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Decision-making in major investment projects with a life cycle cost: improvement with sensitivity analysis and sustainability assessment

Keywords: decision-making, life-cycle cost analysis, case studies, sensitivity analysis, weighted scoring, sustainability assessment, OPEX, energy costs

Introduction

Decision-makers need a reliable basis on which appropriate decisions for a company's business development can be made. In this context, decisions regarding investment in a company's technical facilities and equipment, which have a primary impact on a company's success and market assertions, are of crucial importance. In many cases, this investment is a strategic decision. Technical equipment, such as production facilities and machinery, represents a significant long-term financial investment. The evaluation of investment projects is primarily based on the discounted cash flow method, with the net present value (NPV) method constituting the most commonly applied approach. In some business areas, such as the energy sector, a life cycle cost (LCC) analysis and NPV are the preferred methods. For investment projects, decision-makers need a solid basis from which the best options can be selected.

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This also applies to transmission system operators (TSOs) in Germany, who operate in high-pressure natural gas pipeline networks. They plan to invest approximately 8 billion EUR by 2030 (Gasunie, 2021) and an additional investment of 20 billion EUR by 2032 for the hydrogen core network setup. To create a reliable basis for decision-making, the TSOs prepare case studies from which the best options for defined operation tasks, such as compressor station tasks, can be selected. Most case studies follow the LCC analysis procedure. In this context, reference should be made to the evaluation of operational expenditure (OPEX), such as energy and maintenance costs, and above all, to the future development of OPEX during the period under consideration. In the case studies, the period under consideration is generally set between 10 years and more than 20 or 30 years. These OPEX uncertainties, which constitute input data for the NPV calculation and future development of input data, create the risk of failing to select the best investment options, causing the misallocation of limited funds. An analysis of TSO case studies shows that the prediction of energy costs (among other cost drivers) involves high uncertainty and can lead to incorrect decisions. As these uncertainties and risks must be addressed in the evaluation, probabilistic and deterministic methods have been proposed.

This study introduces a sensitivity analysis as a deterministic method. The variation in the discount factor and operating hours allows for an assessment of the LCC outcome and provides a broader basis for decision-makers. Sustainability is becoming increasingly important and is key to a company's market success. Changes in economic, ecological, social, and technical decision-making requirements have been ignored in many case studies. Sustainability assessments with weighted scoring have been introduced, allowing for the incorporation of ecological and social aspects into decision-making. Seven case studies, performed by experts from consulting firms and reviewed by experts from the TSOs, are available for assessment. These case studies serve as the basis for decision-making on natural gas infrastructure investments and represent experts' opinions (i.e., experts from consulting firms and the TSOs). However, these case studies are not publicly accessible, which is generally the case with private sector case studies. Therefore, such case studies are typically not available for scientific research. This study focuses on investments in compressor stations in Germany's natural gas infrastructure. Its results are applicable to other investment decisions involving machinery, energy, and maintenance costs as drivers.

Material and method

Managing uncertainties using deterministic methods

Deterministic methods are used if the input data can be determined; for example, if historical data are available. However, the extrapolation of historical data for future development is associated with several uncertainties that must be quantified and evaluated. With the help of deterministic methods, the evaluation of the future development of input data can be conducted. Scope et al. (2016) suggest the following methods for mitigating uncertainties: rule of thumb/best guess and sensitivity analysis.

The rule of thumb procedure appears to have no stable foundation and is based solely on the experience of the study authors. It is a simplified procedure that is often used, as in the case studies examined herein. For example, historical data are simply extrapolated as percentages for the future. However, this does not represent an uncertainty assessment or risk analysis. A sensitivity analysis is a suitable method for estimating uncertainties because it is established, straightforward, easy to apply, and provides a comprehensive assessment of the input data's validity. The EN 15663 standard (European Committee for Standardization [CEN], 2017) refers to a sensitivity analysis method for evaluating uncertainties. Nábrádi and Szöllösi (2007) state that "given the uncertainty that may exist about the future, it is often useful to make a sensitivity analysis, which asks a number of 'what if' questions".

