A Survey on Post-Evaluation Indicator System for Multi-Energy Infrastructure Investments

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ABSTRACT With the growing concerns on the energy crisis and the strong support of policies, the development and construction of the multi-energy infrastructure are booming in the world. The post-evaluation for the multi-energy infrastructure investment projects can discover problems, giving advice for improvement, and guide the future project process management, which plays a significant role in achieving closed-loop and lean management. In this article, a comprehensive overview on the post-evaluation indicators of overall multi-energy infrastructure construction processes is illustrated. Then, the post-evaluation indicators on economic benefits are surveyed from the financial and national economic perspectives. Furthermore, the indicators to evaluate the impact on society and environment induced by the multi-energy infrastructure are thoroughly analyzed and investigated. Also, the post-evaluation indicators on the sustainability of the multi-energy infrastructure investment projects are summarized. Lastly, some challenges with great importance in the future research are presented. This review contributes to finding out the problems existing in the multi-energy infrastructure projects and analyzing the causes of the problems, which helps to guide the enterprise’s future investment direction, decision-making, and realize an accurate investment.

INDEX TERMS Multi-energy infrastructure, post-evaluation, indicator system, comprehensive evaluation.

I. INTRODUCTION

In order to handle the challenge of global climate change and reduce the utilization of fossil energy, the carbon-free is now the core content of the third era of energy transitions in the world, thus leading to the widespread use of renewable energy sources (RESs), i.e. solar, biomass, wind, and geothermal power. The appropriate energy infrastructures are needed to transform, store, and transport these RESs in one of the three basic forms: electricity, heat, and gas [1]. However, most of the existing energy infrastructures were constructed in the beginning or the middle of the last century, thus resulting in several problems and challenges. Firstly, many energy infrastructures are close to the end of their lifetime. Additionally, the further challenges are produced by continuously increasing energy demand, reorganization processes of energy industries, and growing social desire to make use of more environmentally sustainable energy sources [2]. Furthermore, the increment of interdependencies among various energy infrastructures is significant, and the development of energy conversion technologies enables the possibility of constructing multi-energy interconnection infrastructure that can integrate various energy sources [3, 4]. All these issues prompt to construct or upgrade the multi-energy infrastructures to guarantee an economical, reliable, and environmentally sustainable multi-energy supply in the long term. Many multi-energy infrastructures have been studied in [5]–[10].

The post-evaluation of a project started with the World Bank in the 1830s, and it has now been widely used in energy field [11]–[15]. The post-evaluation is a kind of technical and economic activity to analyze and sum up the purpose, execution, efficiency, investment benefits, the functions and the impacts of the project objectively and systematically when the project has been completed and run for a period of time [16]. The objectives of post-evaluation of a project can be summarized as follows: 1) To make sure whether the
project achieves intended objectives, especially, if the main benefit goal is achieved [17]; 2) To find out the causes of failures through analyses and evaluations [16]; 3) To sum up experiences and learn from the failures [18]; 4) To provide a basis for future project decisions through the timely feedback of the information produced during the process of analyses and evaluations [19]. Thus, the post-evaluation for the multi-energy infrastructure investment projects can guide the future project construction to scientifically and rationally allocate funds in the case of limited funds, thus achieving green, clean, and efficient operational objectives. At present, there are many methods for the post-evaluation, such as fuzzy comprehensive evaluation [16], attribute theory [17], analytic hierarchy process [19], comparison method [20], and so on. These methods have realized some effects in different aspects and degrees. However, due to the inherent subjectivity nature of comprehensive evaluation, it is impossible for these methods to eliminate the randomness and subjectivity of the evaluation process, the calculation speed, and results accuracy also can not be ensured by these methods [21].

The evaluation indicator system is the basis of implementing post-evaluation of the multi-energy infrastructure investment projects. The evaluation indicator system is a set of indicators that can comprehensively reflect the performance of the multi-energy infrastructure investment projects according to certain principles [20]. In order to guarantee the objectivity, fairness, accuracy, and effectiveness of evaluation results, the selection of indicators should follow the principles of completeness, scientificity, purposefulness, incompatibility, objectivity, comparability, simplicity operation, stability, and foresight [22], [23]. So far, some literatures have been published for establishing post-evaluation indicator system for the multi-energy infrastructure investment projects. The post-evaluation indicator of the project implementation process was established for power transmission and transformation (PTT) project in [19]. The indicators to evaluate the finical benefits of power grid projects were presented in [24]. The post-evaluation indicators on social environment impact and sustainability of wind power project were presented in [25] and [26] respectively. It can be observed that several aspects related to the post-evaluation indicator system for the multi-energy infrastructure have been analyzed in the literature. An extensive review paper that includes several aspects related to the post-evaluation indicator system for the multi-energy infrastructure investment projects may be of interest to readers. This article presents a comprehensive state-of-the-art literature review of the post-evaluation indicator system for the multi-energy infrastructure investments from the perspectives of the project overall construction process, economic benefits, impacts, and sustainability. The following are the major highlights of this article.

