Sustainable measures in heating application in a manufacturing system with multi-criteria decision analysis – A case study.

A Ameena
Department of Production Engineering,
National Institute of Tiruchirappalli,
Tamil Nadu, India
ameenashine2005@gmail.com

S Kumanan
Department of Production Engineering,
National Institute of Tiruchirappalli,
Tamil Nadu, India
kumanan@nitt.edu

Jatin Akhani
Department of Production Engineering,
National Institute of Tiruchirappalli,
Tamil Nadu, India
jatinthakkar97@gmail.com

Abstract

Natural resource conservation and environmental protection are essential due to the rapid depletion of natural resources and unfavorable environmental changes on a worldwide scale. Sustainable measures are targeted at decreasing ecological impacts, mainly through technical innovation in producing goods and processes, resulting in increased operational efficiency and higher natural resource management, lowering emissions and waste. Energy is a critical component in sustainable industrial measures to enhance overall production sustainability in pollution prevention and control.

Industrial process heating consumes more energy than any other type of energy in the manufacturing industry. Around the world, industrial heating systems are a significant energy consumer and CO2 (GHG) emitter. Most of the direct emissions within the company's organizational borders are caused by the combustion of the primary fuel used for plant heating, heat production, and other vehicle manufacturing operations. This motivated us to analyze and develop reliable sustainability measures for industrial heating systems.

A case study is conducted in the domain of industrial heating systems in an automobile manufacturing plant The study provides an intricate understanding to assess a heating system and its impacts. It will offer opportunities to opt for alternate possibilities of materials & methods to reduce the harmful effects. It also gives a brief idea of the application of the MCDM approach in energy decision making. Furthermore, finding heating applications procedures that use energy-efficient solar thermal systems is crucial for enabling industries with large solar energy potential to reduce their reliance on non - renewable and develop more environmentally friendly industrial systems in the future.

Keywords: Sustainability measures, Energy efficiency, MCDM, TOPSIS, Manufacturing system, Sustainable manufacturing.

I. INTRODUCTION

Nowadays, sustainable industrial systems are a must to reduce environmental and health concerns while preserving energy and natural resources. Industry must employ a variety of various implementations to improve processes and practices in the production system to attain sustainability [1]. Sustainable measures are targeted at decreasing environmental impacts mainly through technical innovation in the product-producing processes, which results in increased operational efficiency and higher natural resource management, lowering emissions and waste. Reduced energy consumption, minimizing waste, improved product durability, reduced environmental and health issues, improved product quality, and generation of renewable energy supplies are the key goals of establishing a sustainable manufacturing system [2]. A sizable portion of the world's overall energy consumption and CO2 emissions are caused by industrial activity [3]

Industrial process heating consumes more energy than any other type of energy in the manufacturing industry, accounting for more than 70% of total process energy end-use [4]. Around the world, reduction in energy consumption for industrial heating applications can be done by using various energy savings strategies [5]. The

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complexity of energy consumption sources, their variability, and the multiple levels of energy consumption in manufacturing systems are the focus of energy performance [6]. Reduced energy consumption and associated costs can result from investments in energy-efficient measures, which can offer a variety of benefits. Energy efficiency reduces reliance on fossil fuels, reduces harmful emissions, and has a positive influence on the environment [7].

Consequently, the broad adoption of energy-efficient technology and processes is a critical component in the manufacturing system for sustainable development [8]. The global decrease in carbon emissions is the primary force behind technological advances in energy efficiency and renewable energy. Several medium-energy-consuming enterprises are also encouraged to use energy-efficient technology due to the cost reductions associated with those technologies [9]. Employing renewable energy sources has several advantages, including reducing dependency on fossil fuel supplies and ecological damage from carbon emissions. [10,11]. The use of heat recovery and heat pumps lowers total costs while increasing system efficiency [12]. Khan et al discussed the impact to reduce the usage of fossil fuels, reduce the CO_2 emission level, and energy conservation [13].

To identify sustainability problems and suggest workable solutions in the specific application, the study is carried out systematically. A case study methodology is adopted in industrial heating systems in an auto manufacturing facility. MCDA TOPSIS approach is used to determine the viable solution in a conflicting condition in energy decision-making [14].

