗	✓	✓	✓	✗	✓	✓	✗	✓	✓	✗	✓	✓	✗	✗	✓	✗	✗	17	18	20	4
SEE	✗	✗	✗	✓	✓	✗	✓	✗	✓	✓	✗	✓	✓	✓	✓	✓	✗	✗	15	16	18	0
SEI	✗	✓	✓	✓	✗	✓	✓	✗	✓	✓	✗	✗	✗	✗	✓	✓	✗	✗	14	15	16	4
SESdT	✗	✓	✓	✓	✗	✓	✓	✗	✓	✓	✗	✓	✓	✗	✗	✓	✗	✗	17	18	20	4
SFA	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✗	✗	✓	✓	20	22	15	25
SIC	✓	✓	✓	✓	✗	✗	✓	✗	✓	✓	✗	✗	✗	✗	✗	✗	✓	✓	13	17	18	5
TbEM	✓	✓	✓	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓	✓	✗	✓	✗	✗	16	22	15	5
TD	✓	✓	✓	✓	✗	✓	✓	✗	✓	✓	✗	✗	✗	✗	✗	✗	✓	✗	13	16	18	5
TE	✗	✗	✗	✓	✓	✗	✓	✗	✓	✓	✗	✓	✓	✓	✓	✓	✗	✗	15	16	18	0
Teff	✓	✗	✗	✓	✓	✗	✗	✗	✓	✓	✗	✓	✓	✓	✓	✓	✓	✗	16	15	20	1
TEO	✗	✗	✗	✓	✓	✗	✓	✗	✓	✓	✗	✓	✓	✓	✗	✓	✗	✗	14	15	18	0
TSE	✗	✗	✗	✗	✗	✗	✓	✓	✗	✓	✓	✓	✓	✓	✗	✗	✓	✗	11	14	9	20
TW	✗	✓	✓	✓	✓	✗	✗	✗	✓	✓	✗	✗	✗	✓	✓	✓	✓	✗	15	12	18	4

5.2. *Environmental Indicators*

This study identified the following environmental indicators:

Table 6. Evaluation of environmental efficiency evaluation metrics based on the yes/no criteria defined in Table 3 for the three levels of the efficiency evaluation, with a maximum score of 25 points.

Abbrev.	1.1	1.2	1.3	2.1	2.2	2.3	2.4	2.5	3.1	3.2	3.3	4.1	4.2	4.3	5.1	5.2	5.3	5.4	Total	Level 1	Level 2	Level 3
CF	✗	✓	✓	✗	✗	✗	✗	✗	✓	✗	✓	✓	✓	✓	✗	✓	✓	✓	16	16	13	4
EF	✗	✓	✓	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✗	✓	✓	✓	16	16	13	4
EE	✓	✓	✗	✓	✗	✓	✓	✗	✓	✗	✓	✓	✗	✗	✓	✓	✓	✓	16	17	17	3
EE-I	✗	✓	✓	✓	✗	✓	✓	✗	✓	✓	✗	✓	✗	✗	✓	✓	✓	✓	18	19	18	4
EnV	✗	✓	✓	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✗	✓	✓	✓	16	16	13	4
EIA	✓	✓	✓	✗	✗	✗	✓	✗	✗	✓	✓	✓	✗	✗	✗	✗	✓	✓	13	19	11	5
EPD	✓	✓	✓	✗	✗	✗	✓	✓	✗	✓	✓	✓	✗	✓	✗	✓	✓	✓	16	22	13	5
EEIO	✓	✗	✗	✓	✓	✗	✓	✗	✓	✗	✓	✓	✓	✓	✓	✓	✓	✗	4	17	9	1
GWP	✗	✓	✓	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓	✓	✗	✓	✓	✓	17	21	13	4

