IOP Conf. Series: Earth and Environmental Science **100** (2017) 012180 doi:10.1088/1755-1315/100/1/012180

Evaluation of a novel waste heat recovery system for the cement industry using multi-criteria analysis (MCA) approach

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Abstract. Based on a novel waste heat recovery project established in a cement plant, this paper aims to evaluate the performance of the project using multi-criteria analysis (MCA) approach. Economic, environmental, social, and technical perspectives were concerned and analyzed. Different sustainability criteria and indicators related with the project were evaluated through ranking/rating process and pairwise comparison. Results have shown similar outcomes, that ten out of eleven criteria are favorable at a high standard, which reveals the project's success. Although the project has performed so well in economic, environmental and technical terms, social aspects have some weak points, and measures should be taken to improve social benefit.

1. Introduction

Cement production is one of the most energy-intensive and high polluted industrial processes. For typical dry process, 85% of the total energy is used for clinker formation in the rotary kiln during cement production [1].According to a Turkey study, waste heat was dissipated in different ways, including radiated and convective heat losses from kiln surface, as well as exhaust flue gas and hot air emitted out of the kiln and cooler stack, which respectively accounted for around 15.11% and 24.76% of the total energy loss [2]. Considerable economic, environmental, and social benefits will be obtained if this part of waste energy is recovered and integrated into the existing power generation system in the cement plant.

A novel waste heat recovery system is proposed and established in a cement plant, which has optimized the previous heat recovery system. It is composed of two sub-systems: heat collector system and waste heat recovery boiler system. Heat collectors are installed out of the rotary kiln, and water is used as working fluid in water wall and tubular heat exchangers in order to recover the radiated and convective heat from the kiln surface. Hot water after the heat collectors enters the waste heat recovery boiler system to get further heated. The final product is super-heated steam, which is integrated into the waste heat power generation system of the plant. Heat source of the boiler is primarily the hot air emitted out of the low-temperature section of the cooler stack, which was previously not included in the energy recovery system.

This paper aims to evaluate the performance of the waste heat recovery project, not only from the energetic point of view, but also from a comprehensive perspective. Economic, environmental, social, and technical aspects are concerned and analyzed. Different sustainability criteria related with the project are listed and compared, and the most important ones are identified so that special attention could be focused on those relatively poor performances. Practical experience is thereby provided for future design, operation, and optimization.

2. Methodology

Multi-criteria analysis (MCA) is applied for this study, which helps to address problems and cases involving a variety of attributes or criteria [3]. The final results would be much broader and comprehensive rather than only taking into account the monetary values. The evaluation process is conducted in two means: The first one counted on a ranking/ rating process, and the second one on a pairwise comparison known as Analytic Hierarchy Process (AHP).

For ranking/ rating process, the MCA manual published by the Center for International Forestry Research (CIFOR) in 2009 has provided a guide to implement this decision-making tool and to evaluate the relative importance of all the criteria that are involved [4]. The procedure is shown as follows:

Step 1 Establish a set of Principles, Criteria and Indicators;
Step 2 Individual judgment on each of the Principles;
Step 3 Individual judgments for all the Criteria under each Principle;
Step 4 Prioritize Principles and Criteria, according to their Relative Weights;
Step 5 Calculate the Relative Weights of each Indicator;
Step 6 Prioritize the Indicators according to their Relative Weights;
Step 7 Score the indicators based on the selected set.