II. LITERATURE REVIEW

Measuring sustainability performance is essential for industrial firms that are also considering the wider impact of sustainability objectives on the economy and future policies [19]. More energy is used for industrial process heating than for any other purpose in the manufacturing sector, and it comes from several sources, including electricity, steam, and fuels [4]. Numerous process heating unit operations and related machinery are used to accomplish significant material transformations that are essential steps in the production of the majority of consumer and industrial goods [7].

How to lower energy consumption, production costs, and the environmental impact of the manufacturing systems is a key challenge for the industry's expansion [6]. Sustainability issues in manufacturing have motivated industries to focus more on suitable Industry focus has shifted to more appropriate operations and management methods because of manufacturing sustainability concerns, but there is no one proven strategy for successful adoption [23]. The first step in reducing dependence on fossil fuels is to use energy-saving programs designed to cut energy consumption and boost industrial energy efficiency [24]. Utilizing renewable energy sources is another method [5,12]. In a unique setting with a high-temperature heat pump system, energy use and greenhouse gas emissions can be decreased up to 90 percent and 40 percent, respectively [25].

Several studies have mentioned the advantages of solar heater water heating for domestic and industrial purposes and have stated the potential scope areas in order to use solar heat in industrial operations [26]. The majority of industrial solar thermal applications use solar water heating (SWH), which is the most affordable of all solar thermal technologies now in use [27]. The operations that require low temperatures, a constant amount of energy throughout the hours of sunlight, and high prices of conventional energy in the existing system are those that are most conducive to the integration of solar thermal energy in industrial applications [28]

Energy strategy can be effectively addressed by using MCDA, which is also increasingly used to resolve the conflicts that arise, by aggregating either performances or personal preferences, as it is a multidimensional problem [29]. Environmental, socio-economic, technical, and institutional constraints to energy planning are addressed using MCDM as an evaluation structure. In contrast to many other tools, MCDM tools are adaptable enough to address multi-criteria challenges linked to a variety of application [30].

III. PROBLEM DESCRIPTION

The present situation in the industrial sector is shifting in the direction of sustainability. A large global energy consumer and CO2 emitter are industrial heating systems. Even the slightest innovation or improvement in horizontal deployment can have a significant positive impact on sustainability. This motivated us to do research and develop credible sustainable heating system initiatives. The case study methodology is more dependable, they can deal with both tangible and intangible data, and they can calibrate outcomes. Many works successfully implemented case studies in Indian contexts using a variety of cutting-edge methodologies [31–33]. A case study methodology is utilized to analyze the best options for environmentally friendly heating applications in automobile manufacturing industry.

For the current study, gear component washing in an Engine shop was selected while reviewing the existing system. Presently Heating sources for washing gear components are catered with electric heaters will lead to high CO2 emissions, as fossil fuel (fuel-fired boilers) is the source of electricity generation. To enhance sustainability in the heating system there is potential scope for improvements in the factors like energy efficiency, energy conservation, and pollution reduction was reviewed. The major sustainability practices in the industrial heating system have been in two ways. First, modify the existing system to be better sustainable. Second, select and design alternate solutions from a sustainability point of view. Since selecting the best heating method involves complex decision variables. To develop a sustainable solution for the existing problem, two better sustainable heating systems were sized for the same application and their respective performance indicators were computed. The performance indicators of the existing electric heater system and alternatively sized systems were compared, and the appropriate system was selected as a sustainability measure.

IV. METHODOLOGY

The evaluation of heating systems is significant as they give information of its performance. The right data & information about are essential to deciding on appropriate improvement actions. The evaluation has four basic steps. First, examine the existing system, with detailed analysis of the energy use, energy demand, and energy losses in the existing system. This helps in reviewing possibilities to reduce the energy use or losses by suitable measures and identifies the parameters which are highly valued in terms of performance. This will give a basic understanding of the actual level of the performance performed by the present heating system, and it can be compared with the measures. Appropriate measures can be decided to achieve the desired level of performance numbers.