Moins et al. (2020) assert that deterministic methods are easy to apply because they involve the use of discrete variables that cause a single output value. If a sensitivity analysis is performed, a one-factor-at-a-time (OFAT) simulation is performed (Moins et al., 2020). The results can be evaluated and compared with those of the initial calculations to identify whether a change in the input affects the overall conclusion and ranking of the alternatives (Moins et al., 2020).

Weighted scoring

Zardari et al. (2014) provide a summary of the main categories of multi-criteria decision-making methods and the key issues that arise from their application. Zardari et al. (2014) describe a 'weighted summation' as the simplest form of a multi-attribute utility analysis that applies a linear relationship. It involves standardizing the scores across all criteria, assigning preference weights, multiplying the weights by the scores, adding up the resulting scores to obtain total weighted scores for each alternative, and determining the ranking of the total weighted scores.

Although this method requires quantitative information on scores and priorities, only the relative values are used in the assessment. However, the method provides a complete ranking of options and information on the relative differences between options. The weighted summation results can be presented in bar graphs showing the relative contribution of all criteria or objectives compared to the overall rankings of alternatives. These rankings can be used to analyze the sensitivities of the rankings of alternatives to the overall uncertainties in both effects and priorities.

According to Baskaran (2018), weighted scoring is a multi-criteria decision--making method used to discover the relationship between the criteria and alternatives. When using this method, the weights of the criteria are multiplied by the values of alternatives, and the weighted sum indicates the overall sum of the process. Here, the terms 'option' and 'alternative' are synonyms.

Sustainability assessment

Companies are defined by their economic success and sustainability, and company policies designed to promote sustainability are becoming increasingly important. Visentin et al. (2020) assert that countless methods have been developed for assessing sustainability. In this context, a life cycle assessment (LCA) is an important tool for scientific investigations and is normalized using the ISO 14040 standard (International Organization for Standardization [ISO], 2006). However, it only includes the environmental dimension of sustainability. Due to the need to implement a broader and more complete approach to sustainability, the life cycle sustainability assessment (LCSA) method was developed (Visentin et al. 2020). According to Klöpffer (2008), LCSA combines LCA, LCC, and social life cycle assessment (S-LCA). Although LCA is the most popular tool, significant efforts have been made to develop methodologies for LCC and S-LCA (Visentin et al. 2020).

The Corporate Sustainability Reporting Directive (CSRD) was enacted by the European Union on January 5, 2023 (Directive (EU) 2022/2464). The following can be read on the European Union's website:

"The CSRD modernizes and strengthens the rules concerning the social and environmental information that companies have to report.

The new rules will ensure that investors and other stakeholders have access to the information they need to assess the impact of companies on people and the environment and for investors to assess financial risks and opportunities arising from climate change and other sustainability issues." (European Commission [EC], n.d.).

This means that companies are not only assessed on the basis of their financial performance, but also on the basis of non-financial indicators.

The application of ESG criteria from ESG reporting makes the weighted scoring and thus the assessment of sustainability more objective. Oliver Yébenes (2024) provides an overview of the criteria. Environmental criteria include, for example, physical risks, transition risks or market risks. Social criteria include the company's social responsibility for the products, health and safety of the process.

Sensitivity analysis as a deterministic method

As described in the ISO 15663 standard (ISO, 2006), a sensitivity analysis involves testing LCC outcomes to establish whether the conclusion is sensitive to changes in assumptions. This study applies the OFAT method. Accordingly, this study applies a sensitivity analysis to the deterministic input data. In LCC, the following constitute key data to identify the best options for investments in compressors: the discount rate for calculating the NPV (and discounted cumulated expenditure [DCE]), and operating hours. As the discount rate is not easy to fix, a range is used to give decision-makers a broader basis from which they can choose. The operating hours of the equipment determine the energy and maintenance costs. The number of hours (i.e., 2,000 hours per year or 8,000 hours per year) significantly impacts these costs and the DCE. A high number of operating hours gives energy costs greater leverage over CAPEX.

