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LIFE CYCLE ASSESSMENT OF ENERGY PROJECTS IN CONSULTING: APPROACHES AND TOOLS

Summary. *This article provides a comprehensive study of methodological approaches and tools for life cycle assessment (LCA) of energy projects within the framework of consulting activities. The relevance of the study is due to the growing need for a comprehensive consideration of environmental, economic and social aspects in the planning and implementation of large energy initiatives. The work examines in detail the key stages of LCA, including defining the boundaries of the system, inventory analysis, assessing environmental impacts and interpreting the results. Particular attention is paid to modern software solutions and international standards (ISO 14040, ISO 14044), which are actively used by consulting companies when conducting such assessments. Specific examples demonstrate the practical application of the LCA methodology for various types of energy projects - from traditional hydrocarbon generation to renewable energy sources. The final part of the article formulates practical recommendations for optimizing assessment methods and increasing the effectiveness of their application in consulting practice.*

Key words: *Life Cycle Assessment (LCA), energy consulting, sustainable energy, carbon footprint, ISO 14040, renewable energy projects, LCA software, environmental impact assessment, energy transition, circular economy.*

Introduction. Over the past decades, life cycle assessment (LCA) has become one of the most popular tools for analyzing the sustainability of energy projects of various scales and focus. In the context of the global transition to a low-carbon economy and tightening environmental legislation, consulting companies are increasingly using the LCA methodology to justify strategic decisions and select optimal technological solutions. This approach is especially important when comparing various options for the development of energy infrastructure and assessing their long-term consequences for the environment and society.

Modern energy projects, whether it is the construction of large power plants, the introduction of renewable energy facilities or the modernization of grid facilities, require a comprehensive assessment at all stages of their implementation - from the extraction of raw materials and equipment production to operation and subsequent disposal. The LCA methodology allows not only to minimize potential environmental risks, but also to optimize economic costs throughout the entire life cycle of the project, which makes it an indispensable tool for energy companies and consultants. In consulting practice, LCA is used in a variety of aspects - from comparative analysis of various energy technologies to calculating the carbon footprint of products and assessing the compliance of projects with the ever-stricter ESG (Environmental, Social, and Governance) requirements. This methodology is becoming especially popular in light of new regulatory requirements, such as the European Taxonomy of Sustainable Finance or the directives on disclosing the carbon footprint of products.

This article provides a detailed analysis of modern approaches to conducting LCA in the energy sector, including an overview of specialized software (SimaPro, OpenLCA, GaBi) and international standards of the ISO 14000 series. Particular attention is paid to practical cases of LCA application in consulting projects, which allows demonstrating the real value of this methodology for making informed management decisions.

The main goal of this study is to systematize modern methods for assessing the life cycle of energy projects, identify key problems of their practical application and formulate recommendations for improving the methodological base for consulting companies operating in the energy sector.

Methodological foundations of LCA in the energy sector

The life cycle assessment methodology is based on four interrelated and sequentially implemented stages, each of which requires careful development in relation to energy projects. The first and fundamental stage is the definition of the purpose and boundaries of the study system, which involves a clear formulation of the analysis tasks, the selection of the products or processes under study, and the establishment of spatial and temporal frameworks for the assessment. For an energy project, this may mean, for example, a decision to include in the analysis only direct emissions from the operation of a power plant or to take into account the entire supply chain, starting from fuel extraction.

The inventory analysis stage (Life Cycle Inventory, LCI) is the most labor-intensive part of the study, requiring the collection and processing of huge arrays of data on resource flows and emissions at each stage of the life cycle under consideration. In the context of energy projects, this may include data on water consumption, greenhouse gas emissions, waste generation and other environmental aspects related to fuel extraction, equipment manufacturing, construction, operation and decommissioning of facilities. To obtain reliable data, consultants often use specialized databases such as Ecoinvent or ELCD, as well as conduct their own measurements and calculations.