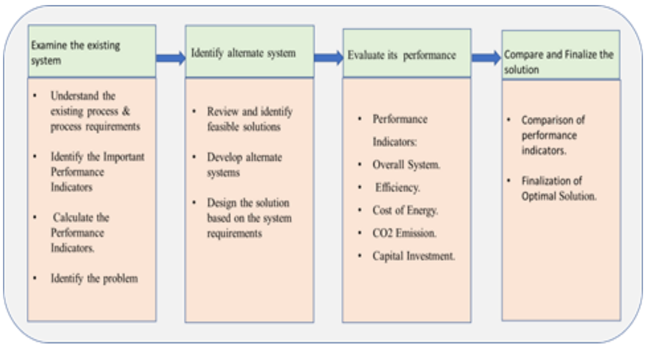

Figure 1. The methodology applied in this study

The goal of the present study is to select the best possible alternate energy-efficient heating system in sustainability. To achieve this goal, a methodology is proposed in this work. Figure 1. gives a brief overview of the used methods. The work is employed in a systematic way to analyze, develop, evaluate, and select the sustainable measure in an existing industrial system.

A. Analyze the performance measures of the existing system

First, we analyze the existing heating system and evaluate the performance measures. The evaluation of heating systems is important since it provides information about the system's performance. It's crucial to get the necessary data and information about a heating system's functioning before deciding on the best strategy [25]. Many factors contribute to the overall performance of the heating system & decision making of an industrial heating system, this framework has identified ten specific factors at two levels. These factors will add value to the evaluation and understanding of a particular system, and in turn, assists to select a suitable heating system for a specific application [34].

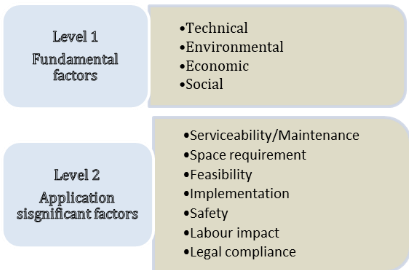

Figure 2. Performance indicators level

The fundamental factors in level 1 and application-specific factors in level 2 are described in Figure 2. The fundamental factors consist of technical, economic, environmental, and social factors. At the factory level, four significant performance indicators are considered for the systems' evaluation i.e System efficiency, Cost of energy, Impact on ecology (CO_2 emission), Capital investment & return of investment (ROI). Though various factors affect the net systems' performance in terms of System efficiency, Profitability & Impact on Ecology. The Level 2 factors are specific factors that demand unique requirements based on the specific application. These performance indicators can be used to assess an existing system, and compare an existing system with alternate systems, thereby guiding decision-making for energy conservation, energy efficiency improvements, and sustainability improvement activities. These indices will assist during the design stages of an industrial heating system by providing an intricate understanding of the sustainability factors.

The actual energy usage must be determined in order to assess the performance indicators of the particular industrial heating system. The actual energy consumption was measured with an Energy meter & it was observed that 18.31 KW was consumed in 3.23 hrs. Implies of 6.80 kW / hr and a maximum of 7.2 kW / hr were recorded as the highest energy consumption at a single point in time. The process is a high energy-consuming process, energy conservation can be reviewed. The cost of energy is INR 7.1 / kWh, which can be reviewed for cost reduction. Reduction in CO2 emission and reduction in energy consumption will add value from a sustainability point of view. The existing sustainability problems associated with the electric heater system are clearly defined.

Table 1. Performance of the electric heating system

1.	Energy consumption calculation: 7.2kW/hr
2.	CO2 emission calculation :129.8 Kg / day
3.	Cost of Energy: The cost of 1KW of energy from TNEB is INR 7.1 Cost of energy / day = INR 1124.64 / day
4.	Energy Conversion Efficiency – 97-99%