1) The post-evaluation indicators of overall multi-energy infrastructure construction processes, from the planning stage to the operation stage, are elaborated.

2) The post-evaluation indicators on economic benefits for the multi-energy infrastructure investment are thoroughly analyzed and investigated from the financial and national economic perspectives.

3) The indicators to evaluate the impact on society and environment induced by the multi-energy infrastructure construction, as well as the post-evaluation indicators on sustainability are summarized.

4) The main challenging problems of establishing a comprehensive post-evaluation indicator system for the multi-energy infrastructure construction are explored.

The remainder of this work is organized as follows: Section II provides a comprehensive overview on the post-evaluation indicators of overall multi-energy infrastructure construction processes. The post-evaluation indicators on economic benefits for the multi-energy infrastructure investment are surveyed in Section III. In Section IV, the indicators to evaluate the impact on society and environment induced by the multi-energy infrastructure construction are thoroughly analyzed and investigated. The post-evaluation indicators on the sustainability of the multi-energy infrastructure investment projects are summarized in Section V. Section VI discusses several challenging problems for the future research of post-evaluation indicator system. Finally, the conclusion is presented in Section VII.

II. POST-EVALUATION INDICATORS OF OVERALL CONSTRUCTION PROCESSES

A. EVALUATION INDICATORS AT THE PLANNING STAGE

The planning stage is the initial stage of the multi-energy infrastructure investment projects. The feedback on the basis between the project operation and the anticipated decision-making is given through the post-evaluation at the planning stage, thus measuring the project management level, strengthening the subsequent decision-making, improving investment benefits, and optimizing the operation process [27]. Generally, the evaluation indicator system at the planning stage is established from the perspectives of decision-making, engineering design, bidding and contract management, and implementation preparation. The evaluation indicators on the decision-making of the infrastructure projects of the electricity, heat and gas energies are to evaluate the project approval process and the appropriate documents [17], [19]. The evaluation indicators on the engineering design of the multi-energy infrastructure projects aim to evaluate the rationality of preliminary design, the progress of preliminary design, the progress of construction drawings and the quality of construction drawings [27]. The evaluation indicators on the bidding and contract management are to check the lawfulness and integrity of the bidding and contract process. The evaluation indicators on the implementation preparation concentrate on the integrity of construction preparation conditions [18]. In [6], the worst case of the electricity and natural gas infrastructures construction were considered in the engineering design to improve the robust of the infrastructure. In [28] and [29], the evaluation indicators about feasibility, bidding procedure, and construction drawings at the planning stage were considered for
TABLE 1. The post-evaluation indicator system at the planning stage.

| Evaluation content       | Evaluation indicators                                                      |
|--------------------------|---------------------------------------------------------------------------|
| Decision-making          | • Project objectives and market                                            |
|                          | • Technology maturity                                                     |
|                          | • Feasibility evaluation                                                  |
|                          | • Construction necessity                                                  |
| Engineering design       | • The rationality of preliminary design                                   |
|                          | • The progress of preliminary design                                       |
|                          | • The progress of construction drawings                                   |
|                          | • The quality of construction drawings                                    |
| Bidding and contract management | • Bidding design management                                               |
|                          | • Construction bidding evaluation                                          |
|                          | • Supervision bidding evaluation                                           |
|                          | • Contract management                                                     |
|                          | • Investment estimation                                                   |
|                          | • Investment payback period                                               |
| Implementation preparation | • Completeness of the construction design outline                         |
|                          | • The admittance of construction units                                    |
|                          | • Review meeting of working drawings                                      |
|                          | • The admittance of supervision units                                     |
|                          | • Resources and construction conditions                                    |

The post-evaluation indicator system at the planning stage includes project objectives and market, technology maturity, feasibility evaluation, and construction necessity. It also considers the rationality of preliminary design, the progress of preliminary design, the progress of construction drawings, and the quality of construction drawings. For bidding and contract management, it includes bidding design management, construction bidding evaluation, supervision bidding evaluation, contract management, investment estimation, and investment payback period. Implementation preparation considers completeness of the construction design outline, admittance of construction units, review meeting of working drawings, admittance of supervision units, and resources and construction conditions.