The impact assessment stage (Life Cycle Impact Assessment, LCIA) involves transforming inventory data into indicators of potential impacts on the environment and human health. In energy projects, special attention is traditionally paid to such impact categories as climate change (carbon footprint), acidification of the environment, eutrophication, resource depletion and toxicity. To conduct LCIA, consultants use various methodologies, among which the most common are ReCiPe, CML and TRACI, each of which has its own characteristics and areas of application.

The final stage of interpreting the results requires a comprehensive analysis of the data obtained, checking their reliability and sensitivity, as well as formulating conclusions and recommendations. In energy consulting, this may mean, for example, identifying "hot spots" in the project life cycle that contribute most to the environmental impact, or comparing different technology options in terms of their sustainability. Of particular importance at this stage is taking into account the uncertainties and limitations of the study, which helps avoid erroneous conclusions and recommendations. It should be noted that the LCA methodology is constantly evolving, adapting to new challenges in the energy sector. In recent years, more and more attention has been paid to integrating traditional environmental LCA with economic and social aspects (the so-called Life Cycle Sustainability Assessment), which is especially relevant for the comprehensive assessment of large energy projects that have a significant impact on local communities and regional development.

Tools and software for LCA in the energy sector

Modern consulting companies have a wide range of specialized software for conducting a comprehensive assessment of the life cycle of energy projects. Among the most popular solutions, SimaPro, OpenLCA and GaBi should be highlighted, which allow not only to automate complex calculations, but also to visualize the results obtained in a form convenient for analysis. These tools differ significantly in their functionality, interface and cost, which allows consultants to choose the optimal solution depending on the specifics of the project and the client's budget. It is important to note that the choice of a specific software product largely determines the depth and reliability of the analysis, as well as the efficiency of the consultants.

SimaPro is rightfully considered one of the most powerful and popular tools for conducting LCA in the energy sector. Its key advantages are an extensive built-in database, including thousands of different processes and materials, as well as flexibility in setting up assessment parameters. The program supports all major impact assessment methods (ReCiPe, CML, IMPACT 2002+, etc.) and provides ample opportunities for comparative analysis of various energy project development scenarios. The uncertainty module is especially valuable for consultants, allowing them to assess the reliability of the results obtained. However, the high cost of the license and the complexity of mastering it make this product available mainly to large consulting companies.

OpenLCA is open source software that is widely used in scientific research and small consulting projects. Its main advantage is that it is freely distributed and has an open source code, which allows the program to be adapted to specific tasks. The modular architecture of OpenLCA makes it possible to integrate additional databases and calculation methods, which is especially important when working with innovative energy technologies. The program supports all major LCA stages and is compatible with other tools via the EcoSpold format. However, compared to commercial analogues, OpenLCA has a less user-friendly interface and limited technical support capabilities, which can create difficulties for novice users.