B. Alternate measures for the existing system

Industrial heating systems are a major energy user and CO_2 polluter across the world. Even a minor innovation or improvement, on horizontal deployment, can contribute to a large extent towards sustainability. In recent solar energy, utilization has been an important area of sustainability. And in the last decade, Industrial heat pumps have gradually attained maturity in terms of performance and reliability. Hence a Solar thermal system and a Heat pump system can be considered an alternative to the existing electric heater [35,36] [37]. The basic categories of industrial heating systems are based on the source of heat generation [38]. In the existing system energy delivered by an electric heater is 100% sourced from electricity, whereas in a solar thermal & heat pump system, energy from nature is utilized which is renewable. Such systems will help for sustainability. So as an alternate method, heat pump, and solar thermal systems were selected. Performance evaluation of the alternate sources is done with the data's obtained from the plant's energy management department (utilities & services department) and a comparative study was carried out to find the alternate method (boiler heating systems, electric heater systems, heat pump systems, solar systems) for an energy-efficient heating system [39].

C. **Evaluate performance measures of an alternate system.**

1) Heat pump system

The heat pump system's benefit is, it extracts heat energy from the atmosphere and makes use of it for the initial heating of the refrigerant before it gets into the compressor. Hence, the required external power is considerably reduced as a benefit. Conservatively, the matured industrial heat pumps offer a co-efficient of performance of 2.3~3.0, based on the effectiveness of the heat transfer and the use of the heat pump equipment's cooling benefits [40]. Based on the heating requirements heat pump with a capacity of 14 kW was decided. If the cold load is used, energy due to chiller load consumption can be saved.

Table 2. Performance of heat pump heating system

1.	Operating hours /day -22 hrs
2.	Energy required for process / hr = 7.2 kW.h (HMT data)
3.	COP of Heat pump 2.3
4.	To deliver 7.2 kWh of energy, a Heat pump will require [(1/2.3) *7.2 of energy 7.2] of energy
5.	Energy consumption by heat pump / hr = 0.43 * 7.2 = 3.1 kWhr.
6.	Energy-saving / year through heat pump = 28169.8 kWhr. /Year
7.	CO2 emission / year = 13380.4 Kg / year
8.	The cost of 1KW of energy delivery through the heat pump is INR
9.	Cost of energy / day = INR 483.51 / day
10.	Cost saving / year through heat pump = INR 2,00,032 / year

COP (Coefficient of Performance) of a Heat pump is Considered conservatively 2.3 excluding the cooling load Electricity Price. Table 2. shows the performance evaluation of deploying a Heat pump as an alternate measure.

2) The solar thermal system

A solar thermal system with EVT (Evacuated Tube Collectors) is another alternate method of electrical heater system [13]. The solar thermal system can also be integrated into an already existing boiler or electrical heater system constituting a hybrid system, which will primarily operate with the energy generated by the solar thermal system, and in case of poor sunlight or non-capability of the solar thermal to generate sufficient energy, the boiler or an electric heater operates as an auxiliary system. Based on the requirement of the application and geographical location parameters considered for the design of solar heating are:

Initial feed water temperature - 25˚C. The final temperature of the water/storage tank water temperature -65˚C. Sunshine hours in plant location (Chennai)- 6 hrs. Energy requirement / day-158.4 KW to be generated in 6hrs. Required Solar thermal capacity/sizing = 26.4 kWhr, M = Mass flow rate, liters per day 3405.6 liters (storage tank capacity, Mass flow rate, liters per day=3916.4litres (calculating with 15% buffer capacity).

Table 3. Performance of solar thermal heating system

1.	Investment Cost: Cost of investment / kWh, inclusive of piping & equipment = INR 45,000
2.	Total cost of investment = 26.4 x 45,000 = INR 11,88,000
3.	Total Cost = ETC equipment + Storage Tank + components (heat exchangers) + pump primary circuit & secondary circuit (Pumps & water lines) = INR 11,88,000
4.	Total energy used by the existing system per day = 158.4 kWh
5.	Total energy used by the present system per year = 49420.8 kWh
6.	Energy saved by deploying solar thermal system = 49420.8 kWh
7.	Cost-saving per year: Total energy saved / day = 158.4 KW
8.	Cost saved per day = 158.4 x 7.1 = 1124.64 INR
9.	Cost saved per year = 1124.64 x 312 = 3,50,888 INR

D. Comparison of Performance Indicators

The comparison of performance indicators of the different systems will provide an intricate understanding of the possibilities to reduce harmful effects, reduce energy consumption, optimize energy efficiency, reduce costs, etc. This understanding will be helpful in the design stage of an industrial heating system, to design the heating system in a sustainable manner. With respect to the case study, the performance indicators of alternate measures of heating systems with the existing system are compared.