In the DCE calculation, the discount rates are calculated for each option in each case study within a broad range of 4% and 15%. Figures 1 and 2 show their impacts on the magnitudes of the costs and rankings of the options. The DCE calculations for each option in every case study are undertaken with three selected assumptions for operating hours per year. The case studies' required operating hours per year are provided by the TSOs. Unfortunately, assumptions regarding the operating regime and projected annual operating hours are difficult to establish; therefore, they are associated with uncertainties. For this reason, the impact of the number of operating hours per year on the outcome provides valuable information for decision-makers. As explained earlier, operating hours significantly affect the OPEX and OPEX–capital expenditure (CAPEX) ratios. Moreover, similar to the discount rate, operating hours impact both the DCE amount and ranking of options.

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Equal DCE for the ratio of energy costs

This study extends the sensitivity analysis to include further aspects of the energy costs evaluation as the main cost driver of OPEX. Thus, the electricity–natural gas cost ratio is calculated; the DCE is equal for both. The value of this ratio (which is a factor) gives decision-makers another indicator on which they can base their decisions regarding the options under consideration. This clarifies the factor that may lead to a form of energy (e.g., natural gas) becoming more expensive and cause the same DCE as that calculated for another energy form (i.e., electricity). This factor is implemented and evaluated based on the energy costs in the three case studies' options.

Sustainability assessment with weighted scoring

The economic, environmental, social, and technical decision-making requirements are rapidly changing. Germany's natural gas industry has been responding and adapting to these changing requirements for over a decade. In the decision-making process, LCC does not sufficiently reflect these aspects when selecting the best options. Climate protection issues are gaining importance, which, in this context, relate to the CO_2 emissions of the prime movers. However, these issues cannot be addressed using the LCC model alone. TSOs must also minimize emissions and select compressors/drivers with low-to-zero emissions. The selection of hermetically sealed compressors can support this goal. TSOs will continue to evolve from transporters of natural gas to hydrogen during decarbonization. The technical preconditions for this transformation must be implemented; thus, climate protection has become increasingly important. TSOs have already started to make green engineering a key factor. The social acceptance of this business sector is at stake. The preparation for hydrogen transport (H_2 readiness) and compliance with climate protection targets increase the public's acceptance of pipeline operators (i.e., TSOs). Every technical facility in Germany sits alongside a residential neighborhood. Smooth operations are guaranteed only if residents accept the technical facilities. The more sustainable the facility, the more acceptable it is. The facility operators depend on the neighborhoods; for example, in the case of a fire, support depends on voluntary fire departments.

TSOs are employers that provide high-quality jobs associated with the facilities. Providing good jobs with modern working conditions is an important aspect of a social assessment. Consumers are more likely to accept companies if they are sustainable. Raising funds from investors is easier if a company or sector is considered sustainable. Meanwhile, good relationships with local communities are important because legal authorizations depend on them.

Accordingly, these aspects must be addressed when selecting the best investment options. An LCC analysis is important, but not the only criterion. The LCC results represent the economic part of a sustainability assessment, while the CAPEX, maintenance costs, and energy costs can be considered as the criteria. Moreover, TSOs have special characteristics that are not considered in the LCC model; for example, operating personnel's experience with new compressors and drivers to be installed. In this case, if the operating personnel are experienced only with gas turbines (GT), then installing an electric motor poses an organizational challenge. So, operating personnel must be retrained or supplemented with specialists. These criteria can be included in the weighted scoring. As these criteria are not associated with sustainability, they are omitted. The weighted scoring highlights other significant aspects apart from LCC. Economic considerations are of fundamental importance and must be included in a sustainability assessment. These questions and aspects, which are of great importance for a company's further development, cannot be sufficiently considered by the LCC model alone. Therefore, an established procedure must be introduced to consider these aspects. So, the sustainability assessment utilizes weighted scoring. In the course of the sustainability assessment, a full-scale life cycle assessment (LCA) could be included.

In the weighted scoring, the criteria are weighted, and the fulfilment of these criteria is assessed using points that represent the fulfilment degree of the criteria. The scores range from 1 to 10 (10 = 100% fulfilment). The criteria and weightings must be determined in advance by the team that prepares the case study, which forms the basis for the decision-makers. The methodology is as follows: the weighted scoring involves standardizing the scores for all criteria, assigning preference weights, multiplying the weights by the scores, adding the resulting scores to obtain the total weighted scores for each alternative, and ranking the total weighted scores (Zardari et al., 2014).