Table 6. *Cont.*

Abbrev.	1.1	1.2	1.3	2.1	2.2	2.3	2.4	2.5	3.1	3.2	3.3	4.1	4.2	4.3	5.1	5.2	5.3	5.4	Total	Level 1	Level 2	Level 3
GGA	✗	✓	✓	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓	✓	✗	✗	✓	✓	15	19	13	4
HPI	✓	✓	✗	✗	✗	✗	✗	✗	✗	✓	✓	✗	✗	✓	✓	✓	✓	✓	12	14	9	3
HDI	✓	✓	✗	✗	✗	✗	✗	✗	✗	✓	✓	✗	✗	✓	✓	✓	✓	✓	12	14	9	3
ISEW	✓	✓	✗	✗	✗	✗	✗	✗	✗	✓	✓	✗	✗	✓	✓	✓	✓	✓	12	14	9	3
LCA	✓	✓	✓	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	19	25	15	5
MCDA	✓	✓	✗	✗	✗	✗	✓	✓	✗	✓	✓	✓	✗	✗	✓	✓	✓	✗	14	19	9	23
OLS	✗	✗	✗	✓	✓	✗	✓	✗	✗	✓	✓	✓	✗	✗	✗	✗	✓	✓	10	12	5	0
PPI	✗	✗	✗	✓	✗	✓	✓	✗	✗	✓	✓	✓	✓	✗	✗	✓	✓	✗	13	15	7	0
SEA	✓	✓	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✗	✗	✓	✓	✗	13	15	11	3
SEI	✗	✓	✓	✓	✗	✓	✓	✗	✓	✓	✗	✗	✗	✗	✓	✓	✗	✗	14	15	16	4
SEEA	✗	✓	✓	✗	✗	✗	✓	✗	✗	✓	✓	✗	✗	✗	✓	✓	✓	✓	16	20	11	4
WF	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✗	13	17	9	0
WUE	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✗	13	17	9	0

5.3. *Economic Indicators*

This study identified the following economic indicators:

Table 7. Evaluation of economic efficiency evaluation metrics based on the yes/no criteria defined in Table 3 for the three levels of the efficiency evaluation, with a maximum score of 25 points.

Abbrev.	1.1	1.2	1.3	2.1	2.2	2.3	2.4	2.5	3.1	3.2	3.3	4.1	4.2	4.3	5.1	5.2	5.3	5.4	Total	Phase 1	Phase 2	Phase 3
AE	✗	✓	✗	✗	✗	✗	✓	✗	✓	✗	✗	✓	✗	✗	✓	✓	✓	✓	12	14	14	2
CBA	✗	✓	✗	✓	✗	✗	✓	✗	✗	✓	✓	✓	✗	✗	✓	✓	✓	✗	13	16	7	2
CRR	✗	✓	✗	✓	✗	✗	✓	✗	✗	✓	✓	✓	✗	✗	✓	✓	✓	✗	13	16	7	2
DEA	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✗	✓	✗	✗	✗	✓	✓	✓	17	21	10	25
DA	✗	✗	✗	✓	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✓	✓	✓	✓	9	8	3	0
EpCpC	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✗	✓	✓	✓	✓	✓	11	11	7	0
GPI	✗	✓	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✗	✗	✗	✗	✗	✗	7	7	7	2
ITCE	✗	✗	✗	✓	✗	✓	✓	✗	✗	✓	✓	✓	✓	✗	✗	✗	✗	✗	11	12	7	20
IWUE	✗	✗	✗	✓	✗	✓	✓	✗	✗	✓	✓	✓	✓	✗	✗	✗	✗	✗	10	12	7	0
LACE	✗	✗	✗	✓	✗	✓	✓	✗	✗	✓	✓	✓	✓	✗	✗	✗	✗	✗	10	12	7	0
LCOE	✗	✗	✗	✓	✗	✓	✓	✗	✗	✓	✓	✓	✓	✗	✓	✓	✓	✗	14	16	7	0
LCOH	✗	✗	✗	✓	✗	✓	✓	✗	✗	✓	✓	✓	✓	✗	✓	✓	✓	✗	14	16	7	0
SPB	✗	✗	✗	✗	✗	✗	✓	✗	✗	✓	✓	✓	✗	✗	✓	✓	✗	✗	9	13	5	0
SEEA	✗	✓	✓	✗	✗	✗	✓	✗	✗	✓	✓	✗	✗	✗	✗	✓	✓	✓	16	20	11	4