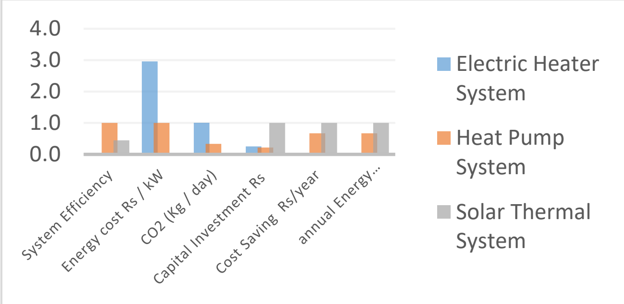

Figure 3. Comparison of heating system

A comparison of the performance of different heating systems is shown in Figure 3.

To summarize the comparison, calculations of system efficiency that the heat pump is more efficient compared to electric and solar heating. The advantage of the heat pump system is that it may heat up the refrigerant initially before it enters the compressor by using heat energy that is drawn from the atmosphere. As a result, energy use associated cost and CO_2 emission are significantly reduced. Solar thermal system heating systems reduced carbon footprint and energy cost. . Solar thermal systems have high capital investment costs & late Returns on Investment are disadvantageous. Practically, the Solar thermal system has less proven in large energy applications. It is not preferred due to its difficulty for system modification at times of process flexibility, the Heat pump can be considered energy-efficient but cost reduction and maintenance cost it's not recommended. A conflict arose between the sustainable performance and energy-efficient system. To choose the appropriate decision of the sustainable measure for the energy-efficient heating system.

The problem at hand will be tackled using a multicriteria approach that considers the requirement for sustainability as well as criteria for energy efficiency, cost-effectiveness, and technical viability. We should also confirm that the measures in the situation under co nsideration are financially viable. MCDA tool is the best option for finding a feasible solution in this scenario.

V. Sustainable performance evaluation with TOPSIS method

The MCDA tool is becoming more and more well-liked in the field of energy planning since it allows to make choices while simultaneously considering all the criteria and objectives [16]. MCDA is a tool that supports alternative energy technologies. The broad usage of MCDM techniques shows that they are effective at assisting decision-makers in addressing issues related to energy sustainability [17] [18]. MCDM TOPSIS is a preferred method in the evaluation of optional energy source which allows direct comparison with the alternative solutions [16]. The methodological framework developed for ranking the alternatives is TOPSIS (Technique for Order Preference by Similarity to Ideal Solutions) approach is easily scalable to tackle diverse energy sustainability problems [41]. The TOPSIS method requires minimal input data and results are easy to understand and it is with shortest geometrical distance to ideal result [42].

The approach enables a comparative evaluation of different heating system with existing fuel fired heating to enhance sustainability in the selected automobile production unit. While considering the selection of criterions in sustainable dimension, performance in the social dimension such as legal compliance, workers safety and labour impact can't be considered as it is not an implemented system. The criteria selected in the two levels for applying the TOPSIS methodology are presented in a hierarchical form as in Figure 4.

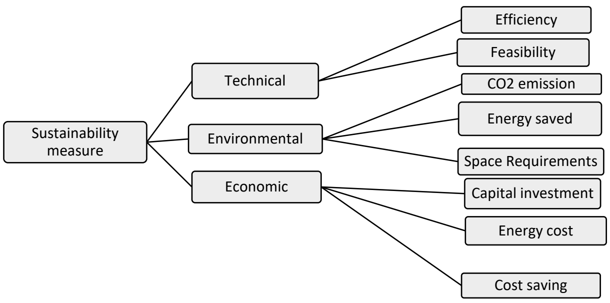

Figure 4. MCDA framework.