Results and discussion

Sensitivity analysis of discount rates and operating hours

Figures 1 and 2 illustrate the effects of different discount rates and operating hours per year on the DCE calculations of the case studies. Each graph depicts the DCE calculation as a function of the discount rate. The results for all case studies are not presented here due to space limitations. Instead, the results for the models used in

Case Studies 2 and 6 are shown. While Case Studies 2 and 6 are selected because the sensitivity analysis effects are significant, the other case studies also show significant sensitivity analysis effects. The graphs are based on real historical data for the energy and maintenance costs, and the discount rate is plotted for each option. For each of the two options, the operating hours per year range from approximately 6 to 15% and from 4 to 12%, respectively. In Figure 1 (Case Study 2), the three graphs show the calculated DCE as a function of the discount rates for 1,000, 2,880, and 8,000 operating hours.

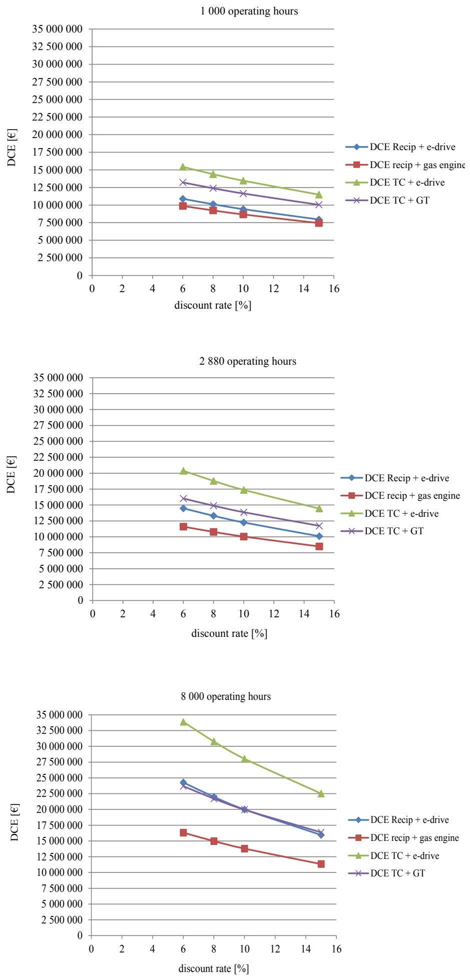

FIGURE 1. Case Study 2: DCE for real (historical) input data, calculated for several discount rates and three different operating hours per year

Source: own work.

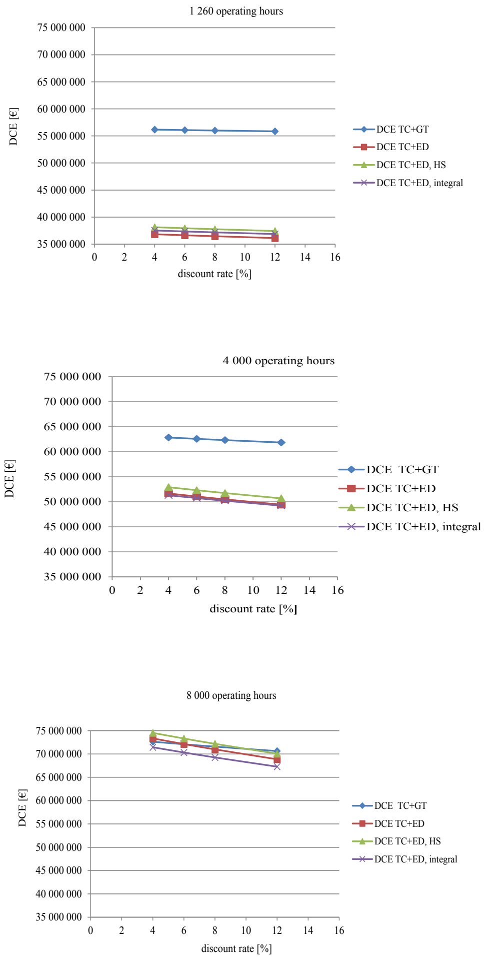

FIGURE 2. Case Study 6: DCE for real (historical) input data, calculated for several discount rates and three different operating hours per year

Source: own work.