6. Discussion of the Research Findings

Based on the respective indicators' total scores in the tables, the authors identified methods best suited for the overall evaluation of P2X processes. They additionally identified the methods best suited for the three defined levels of process evaluation using the weighting factors described in Table 4. The compliance of the investigated evaluation methods with these specified criteria is indicated in the respective tables for each evaluation phase in points out of 25. The results are illustrated in Figure 3. It should be noted that the answers to the yes/no criteria are, in some cases, based on the subjective opinion of the authors. Especially the derivability of recommendations for actions, as well as the applicability by nonexperts, can only be scientifically proven in a few cases. In order to adapt the efficiency rating to the subjective needs of the user, the reader, according to his preferences, can adjust the weighting of the respective criteria. Furthermore, depending on the level of knowledge of the methods considered, the answers to criteria 5.1 and 5.2, in particular, should be adapted according to the user's expertise.

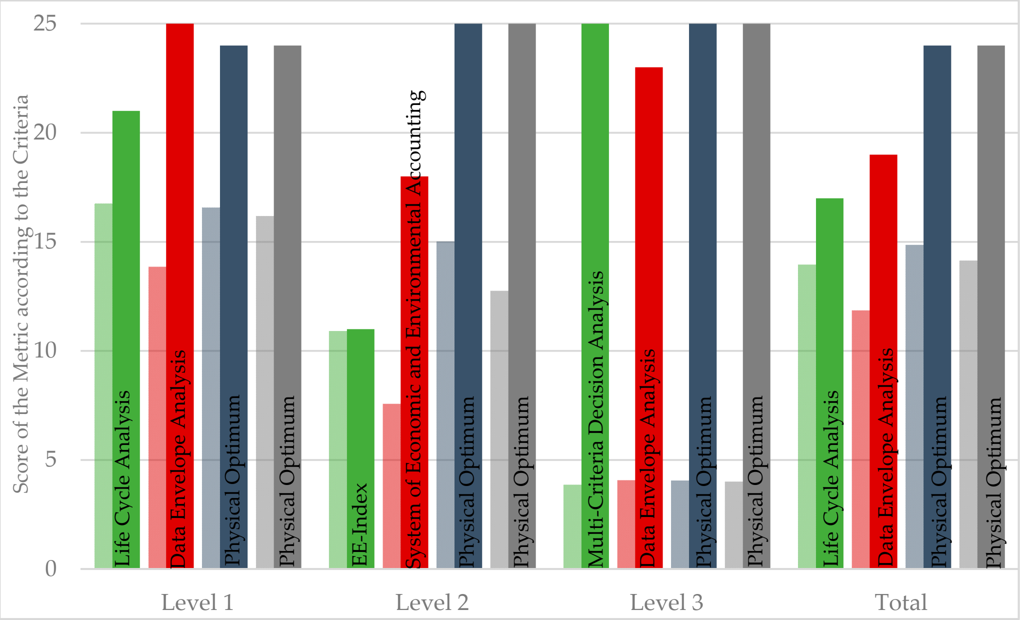

Figure 3. Illustration of the achieved score of a maximum of 25 points according to the defined criteria in each case on average and for the best metric (in each case subdivided into ecological—green, economic—red, and physical—blue).

In the following subchapter, the method that achieved the highest score in its classification (economic, environmental, and physical) is described in each case. This description focuses on the applicability and limitations of each method for P2X systems.

Existing challenges arising from this analysis are discussed, and solutions from the literature are analyzed. Furthermore, an independent solution approach for the evaluation of P2X systems is explicitly discussed.

6.1. Life Cycle Analysis

The evaluation presented in Table 6 identified life cycle analysis (LCA) as the best environmental metric for the first level of efficiency evaluation.

In life cycle assessment (LCA), the environmental impacts of products, processes, or services are systematically analyzed along their entire life cycle, "from the cradle to the grave. This includes all environmental impacts that occur during production, the use phase, and disposal, as well as the associated upstream and downstream processes.

Unlike most physical indicators, LCA refers to the complete product life cycle and can, therefore, not only evaluate the efficiency of a technical process but, above all, also estimate a product's cumulative environmental impact from manufacture to recycling. Three types of LCA can be distinguished: environmental, focused on a single product; comparative, focused on several products; and holistic, focused on economic, technical, and social factors [23].