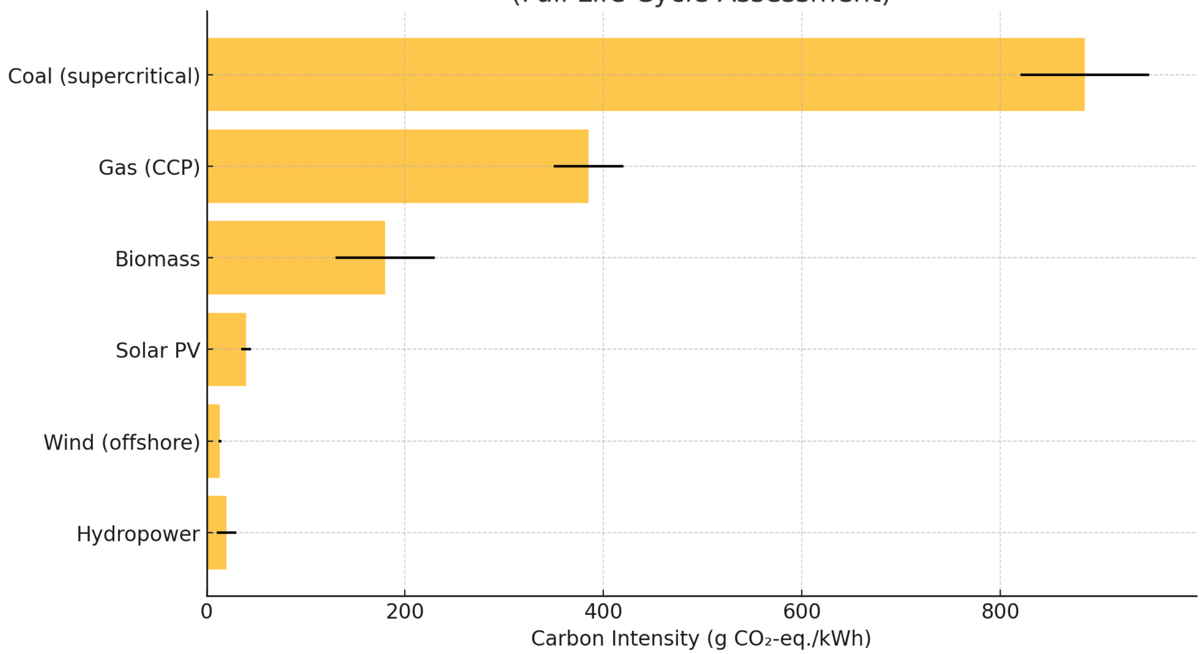
GaBi Software traditionally occupies a strong position in the industrial sector, including energy. Its distinctive feature is its tight integration with CAD systems and powerful capabilities for modeling complex production chains. This makes GaBi especially useful for life cycle assessment of large energy facilities, where it is important to consider the interrelations between different technological processes. The program offers extensive databases on energy processes and materials, as well as specialized tools for calculating the carbon footprint. The latest versions have introduced functions for conducting a socio-economic assessment (SLCA), which corresponds to modern trends in the field of sustainable development. However, its high cost and demand for computer resources limit its use in small consulting organizations. In addition to specialized software, many consulting companies use combined approaches that combine Excel models with cloud platforms such as Sphera or EarthShift Global. Such solutions are especially in demand when working with distributed teams and the need for prompt data exchange between different project participants. Cloud platforms often offer ready-made templates for assessing specific types of energy facilities (solar stations, wind farms, thermal power plants), which significantly speeds up the LCA process. Recent years have also seen growing interest in the application of artificial intelligence and machine learning technologies to large-scale LCA data processing, opening up new opportunities to improve the accuracy and efficiency of assessments.

Application of LCA in consulting: practical cases

The life cycle assessment methodology finds various applications in consulting practice when working with energy projects of various scales and focuses. One of the most popular areas is a comparative analysis of various scenarios for the development of energy infrastructure, where LCA allows for a quantitative assessment of the long-term environmental and economic consequences of each option. A typical example is the choice between the construction of a gas power plant and the development of wind generation in a specific region. In this case, consultants conduct a comprehensive assessment of all stages of the life cycle of both options, taking into account not only direct emissions during operation, but also indirect impacts associated with equipment production, fuel transportation, land use and other factors.