The DCEs of four different options are compared. The options constitute combinations of different compressor types and drivers. The drivers are powered by either electricity (electric drive) or natural gas (gas engine and GT). The option with the lowest DCE is the preferred option.

In Case Study 2, the dependency of DCE on the discount rate is immediately apparent. As the number of operating hours increases, the calculated DCE also increases, since the number of operating hours directly determines the energy and maintenance costs. At 1,000 and 2,880 operating hours, there are no changes in the option rankings. At 8,000 operating hours, DCE increases, and the ranking order changes. Compared with CAPEX, the influence of OPEX is clear when the compressors are almost fully utilized. Although the “Recip+Gas engine” option remains the most advantageous, the “TC+GT” and “Recip+ED-” variants switch positions at a discount rate of 9%. The gas engine option remains the best over the range of operating hours.

In Figure 2 (Case Study 6), the three graphs show the calculated DCE as a function of the discount rates for 1,260, 4,000, and 8,000 operating hours, respectively. In contrast to Case Study 2, only the turbo compressors (TC) and reciprocating compressors (Recip) are considered. The electric motors in the various designs (electric drive [ED], high speed [HS], and integral) and GT are examined as drivers.

Case Study 6 demonstrates the same pattern as that observed in Case Study 2. DCE increases with the operating hours. At 4,000 operating hours, the “TC+ED, integral” variant is equivalent to the “TC+ED” variant or is more advantageous, depending on the discount rate. At 8,000 operating hours, the “TC+ED, integral” variant is the variant to be selected for all discount rates. The graphs are not shown due to place constraints.

The discount rate and number of operating hours can change the ranking of options and affect the calculated DCE.

Decision-makers can use these measures to assess the changes in major cost drivers (i.e., electricity and natural gas) and analyze their impact on the calculated DCE using the cost model. Here, this study presents the effect of the discount rate. The decision--making can be effectively supported with the sensitivity analysis results, as the decision-makers can obtain a clearer picture of the impact of the main cost drivers.

Equal DCE for the ratio of energy costs

The main cost driver for OPEX are the energy costs combined with operating hours. While the electricity and natural gas costs greatly differ, they are still included in the model regardless. For the decision-makers, the quotient of the energy costs to achieve the same DCE is an additional valuable basis for securing their decisions.

To investigate the ratio of electricity to natural gas costs, DCE is considered equal, and two examples are selected to show the efficiency of the approach. For this purpose, this study analyzes the DCE calculations that use real historical data. It selects case studies that compare options and operate with different energy sources; no more than four options are compared to ensure clarity. Case Studies 2 and 4 fulfil these requirements.

Figure 3 shows the results for Case Study 2. This case study compares four options: two powered by electric energy and two powered by natural gas. Figure 1 (2,880 operating hours) demonstrates the DCE calculation using real historical energy data (factor 1 for increase of price of natural gas). In Figure 3, the costs for natural gas are increased by a factor of 2.3, such that the options for choosing natural gas and electric are (almost) congruent.

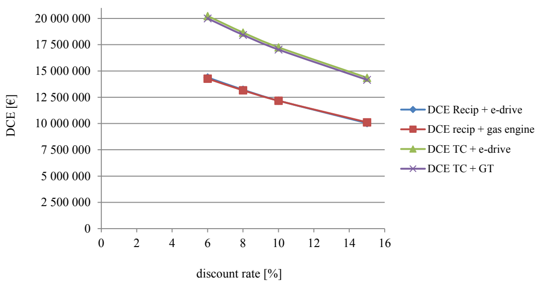

FIGURE 3. Case Study 2: equal DCE by increase in the price for natural gas

Source: own work.