The advantage of LCA over physical and economic indicators is that it allows for the evaluation not only of an operation (e.g., of a production line) but also of a product's entire life cycle. This is particularly important in manufacturing since it includes the resources used to construct the manufacturing facility in addition to the resources used to manufacture a product. For example, it can be revealed that the purchase of an electric car is more environmentally sensible than the purchase of a conventional vehicle with a combustion engine if the vehicle has a minimum service life [80].

6.2. Data Envelope Analysis

Economic metrics are often highly dependent on the current political and economic situation since they are responsible for price development.

With 21 out of 25 possible evaluation criteria points for the first level of an efficiency evaluation of P2X systems, the most appropriate economic evaluation method is data envelopment analysis (DEA). DEA is an efficiency analysis technique used in operations research. Although the method is intended to measure the efficiency of organizational and decision-making units, it can be applied to technical processes. The evaluated subprocesses are treated as decision-making units. The weighted sum of the input and output variables is employed to measure the efficiency value. This efficiency value indicates the distance to the efficient edge (data envelope) based on the observed inputs and outputs of a decision unit. This efficient margin is formed from the group of decision units analyzed by the DEA. From the efficiency value of a decision unit, improvement potentials can be derived directly for its management [43].

The data envelopment analysis is also suitable for the third level of efficiency evaluation if it is considered in sufficient detail. When the efficient edge of the system used in the assessment describes internal transport processes, specific causes of inefficiencies can be identified, and recommended actions can be derived based on the investigations.

Research by A. Hougaard et al. (2013), however, suggests that DEA results are not necessarily comparable across sectors and are only transferable to similar organizational and decision-making units [81].

6.3. Physical Optimum

The PhO scored best based on the defined criteria for the first level of efficiency evaluation. The physical optimum describes a reference process that is modeled based on natural laws and, thus, is supposed to define the ultimate limit of optimality.

This method of evaluation distinguishes between the so-called PhO factor (over a defined period of time) and the performance PhO factor. The PhO factor is used to complete the first level of process evaluation, while the performance PhO factor is used to identify inefficient phases of a process [82].

In perspective, the aim of the PhO method is that nonexperts can also apply it. However, especially for complex processes, modeling the physical optimum can be challenging. In many cases, there are different ways of describing and defining the physical optimum based on different physical laws for the same physical event. For this reason, a portfolio of models for the PhO of different processes is currently being developed and will be published as part of an extension of VDI 4663 [82].

6.4. Remaining Problems

The analysis of the KPIs identified during the literature research showed that a holistic evaluation of complex processes is impossible based on a single KPI or method. While environmental and economic evaluation metrics score a maximum of 19 out of 25 points in the overall evaluation, the physical optimum scores the highest with 24 out of 25 points. However, since this method is still relatively new compared to other methods, there is a need to define the modeling laws for specific processes. Otherwise, the comparability of the metric is compromised both for the same process and across different processes. The problem is being addressed by planning an extension to VDI 4663, but it has not yet been completed.

In addition, the comparability of one and the same indicator, in general, is limited by the choice of balance sheet boundaries or the consideration of time (or the neglect of this). For example, various physical indicators can be used to evaluate both a specific time in and a defined period of a process. For instance, in the case of efficiency, this distinction is achieved by the degree of utilization, which explicitly refers to a defined period of time [83]. However, depending on the area of application, the definition of efficiency may differ [84]. This may lead to inaccuracies in the evaluation, especially in the second level of efficiency evaluation.

Furthermore, a purely ecological, economic, or physical examination of a process is usually not sufficient. Economically excellent processes are often not environmentally compatible, and vice versa. Even very high efficiency in the operation of the process can result in very high acquisition costs or the handling of toxic chemicals, for example.

The identified interactions between economic, environmental, and physical efficiency are presented in Figure 4.