An interesting practical case is related to the life cycle assessment of a bioenergy project in the EU countries, where consultants conducted a comparative analysis of the use of local biomass and imported biofuels. The study showed that the option with local biomass (timber and agricultural waste) reduces the carbon footprint by 30-35% compared to imported pellets, even taking into account less efficient combustion. Moreover, the use of local resources created additional socio-economic benefits in the form of new jobs and the development of regional infrastructure. These findings became the basis for adjusting the customer's investment strategy and revising the logistics schemes. Another illustrative example is the LCA for solar photovoltaic plants, carried out at the request of a large energy holding. The analysis revealed that the main contribution to the environmental impact (about 60%) comes from the silicon module production stage, mainly due to high energy costs in silicon purification and wafer manufacturing. This discovery prompted the customer to revise the equipment procurement strategy in favor of manufacturers using renewable energy in the production process, as well as to invest more actively in thin-film module technologies with a lower carbon footprint. In the oil and gas sector, the LCA methodology is actively used to optimize supply chains and reduce methane emissions. One of the completed projects included a comprehensive assessment of various options for transporting liquefied natural gas (LNG) from the Arctic region. The analysis showed that, despite higher capital costs, the option using floating liquefied gas (FLNG) plants allows for a 15-20% reduction in total greenhouse gas emissions compared to the traditional scheme via pipelines and onshore plants. These data were used to justify investment decisions and negotiate with regulators. A special category is made up of consulting projects to assess promising energy technologies, such as hydrogen energy or carbon capture and storage systems (CCUS). In these cases, LCA faces the problem of a lack of reliable data, but even preliminary estimates allow us to identify potential "bottlenecks" and areas for optimization. For example, an analysis of "green" hydrogen showed that up to 70% of the environmental impact can occur at the stage of electrolyzer production, which indicates the need to develop a circular economy in this sector.

Figure 1. Comparative Carbon Intensity of Electricity Generation Technologies (Full Life Cycle Assessment)



Problems and Limitations of LCA in Energy Consulting

Despite the obvious advantages and growing popularity of the life cycle assessment methodology, its practical application in energy consulting faces a number of significant problems and limitations. One of the most acute is the problem of reliability and completeness of the initial data, especially when it comes to new or innovative energy technologies. For example, when assessing promising energy storage systems or hydrogen technologies, consultants are often forced to rely on laboratory data or theoretical calculations, which may differ significantly from the actual indicators during industrial implementation. This problem is exacerbated by rapid technological progress in the energy sector, when equipment parameters and technological processes change faster than LCA databases can be updated.

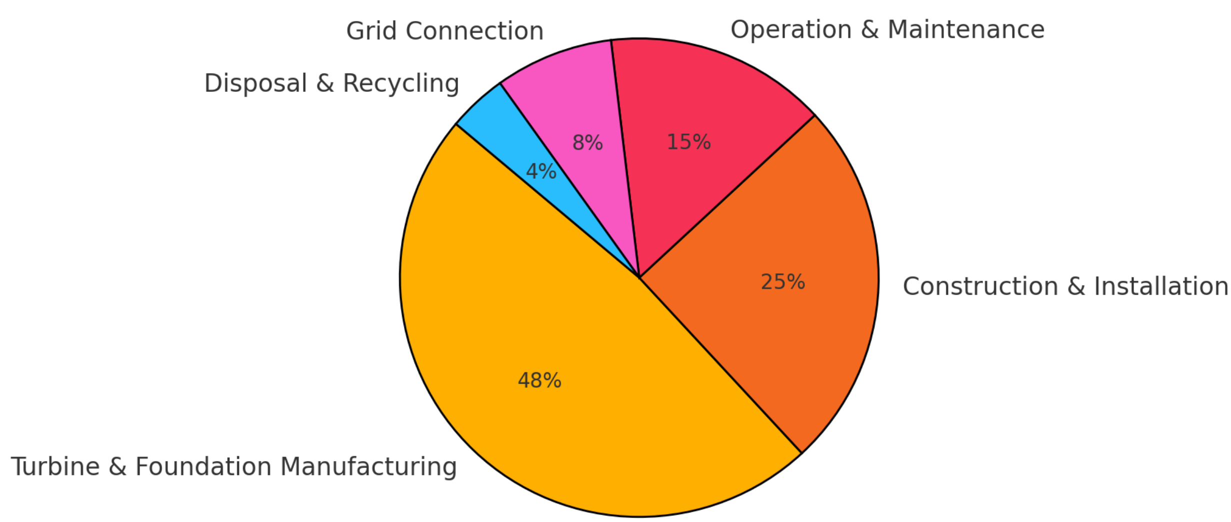
A serious methodological challenge remains subjectivity in defining system boundaries and choosing impact assessment methods. Different consulting companies may have different approaches to including or excluding certain processes from the analysis, which leads to incomparability of results even for the same energy facilities. For example, when assessing the carbon footprint of a wind farm, some consultants may limit themselves to taking into account only the production of turbines and their installation, while others may additionally include the costs of reserve capacity or grid modernization. Such differences in approaches create grounds for manipulation and make it difficult to make informed decisions based on LCA.