TABLE 2. The post-evaluation indicator system at the implementation stage.

| Evaluation content      | Evaluation indicators                                |
|-------------------------|-----------------------------------------------------|
| Construction process    | • Progress management                               |
|                          | • Quality management                                |
|                          | • Safety management                                 |
|                          | • Investment management                             |
|                          | • Supervision management                            |
| Commissioning process   | • Qualification of debug unit                       |
|                          | • Debugging program                                 |
|                          | • Related criteria implementation                   |
| Trial operation period  | • Trial operation preparation                       |
|                          | • Trial operation record                            |
|                          | • Pass rate of the trial operation                  |

TABLE 3. The post-evaluation indicator system at the operation stage.

| Evaluation content      | Evaluation indicators                                |
|-------------------------|-----------------------------------------------------|
| Operation performance   | • Annual energy production capacity                  |
|                          | • Energy consumption of infrastructure               |
|                          | • Operational reliability                           |
|                          | • Use efficiency of energy                           |
|                          | • Annual operation time                              |
| Scientific technology   | • Applicability of technology                        |
|                          | • Technical economy                                 |
|                          | • Technical progress                                |
|                          | • Possibility of technical transformed               |
| Management System       | • Organization                                      |
|                          | • Responsibilities                                  |
|                          | • Personnel quality                                 |
|                          | • Management of maintenance cost                    |

The post-evaluation indicator system at the implementation stage includes construction process, commissioning process, trial operation period, and operation. It focuses on progress management, quality management, safety management, investment management, supervision management, qualification of debug unit, debugging program, related criteria implementation, trial operation preparation, trial operation record, and pass rate of the trial operation. At the operation stage, the evaluation indicators include annual energy production capacity, energy consumption of infrastructure, operational reliability, use efficiency of energy, annual operation time, applicability of technology, technical economy, technical progress, and possibility of technical transformed. The management system considers organization, responsibilities, personnel quality, and management of maintenance cost.

B. EVALUATION INDICATORS AT THE IMPLEMENTATION STAGE

The post-evaluation for the multi-energy infrastructure investment projects at the implementation stage refers to the evaluation of the period from the start of the project construction to the completion of the project construction [31]. Generally, the evaluation indicators at the implementation stage focus on the construction process, commissioning process, and trial operation period [28]. The progress, quality, safety, investment, and supervision management were considered in the post-evaluation for wind power, thermal power plant, nuclear power plant, and natural gas infrastructure [6], [28], [29], [32]–[36]. The engineering qualification rate was proposed in [32] to ensure the high level construction quality of power plant construction project. Also, the evaluation indicator system for the commissioning process and trial operation period was established for the wind power and thermal power plant project in [28], [31], [37], [38]. Besides, the acceptance evaluation was considered in the process of post-evaluation for the cogeneration plant project [39]. Finally, a comprehensive post-evaluation indicator system for the multi-energy infrastructure investment projects at the implementation stage is summarized and illustrated in TABLE 2.

C. EVALUATION INDICATORS AT THE OPERATION STAGE

The post-evaluation for the multi-energy infrastructure investment projects at the operation stage is to assess the function of the multi-energy infrastructure in the production and operation [40]. Generally, the evaluation indicators at the operation stage include three targets which are operation performance, scientific technology, and management system. In [14], the reliability of multi-energy supply including electricity, heat, and gas was considered in the operation of multi-energy system. In [28] and [41], the annual generation capacity and rate of farm power consumption were considered in the post-evaluation of wind power. The increased power supply calculation method for PTT project post-evaluation was proposed in [42]. The indicators to evaluate the operation management and technical progress were proposed in [28] and [34] for the evaluation of wind power and nuclear power plant project. Besides, the network analytic hierarchy process method was applied to represent the correlation among indicators [43]. Finally, a comprehensive post-evaluation indicator system for the multi-energy infrastructure investment projects at the operation stage is summarized and illustrated in TABLE 3.