Analytic Hierarchy Process is a widely used MCA tool proposed by Saaty [5]. The AHP method consists of six steps as follows, to do one-on-one comparisons between each of the Indicators:

Step 1 Establish a numerical scale for comparative judgment of Indicators;
Step 2 Individual comparative judgments on the relative importance of each pair of Indicators in terms of the Criterion they measure;
Step 3 For each individual judgment, calculate the Relative Weights of each Indicator (calculate the sum of each column, and normalize the elements);
Step 4 Calculate Relative Weights for the Indicators;
Step 5 Calculate the final score for each Criterion
Step 6 Calculate the consistency index。

The consistency index (C.I.) is adopted to verify that the experts' judgments are consistent for each of the comparisons. Methodology for calculating C.I. is given by Saaty [6], using the largest eigenvalue of the matrix formed by pairwise comparisons of Indicators. Consistency ratio (C.R.) is adopted to interpret the C.I. values which are divided by a random index (R.I.). R.I. value is 0.58 for Criteria with three Indicators, and 0.90 for Criteria with four Indicators, as for this specific case. If C.R. value is larger than 0.1, the certain comparison is not consistent and judgments should be revised.

Different criteria and indicators related with the project were identified and evaluated by an expert group composed of two professors from Shandong University and one project leader from the cement plant. In addition, the evaluation process is based on experimental and operational data derived from preparation, construction, and operation phases of the project. Concrete data are not directly given in this paper, but serve as a reference to evaluate each of the criteria and indicator which have been identified.

3. Results and discussion

3.1. Identification of principles, criteria and indicators

Table 1. Hierarchical structure of Principles, Criteria and Indicators.

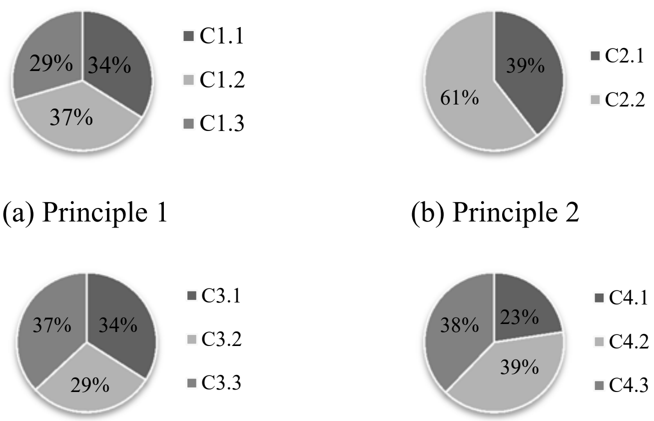
Principle Criterion Indicator		Description
1		**Economic aspects**

1.1		The financial system includes measures that ensure the project sustainability
	1.1.1	Investment costs and operation & maintenance costs are fully detailed and appropriate
	1.1.2	Monitoring of the financial situation is being undertaken on a regular basis
	1.1.3	The project manages financial issues under a range of scenarios, can service its debt, and can pay for all plans and commitments including social and environmental considerations
1.2		Economic benefits
	1.2.1	Power generation that has compensated the electricity use for the plant
	1.2.2	Savings for thermal energy consumption
	1.2.3	Other economic benefits due to the system optimization
1.3		Payback period
	1.3.1	The payback period is short and acceptable
2		**Environmental aspects**
2.1		Water, waste, noise and air quality issues associated with the project are properly managed
	2.1.1	Water quality in the vicinity is not adversely impacted by project activities
	2.1.2	The project wastes are responsibly managed
	2.1.3	Noise and air quality in the vicinity are under control and accepted
2.2		In-use environmental performance
	2.2.1	Reduction of energy consumption
	2.2.2	Reduction of water consumption
	2.2.3	Reduction of emissions
	2.2.4	Improvement of waste management
3		**Social aspects**
3.1		Plans and processes are established to manage environmental and social aspects
	3.1.1	Negative social impacts are identified and managed
	3.1.2	Avoidance, mitigation, compensation and enhancement measures are implemented
	3.1.3	Social commitments are fulfilled
3.2		The project provides safe infrastructure which is properly managed
	3.2.1	Life and property are protected from infrastructure safety risks
3.3		Social benefits
	3.3.1	Improvement of labor and working conditions, including employee and contractor opportunity, equity, diversity, health and safety
	3.3.2	Permanent works and temporary works are generated with the project
	3.3.3	Improvement of social reputation
4		**Technical aspects**
4.1		Installation issues associated with the project are well solved
	4.1.1	Compatibility
	4.1.2	Labor
	4.1.3	Materials
	4.1.4	Installation time
4.2		The project has fulfilled the expected performances.
	4.2.1	The project improves the energy balance and reduces energy loss
	4.2.2	The project generates the quantity of electricity that was expected
	4.2.3	The new system is good for the original system, with little or no negative impacts
4.3		Operation and maintenance
	4.3.1	Reliability
	4.3.2	Efficiency
	4.3.3	Durability
	4.3.4	Flexibility