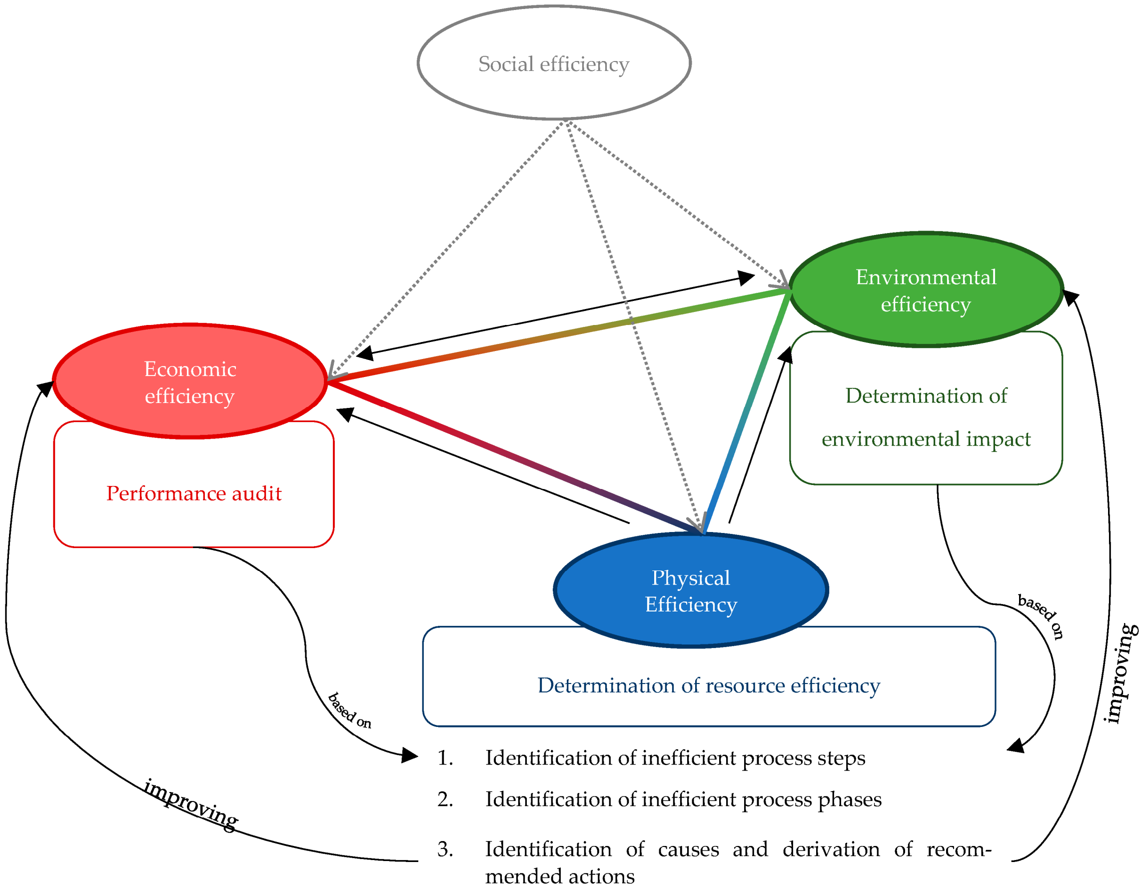

Figure 4. Interactions between economical (red), ecological (green), physical (blue), and social efficiency based on [85,86].

Social factors not analyzed here also play a role in the decision-making process based on the efficiency evaluation since they do not directly reflect the efficiency but rather the social compatibility of a process or product. Before introducing a product and within the scope of planning a technical plant, ethical factors must, of course, be analyzed.

6.5. Approaches in Literature

Some methods already address the challenges described in Section 6.6 in general, but not for P2X systems. Three of these approaches are described in the following subsections.

6.5.1. PIUS-Check

The PIUS-check is a process-oriented material flow analysis for increasing resource efficiency in manufacturing companies. The aim of the PIUS-check is to develop a catalog of economic measures to make specific processes more efficient within a manageable time frame and with a low financial investment. The PIUS-check addresses the following objectives:

- Reduce the use of raw materials
- Reduce production costs
- Minimize scrap
- Increase productivity
- Avoid emissions [87]

The PIUS-check is a consultation on energy efficiency. It is offered by various service providers and is not applicable by laymen or process operators themselves. The application can only be made to existing processes. Process selection based on the PIUS-check is not provided [88].

6.5.2. EDUAR&D

The EDUAR&D methodology, short for energy data and analysis research and development, is used to evaluate energy efficiency techniques. It is a structured search and analysis process that combines different methodological approaches for the presentation, analysis, and evaluation of the technologies. The aim is to derive recommendations for action, e.g., with regard to setting thematic priorities for future energy research within the framework of research funding and for energy policy [89].