III. POST-EVALUATION INDICATORS ON ECONOMIC BENEFITS

A. FINANCIAL EVALUATION INDICATORS

Financial post-evaluation for the multi-energy infrastructure investment projects, such as electricity, heat, and natural gas project, is implemented from the perspectives of managers to evaluate the project financial situation with the data from completion final accounts and the real operation of the project [44]. The detailed function of financial post-evaluation for the multi-energy infrastructure investment...
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FIGURE 1. The financial post-evaluation indicator system.

projects includes five aspects: 1) To compute real financial expenditure and income of the multi-energy infrastructure investment projects by using comparable prices under the present national taxation system and price system. 2) To review the profit and loss situation of the multi-energy infrastructure investment projects. 3) To evaluate the rationality of finance. 4) To compare with the indicators at the planning stage of the project. 5) To analyze the implementation degree of financial benefit and the causes for the discrepancies [45]. Generally, the financial post-evaluation indicator system for the multi-energy infrastructure investment projects is established from the perspective of project profitability, solvency, operation ability and development ability. In [45]–[49], the capital profit margin, net financial present value and internal financial rate of return were considered in the post-evaluation for transformer substation construction project, cascade hydropower stations, ground source heat pump system and power network renovation project. The solvency indicator mainly includes the loan payback period, interest coverage ratio, debt service coverage ratio, asset-liability ratio, liquidity ratio and quick ratio. Besides, the operation ability and development ability of capital were also considered in [24], [50]. The method to calculate the increasing benefit of the abandoned hydropower was proposed in [52], and the increasing benefit was applied as an indicator to evaluate the final benefit of the abandoned hydropower. Finally, a comprehensive financial post-evaluation indicator system for the multi-energy infrastructure investment projects is summarized and illustrated in Fig. 1.

FIGURE 2. The national economic post-evaluation indicator system.

are evaluated based on the principle of rational allocation of resources as well as the analysis method of cost and benefit [45]. Generally, the national economic evaluation includes two targets which are the national economy and development ability. The national economy needs to calculate the economic net present value (ENPV) and economic internal rate of return (EIRR). Both the EIRR and ENPV were considered in the national economic post-evaluation for cascade hydropower station project, RES deployment project and wind power project in [28], [45], [53]. Besides, the indicator to evaluate the development ability was proposed in [21] and [48] for rural electric network reformation project and power network renovation project. The development ability relates to the improvement of regional economics, industry economic and investment environment, rational allocation of resources and economic structure readjustment [20], [22], [28], [21]. Finally, a comprehensive national economic post-evaluation indicator system for the multi-energy infrastructure investment projects is summarized and illustrated in Fig. 2.

IV. IMPACT POST-EVALUATION INDICATORS

A. EVALUATION INDICATORS ON SOCIAL IMPACTS

The multi-energy infrastructure investment promotes the social economic development involving tangible and intangible benefits, and these benefits are calculated and analyzed through the post-evaluation on social impacts for the multi-energy infrastructure investment projects [18]. The post-evaluation indicators on social impacts include two targets which are social economy and social environment. In [11], [16], [54], [55], the development of regional, booming corporate profits, the amount of tax, drawing domestic GDP and land value-added benefit were considered in the post-evaluation for various distributed energy generation project, electric transmission project and navigation and hydropower junction projects. The social environment indicator mainly includes the improvement of energy structure, contribution to energy-efficient scheduling, mutual adaptability with the local community, the comprehensive utilization rate of pollutants, promotion of social employment, resident satisfaction, acceptance degree of social responsibility and the impact on the energy consumption [54]–[57]. Both [29] and [56] considered the improvement of energy structure and improvement of living standards in the post-evaluation,
which increased the feasibility and rationality of social impact post-evaluation. Besides, literature [57] reviewed different approaches in social impact evaluation for dam projects, and suggested to take society, policy and culture into consideration. Finally, a comprehensive post-evaluation indicator system on social impacts for the multi-energy infrastructure investment projects is summarized and illustrated in Fig. 3.

**B. EVALUATION INDICATORS ON ENVIRONMENTAL IMPACTS**

The post-evaluation on environmental impacts for the multi-energy infrastructure investment projects is to analyze the environmental impacts induced by the construction process and the actual operation effect of the project through comparing with relevant regulations of the standard values or thresholds [18]. After the formal completion of the project, the post-evaluation on environmental impacts can improve the resources evaluation level and accurately estimate the generation of energy [58]. The evaluation on environmental impacts is analyzed through the deviation degree between the real indicators and the standard indicators. Generally, the post-evaluation indicators on environmental impacts for electricity, heat and gas infrastructure investment projects include two targets which are resource environment and ecological environment. Resource environment, one of the targets, includes saving natural resources, reduction of damage caused by natural resources, energy loss reduction, the comprehensive utilization rate of waste, the impact on utilization of resources and compliance rate of waste [25], [32], [56]. Ecological environment, the other target, consists of noise pollution, electromagnetic radiation and influence on biodiversity, the impact on natural landscape, reduction of greenhouse gas emissions, clean energy generation and capacity for environment management [25], [28], [56], [58]. In [59], the environment post-evaluation was proposed for cascade hydropower stations considering the relation between water resource protection and economic development. Also, the evaluation indicators about energy loss, pollution coefficient and other conversion coefficient were taken into account in [60]. The post-evaluation indicator system for multi-energy infrastructure investment projects on environment-mental impact was summarized and illustrated in Fig. 4.