A significant barrier to the widespread introduction of LCA into consulting practice remains the high cost of high-quality research. A full-fledged life cycle assessment of a serious energy project requires significant time and financial costs for licenses for specialized software, access to commercial databases, and the work of qualified specialists. For small consulting firms and projects with a limited budget, this often makes LCA economically inexpedient, forcing them to limit themselves to simplified assessment methods that do not reflect the full complexity of real systems.

Traditional LCA methodology is also criticized for its excessive focus on environmental aspects with a relative disregard for social and economic factors. In the context of energy projects, this means that solutions that are optimal in terms of minimizing environmental impacts may be unacceptable for social or economic reasons. For example, the energy supply option with the lowest carbon footprint may require unacceptably high capital expenditure or lead to job losses in the region. In recent years, attempts have been made to develop a comprehensive sustainability assessment (Life Cycle Sustainability Assessment), but the corresponding methodologies are not yet standardized enough for widespread use in consulting.

Another problem is the poor integration of LCA results into decision-making processes at the corporate and government levels. Despite all the efforts of consultants, LCA findings do not always become the basis for specific management decisions, giving way to political considerations or short-term economic benefits. This is due to both the insufficient clarity and visibility of the presentation of LCA results for decision makers and the lack of mandatory requirements for taking the life cycle into account when approving energy projects in many countries.

Figure 2. Distribution of Environmental Impacts by Life Cycle Stage (Offshore Wind Farm)



Conclusion. The analysis shows that the life cycle assessment methodology has become an indispensable tool in modern energy consulting, allowing for more informed and sustainable decision-making. LCA provides a systematic approach to taking into account the environmental impacts of energy projects at all stages - from raw material extraction to equipment disposal, which is especially important in the context of the transition to a low-carbon economy. However, to fully realize the potential of this methodology in consulting practice, it is necessary to overcome a number of significant challenges related to data quality, methodological consistency and integration of results into decision-making processes.

To improve the efficiency of LCA in energy consulting, it is recommended to develop combined approaches that optimally combine specialized software (SimaPro, GaBi) with open solutions (OpenLCA) and cloud platforms. Particular attention should be paid to expanding and updating databases on new energy technologies, including renewable energy sources, storage systems and hydrogen technologies. An important area of improvement is the development of industry standards for conducting LCA for various types of energy projects, which will increase the comparability of results and reduce subjectivity in assessments.

It would be advisable for consulting companies to invest in training LCA specialists, paying special attention not only to the technical aspects of conducting assessments, but also to the skills of presenting results to decision makers. An effective approach can be the integration of LCA with other analysis methods, such as Cost-Benefit Analysis (CBA) and Multi-Criteria Decision Analysis (MCDA), which will allow taking into account not only environmental, but also economic and social aspects of energy projects.

The development of international standards (ISO 14040, ISO 14044) and regulatory requirements will facilitate a wider and more uniform application of LCA in the energy sector. Particularly promising is the development of requirements for disclosure of information on the life cycle of energy products and services, similar to existing standards for corporate carbon reporting. This will create additional incentives for energy companies to order relevant consulting services. In the future, LCA will become a key element of strategic planning in the energy sector, facilitating the transition to truly sustainable development of the industry. Consulting companies that can offer clients comprehensive solutions combining traditional LCA with an assessment of economic and social aspects will gain a significant competitive advantage in the energy consulting market. Further development of the methodology should be aimed at increasing the accuracy of assessments, reducing their cost and simplifying the process of integrating the results into the management practices of energy companies.

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