The focus of this method is already defined in its name and is limited exclusively to research and development. However, the approach could conceivably be applied to process selection and optimization.

6.5.3. Green Chemistry Metrics

Green chemistry metrics (GCM) is a rating system that describes the principles of green chemistry through KPIs. The aim is to be able to quantify technical and ecological progress in the chemical sector.

The evaluation system allows the comparison of different chemical synthesis routes and the selection of the “greenest” process [90].

Admittedly, this evaluation system is limited to the chemical sector. However, the transfer of this approach and the development of a KPI system for P2X systems would be conceivable. Thus, ecological, economic, and social aspects could be used to select the best process or improve an existing one.

6.6. Integrated Approach for Power-to-X Systems

The examination of the researched KPIs has shown that a purely physical, ecological, or economic evaluation is not sufficient. This applies both to process selection and the improvement of existing processes.

However, based on the approaches presented in Section 6.5, a combination of different metrics would be conceivable. The choice of metrics used depends on the use case (such as GCM for the chemical sector) and the expertise of the user.

For the evaluation of P2X systems, according to the previous studies, a combination of LCA, PhO, and DEA seems particularly useful. An iterative approach could identify an intersection between the best economics and the best environmental performance. By including social aspects, this approach would allow for a holistic efficiency assessment. With a defined balance sheet boundary and a defined procedure for determining the three KPIs, comparability across different P2X processes is given. Depending on the focus of the assessment (e.g., economic feasibility or high sustainability with a research focus), weighting factors could be developed to determine an overall value.

The effects of possible process improvements can be examined through an iterative approach and the respective recalculation of the three KPIs. Based on this approach, the selection of the most suitable process in the planning of a P2X process chain would be possible. Furthermore, the holistic view enables the identification of the reasons for inefficiencies and, thus, the derivation of specific recommendations for action.

In further work by the authors, validation of this approach will be carried out using water electrolysis as an example.

7. Conclusions

This study identified various methods for evaluating physical, environmental, and economic efficiency that are fundamentally suited for evaluations of P2X processes. Considering an evaluation system based on simple yes/no criteria, these indicators were evaluated in terms of their applicability.

This study examined the literature on the evaluation of the technical efficiency of P2X processes, which is usually intended to improve a process's resource efficiency. This can only be performed by going through the three levels of efficiency evaluation.

Each method considered in this paper has its advantages and disadvantages. The selection of the evaluation method to be used for the efficiency evaluation is up to the user and largely depends on the objectives of the process evaluation. This study of environmental, economic, and physical indicators for efficiency evaluation demonstrated that the evaluation based on physical indicators is preferable for a comprehensive evaluation of P2X systems. In most cases, these indicators are used to evaluate a process's technical efficiency and identify technical optimization capabilities.

Environmental indicators, on the other hand, are often used to estimate the environmental impact of a particular production process. They are intended to make the user aware of consequences and to create ecological competition without making specific suggestions for improvement derivable [5,91].

Economic indicators are used to evaluate a process's economic efficiency and to classify processes in the market economy framework. Although a process's resource efficiency influences its economic efficiency, resource-inefficient processes may be more cost-effective in a given economic and political situation. Especially concerning the effects of the high greenhouse gas emissions of technically inefficient processes, an economic consideration should only be adopted after extensive testing and improvement of resource efficiency.

Before a process can be implemented on a large scale, its environmental and economic efficiency must be evaluated comprehensively. While a process's environmental efficiency specifies its environmental compatibility throughout its entire life cycle, its technical efficiency can be used to improve its execution. Without an examination of economic efficiency, a market introduction of the process is not economical and, therefore, not reasonable.

This study revealed that no method is fully able to cover all three levels of process evaluation at this time.

However, as part of the investigations, an approach was developed with which it is possible to carry out a holistic efficiency assessment specifically for, but not limited to, P2X processes. This approach combines ecological, economic, and physical aspects of energy efficiency and addresses all three levels of efficiency assessment equally. This can support both process design and selection as well as the improvement of an existing process.

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