**V. POST-EVALUATION INDICATORS ON SUSTAINABILITY**

The post-evaluation on sustainability for the multi-energy infrastructure investment projects, based on the completed project, which is from the long-perspective to evaluate the feasibility of the construction project [26]. Thus, both the characteristics of the current point and the evaluation of future development need to be considered in the sustainability post-evaluation indicator system to ensure continuous evaluation [11], [18], [27]. The internal conditions reflect the financial operational level, the advanced nature of technique level, the level of management system, enterprise competitiveness, primary energy ratio (PER), relative energy saving rate (RESR) and security [11], [34], [56], [61]. The external conditions, considering the impact of economic development social environment and other external factors, are to enhance the ability of a project to maintain a high service level and operating ability, and improve the comprehensiveness and accuracy of the evaluation results [24], [29], [32]. In [11], [18], [49], [56], the tariff policy, completion of macro policy, social economy, support capacity of external resources, the resident satisfaction, load growth and rate of market share change were considered in the post-evaluation for energy internet projects, transmission and distribution electricity price reform, wind/solar hybrid power generation project, photovoltaic poverty alleviation project and ground source heat pump system. In [11] and [18], the project not only considered the indicators such as financial operation level and technique level, but also related to external indicators such as policy, the power grid
project evaluation model. The post-evaluation indicator system for the multi-energy infrastructure investment projects on sustainability is summarized and illustrated in Fig. 5.

VI. CHALLENGES

So far, the establishment of post-evaluation indicator system for the multi-energy infrastructure investment still has some challenges related to multi-energy coupling operation, randomness and subjectivity of evaluation process, and multi-energy infrastructure investment benefits in rural areas.

1) Post-evaluation indicator on multi-energy coupling operation: Multi-energy couplings among electricity, heating and gas networks strengthen the operation complexity of multi-energy interconnection infrastructure. In the multi-energy interconnection infrastructure, different renewable and non-renewable energies can be converted and adjusted by multi-energy converters and storages to form coupled multi-carrier energy supplies for consumers or injected into main energy networks. Thus, it’s difficult to set quantitative indicators to evaluate the energy supply characteristic and operation mode of multi-energy coupling system due to the strong coupling among various energies.

2) Randomness and subjectivity of evaluation process: The subjectivity and randomness are the nature of comprehensive evaluation. In the practical evaluation process, there are many subjectivity factors which affect the evaluation results, such as the knowledge level of researchers and various qualitative indicators. These factors can not be eliminated but can be mitigated. Thus, it’s a challenge to reduce the randomness and subjectivity of evaluation process through improving evaluation method and indicator system.

3) Post-evaluation of multi-energy infrastructure investment benefits in rural areas: There are many problems for the multi-energy infrastructure investment in rural areas, such as poor economic conditions, large poverty population, and severe natural environment. These problems lead to low energy demand, high construction costs, high operation and maintenance costs, unclear investment subject and difficulty in quantifying investment benefits. Thus, the post-evaluation on multi-energy infrastructure investment benefits in rural areas is very complicated.

VII. CONCLUSION

The post-evaluation indicator system for the multi-energy infrastructure investment projects is the basis and key of the post-evaluation of projects, and it has a direct influence on the correctness of evaluation results. In this article, a comprehensive overview on the post-evaluation indicator system for the multi-energy infrastructure investment projects is surveyed from the perspective of project overall construction process, economic benefits, impacts and sustainability, as well as the detailed investigations on financial evaluation indicators, national economic evaluation indicators, evaluation indicators on social and environmental impact. Findings indicate that a comprehensive post-evaluation indicator system at the planning stage contributes to finding out the major problems in preliminary design and providing guidance for following the project decision-making, construction process, and operation management. Moreover, the comprehensive evaluation indicators on economic benefits, sustainability, social and environmental impact help to draw a more scientific conclusion for the multi-energy infrastructure investment projects. Also, the comprehensive post-evaluation indicator system contributes to optimizing decision-making on projects and improving the project management efficiency, thus increasing the utilization of various RESs and meeting the multi-energy demand of customers. Therefore, developing a comprehensive post-evaluation indicator system for the multi-energy infrastructure investment projects is essential to improve the construction level of the multi-energy infrastructure, thus promoting the green energy revolution in the world. Besides, it’s still an open field for researchers to calculate the indicators with a qualitative or quantitative method, even the combination of the two methods.

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