The ranking in Figure 3 shows that the “Recip+Gas engine” option has the lowest DCE; thus, it is the most advantageous. This option is powered by natural gas. The following question arises: what factor must the natural gas price be increased by so that the DCE of the “Recip+Gas engine” option becomes equal to that of the “Recip-ED” option? If natural gas prices increase by a factor of 2.3, there is an almost complete match between the two curves of the “Recip+Gas engine” and “Recip+ED” options over the entire discount rate range. Moreover, a convergence of the curves for the “TC+GT” and “TC+ED” options can be observed.

Another example is Case Study 4 which examines two options. The approach is similar to that used in Case Study 2.

The natural gas option has a lower DCE, making it a suitable option for selection. Multiplying by a factor of 3.4 results in almost a full coverage of the two curves over the entire discount rate range. This result clearly supports the decision in favor of the natural gas-powered option, which, in this case, is the “GT-driven” option.

Sustainability assessment with weighted scoring

Table 1 shows the weighted scoring for the sustainability assessment of Case Study 4. This table shows the sustainability criteria as follows: environmental (30%), social (30%), and economic (40%). Weighting must be determined by TSO experts. The weighting and scoring setting clearly impact the outcome. So, the decision needs to be made before the process starts. The selection of the criteria and their weightings must not change during the decision-making process to ensure that the assessment is as objective as possible.

TABLE 1. Weighted scoring for options in Case Study 4

Sustainability	Weighting [%]	Option 2 TC + EM	Score	Weighted Score	Option 1 TC +GT	Score	Weighted Score
Environmental (LCA)	**30**			**2.15**			**0.75**
Emissions CO_2	15		8	1.2		2	0.3
Emissions CH_4	5		5	0.25		3	0.15
H_2 ready	10		7	0.7		3	0.3
Social	**30**			**2.4**			**0.95**
Neighborhood acceptance	5		8	0.4		3	0.15
High-quality jobs	5		8	0.4		8	0.4
Consumers	15		8	1.2		2	0.3
Local community	5		8	0.4		2	0.1
Economic (LCC)	**40**			**2.3**			**3.3**
CAPEX	10		4	0.4		10	1
Maintenance costs	10		9	0.9		5	0.5
Energy costs	20		5	1		9	1.8

Final weighted scoring (max. 10 points)	**Turbo compressor + Electric drive**	**6.85**	**Turbo compressor + Gasturbine**	**5.00**
Ranking	**1**		**2**	

Source: own work.

The criteria and associated weighting show that the "TC+EM" option is preferable to the "TC+GT" option. The EM is equivalent to the ED. Overall, the former has a higher sustainability assessment score. LCC is included in the sustainability assessment at 40% only. This leads to a different ranking from that of the LCC-only analysis. The DCE calculation for Case Study 4 shows that the “TC+GT” variant is more beneficial according to the LCC analysis. A sustainability assessment can change the ranking of options when compared with a pure LCC analysis, and can provide a more comprehensive approach to assessments.

Table 2 shows only the input values, which are made up of the sustainability criteria and their weighting.

Once the scores have been entered, the weighted scores are calculated, resulting in the ranking.

TABLE 2. Input values for weighted scoring

Sustainability	Weighting [%]	Option 2 TC + EM	Score	Weighted Score	Option 1 TC +GT	Score	Weighted Score
Environmental (LCA)	**30**			**0**			**0**
Emissions CO_2	15			0			0
Emissions CH_4	5			0			0
H_2 ready	10			0			0
Social	**30**			**0**			**0**
Neighborhood acceptance	5			0			0
High-quality jobs	5			0			0
Consumers	15			0			0
Local community	5			0			0
Economic (LCC)	**40**			**0**			**0**
CAPEX	10			0			0
Maintenance costs	10			0			0
Energy costs	20			0			0

Final weighted scoring (max. 10 points)	**Turbo compressor + Electric drive**	**0.00**	**Turbo compressor + Gasturbine**	**0.00**
Ranking				

Source: own work.

Conclusions

The decision-making process for Germany's natural gas infrastructure investments is based on LCC. This study's investigation of seven LCC-based case studies on investment decisions in compressor stations shows that incorrect decisions are made due to the input data used and the predictions of the input data's future development.