Literature review work was done by the expert group consulting papers and reports on MCA approaches [3-12]. Considering the project's initial aim, which is to investigate and develop a novel waste heat recovery system for the cement industry, economic and technical aspects should be undoubtedly considered. Moreover, the evaluation desires to include a sustainable perspective, and thus social and economic aspects are taken into account. Principles, criteria, and indicators are all identified and listed in Table 1 for this specific case.

3.2. AHP process

In the first place, the expert group was asked to judge the importance of each criterion relative to the principle in particular. The judgment was done using the rating / ranking method and the scale is from 1 to 9 where 1 stands for weakly important and 9 stands for extremely important. The results are shown in Figure 1. Larger percentage demonstrates greater importance within the Principle, and vice versa.



(a) Principle 1 (b) Principle 2

(c) Principle 3 (d) Principle 4

Figure 1. Importance of each criterion relative to the principle.

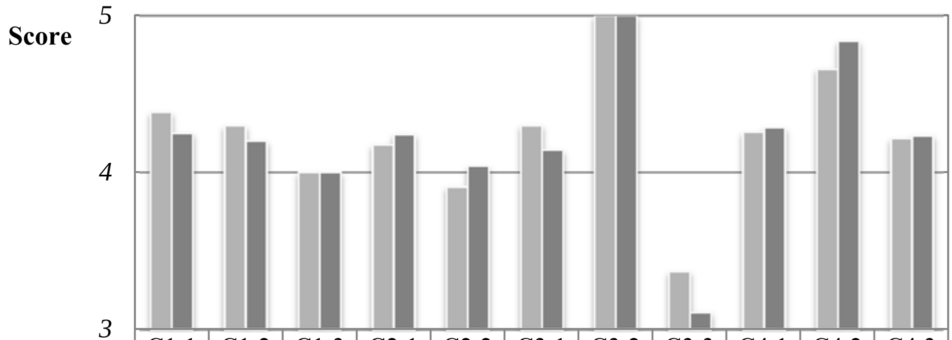
All criteria and indicators were judged through ranking/rating and pairwise comparison. Relative weights were calculated by the percentage estimation of each indicator. Then, we calculated the average weight with the results from the relative weight – that was obtained by Ranking, and the relative weight obtained by Rating. This number was multiplied by the score that was discussed by the group for each indicator, to obtain final scores. The scoring scale is shown in Table 2.

Table 2. Scoring scale.

Scoring scale	Description
0	Not an applicable Criteria or Indicator
1	Extremely weak performance or strongly unfavorable
2	Poor performance, unfavorable, may be the norm for the region, but major improvement needed
3	Acceptable, at or above the norm for good operations in the region
4	Very favorable performance, well above the norm for the region, but still needing improvement to be state of the art
5	‘State of the art’ in region, clearly outstanding performance which is way above the norm for the region

For the AHP process, one-on-one comparisons were done between each of the Indicators. Each expert did his/her comparative judgment for each indicator individually. Through pairwise comparison and normalization, relative weights for each of the indicators were obtained. The results from each expert were summed up; the average was calculated and thereafter multiplied by the same score that was given using the ranking/rating methodology. As the final step, the consistency index was calculated. According to the calculation results, the highest C.R. is 0.076, implying there is no high degree of inconsistency amongst the judgments.

All the criteria scores derived from ranking/ rating as well as pairwise comparison are organized in a final column chart, seen in Figure 2. Certain criteria are not applicable for pairwise comparison since there is only one indicator.



	C1.1	C1.2	C1.3	C2.1	C2.2	C3.1	C3.2	C3.3	C4.1	C4.2	C4.3
R/R	4.38	4.30	4.00	4.18	3.91	4.30	5.00	3.37	4.26	4.66	4.22
P.C.	4.25	4.20	4.00	4.24	4.04	4.14	5.00	3.11	4.28	4.84	4.23

Figure 2. Final results of scores for each criterion

As can be seen from the chart, final results display very similar outcomes using ranking/rating and pairwise comparison respectively. C1.3 and C3.2 are not applicable for pairwise comparison, and they are given the same score as ranking/rating method. All criteria have acquired scores above 3, and eight out of eleven criteria are ranging from 4 to 5, which stand out as clearly prominent performances. Two criteria get approximately 4, and one gets the lowest score around 3. Drawn from the values, almost all criteria have implied favorable performances at a high standard.

In economic terms, the project has proved its success due to excellent financial management and economic benefits. Investment cost is under firm control at an appropriate level to carry on the project from the beginning till implementation. Electricity generation and reduction of coal consumption are the two main benefits. In addition, twelve air blowers which used to cool down the rotary kiln are no longer needed thanks to the heat collectors, and a large quantity of electricity is saved as a result.

From environmental point of view, it is satisfactory to reduce the environmental impacts to the minimum during construction. Materials were environmental friendly, no hazardous wastes were emitted to the environment, water and air qualities in the vicinity were under control, and solid wastes were responsibly managed. The only problem was the noise; but as there are no residents near the plant, the impact is not so serious. Reduction of coal consumption contributes most to the enhancement of in-use environmental performances, consequently decreasing emissions such as CO_2, SO_2, NO_x, and dust.

As to social aspects, the project did very well in planning and fulfilling commitments, and life and property were protected from infrastructure safety risks perfectly; whereas social benefits are slightly beyond satisfaction, which can be deduced from the lowest score obtained by Criteria 3.3. Unquestionably, the project has gained a great deal of social reputation due to its novel energy saving concept and system optimization. However, very little substantially benefit was accomplished with the improvement of working opportunities as well as job creation. A score of 3 is only reaching the minimum requirement, and more measures are yet to be taken for improvement.

Technical criteria all get scores above 4.2, illuminating prominent performances among other principles. Installation process was very smooth without any delay or difficulties. Expected technical performances have been fulfilled, e.g. energy balance of cement production is improved, and much more thermal energy can be used in the kiln for clinker formation while heat loss was reduced. Heat source of the boiler is primarily the hot air emitted out of the low-temperature section of the cooler stack, which was previously not included in the energy recovery system. Moreover, the heat collectors are applied to stabilize the temperature of the kiln through adjusting the amount of recovered heat in case that the working condition of the kiln changes, thus ensuring a better circumstance for both kiln brick under high temperature and clinker formation inside of the kiln. One negative impact on the original system is that temperature of the exhaust flue gas has increased by around 10oC, which affects power generation a little bit. But given the quantity which the new system generates, this deficit could be neglected.

4. Conclusion

Multi-criteria analysis was applied to evaluate the novel waste heat recovery project, and two set of methods, ranking/ rating and pairwise comparison, are conducted respectively. Results have shown similar outcomes, that almost all criteria are favorable at a high standard. From the beginning of the preparation and construction phase, excellent financial management and environmental/ social commitments were considered and performed, laying a consolidated foundation for the project. Environmental impacts were minimized, and technical problems were well solved. During implementation phase, the project has fulfilled its expected economic, environmental, and technical performances, with its primary initial aim be perfectly accomplished.

Final results reveal the project's success: ten out of eleven criteria have achieved more or less favorable performances. Moreover, the new system has solved technical problems such as improvement of energy balance, reduction of heat loss, and optimization of the original system, which are very promising respects for further research and development. Although the project has done so well in economic, environmental, and technical terms, only one social criterion got the lowest score. Measures should still be taken to improve social benefits.

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