To reduce the risk of incorrect decisions, this study examines various methods via a sensitivity analysis of the discount factor and operating hours. The number of operating hours directly influences the energy and maintenance costs. The analysis shows the effects of variations in the input data. Both the calculated DCE and ranking of the options change. A higher DCE means a higher OPEX, which can affect the cash flow and subsequent investment decisions. The effects of the different discount factors are illustrated.

To further validate the investment decisions, the energy costs are set in relation to each other with the same DCE for the options. If the factor is 2.3, as in Case Study 2, then the cost of natural gas can increase by a factor of 2.3 compared to the cost of electricity, until the electricity options are more advantageous than those of the natural gas options. These measures provide decision-makers with additional information regarding the sensitivity of the input data and its influence on profitability.

In addition to the economic criteria, a sustainability assessment can determine a company's market success. Sustainable companies achieve higher levels of social acceptance, which, in turn, affects their economic results. For this reason, this study presents decision-makers with a sustainability assessment that considers social, ecological, and economic aspects. The sustainability assessment is based on a weighted scoring method, as demonstrated in Case Study 4, considering that weighted scoring in sustainability assessments can lead to a change in the ranking of options. Weighted scoring can include a full scale LCA to address the environmental impact.

The definition of the criteria primarily considers the subjective assessment of the team. The criteria should not be subjective, but objective. One possibility is to use ESG reporting, which is based on the Corporate Sustainability Reporting Directive (CSRD) of the EU. Further research shall integrate sustainability assessment with weighted scoring and objective criteria for environmental and social requirements based on LCA and ESG reporting.

In the examined case studies, this study only conducted sensitivity analyses for three studies; specifically, for operating hours. It did not conduct sustainability assessments. Therefore, decision-makers could only receive a limited overview of the effects of their decisions, which could lead to a misallocation of investment funds. To prevent this, the basis for decision-making must be expanded. Sensitivity analyses and sustainability assessments are effective measures that provide decision-makers with much broader bases for their decision-making. Sensitivity analyses are among the deterministic methods used for reducing uncertainties. The effectiveness of probabilistic methods, such as the Monte Carlo simulation for risk mitigation, should also be included in the case studies. Accordingly, the key risk mitigation measures can be implemented, and the decision-makers can obtain a comprehensive overview of investments together with the measures described in this study. Although this study relates to LCC in Germany's natural gas infrastructure, the suggested process can be adopted for other investment projects comprising CAPEX and OPEX.

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Summary

Decision-making in major investment projects with a life cycle cost: improvement with sensitivity analysis and sustainability assessment. This study focuses on compressor station investments in Germany's natural gas infrastructure, offering insights applicable to machinery, energy, and maintenance cost-driven decisions. A life cycle cost (LCC) analysis can guide investment choices; however, uncertainties in input data and future developments pose risks. The LCC-based studies encounter questions impacting their results and optimal selections. These uncertainties may lead to misallocations, emphasizing the need for careful consideration of investment decisions to avoid potential consequences and efficiently allocate limited funds. Various measures are available to mitigate the uncertainties and risks in LCC analyses. Recognized measures are deterministic and probabilistic. Seven case studies on investments in the natural gas infrastructure in Germany were analyzed in this context. In addition to the executed case studies, a case study from a scientific journal (published in 2001) was included in the analysis. The case studies were conducted by transmission system operators from 2005–2015, and a retrospective view made it possible to recognize whether the best options (due to the LCC analysis) were identified. Simulations were conducted with generated models using real historical input data such as energy costs. The re-calculation of the net present value or better discounted cumulated expenditure with real input data shows that the LCC analysis results are significantly dependent on the reliability of the input data and the prediction of their development. Therefore, validating the results using appropriate measures is mandatory. This study illustrates how sensitivity analysis can be used as a deterministic method to evaluate the LCC analysis

results. A company's success is increasingly determined by its sustainability. A pure LCC analysis is insufficient, so social, ecological, and economic sustainability assessments must be conducted. This study demonstrates the effectiveness of the weighted scoring method for sustainability assessments. Although this study relates to LCC in Germany's natural gas infrastructure, the suggested process can be adopted for other investment projects comprising capital and operational expenditures.