The TOPSIS approach uses distance measurements to calculate the relative strength of each alternative based on its positive ideal solution (PIS) and negative ideal solution (NIS). The given numbers are then ranked by evaluating a relative proximity degree for each option based on the values of their respective measures. The steps involved in TOPSIS methodology discussed as follows [15]:

Step 1: By placing criteria vertically and alternatives horizontally, an evaluation matrix is created.

$$Aij = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ a_{m1} & a_{m2}\vdots & \cdots & a_{mn} \end{bmatrix}$$

Step 2 – Evaluation matrix is converted to normalized decision matrix (R) with equation (1)

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{k=1}^{m} a_{kj}{}^2}}$$

$$\text{R matrix: } Rij = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ r_{m1} & r_{m2}\vdots & \cdots & r_{mn} \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Step 3: Third step includes normalized matrix's values multiplied by weights of each criterion and establishing the weighted normalized matrix. $Vij = \begin{bmatrix} w_1r_{11} & w_2r_{12} & \cdots & w_nr_{1n} \\ w_1r_{21} & w_2r_{22} & \cdots & w_nr_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \vdots \\ w_1r_{m1} & w_2r_{m2}\vdots & \cdots & w_nr_{mn} \end{bmatrix}$

Step 4: Finding the ideal best (A+) and ideal worst (A$^-$) for each criterion of each alternative from the above matrix: for beneficial criteria maximum value is the ideal best and minimum value is the ideal worst and vice versa for the non -beneficial criteria.

$$A^{+} = \{(max_i v_{ij} \backslash j\epsilon J), (min_i v_{ij} \backslash j\epsilon J')\} \quad \ldots\ldots (2)$$

$$A^{-} = \{(min_i v_{ij} \backslash j\epsilon J), (max_i v_{ij} \backslash j\epsilon J)\} \quad \ldots\ldots.. (3)$$

Step 5– Measures of separation are calculated using the Euclidian distance, which is used to quantify how far options stray from the ideal best and ideal worst solutions.

(S_i^*) denotes the Euclidian distance from the ideal best and calculated as in equation (4).

(S_i^-) denotes denotes the Euclidian distance from the ideal worst and calculated as in equation (5):

$$s_i{}^* = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j{}^*)^2} \quad (4)$$

$$s_{i^-} = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j{}^*)^2} \quad (5)$$

Step 6– Performance score is calculated as described by equation (6):

$$c_i{}^* = \frac{s_{i^-}}{s_i{}^* + s_{i^-}} \quad \ldots \quad (6)$$

If Ci * values lies between 0 and 1. Value 1 representing the best ideal solution and zero denotes the ideal worst solution

Step 7- Based on the performance score, the alternatives can be ranked.

Table 4. TOPSIS method result and Rank

Heating Systems	Performance score(%) Pi	Rank
Fuel fired boiler	51.21	4
Electric heater	56.91	3
Heat pump system	62.95	1
Solar thermal system	61.62	2

Using the chosen alternatives and competing criteria, TOPSIS analysis was performed on the problem as stated above, and the results are shown in Table 4. A heat pump heating system is the most efficient option for the chosen system.

TOPSIS ranking hierarchy is Heat pump heating system< Solar thermal heating< Electric heating< Fuel fired heating.

VI. RESULTS

The performance indicators of heating systems are compared, and the result as shown in Figure 3. Analytical comparative study shows a conflict between the performances between system efficiency (Heat pump system) and energy consumption (Solar thermal system), thereby it's difficult to find a sustainable solution. If heat pump sourced with renewable energy source can be selected as an appropriate solution from this case study problem, but practically it is not feasible.

Under this uncertainty MCDA TOPSIS method is selected for finding the best feasible heating system. TOPSIS result with ranking of the alternatives are given in Table 4. With MCDA heat pump system secured the first, second is solar thermal system. Hence the heat pump system is the best feasible energy efficient heating system for heating washing liquid for engine component washing in plant to enhance sustainability in manufacturing industry.

With respect to the case study, it can be inferred that there is significant potential to reduce CO_2 emission & to reduce energy consumption with an energy efficient system.

VII. CONCLUSIONS

This paper combines analytical method and MCDM methods to find sustainable measures in heating applications. A case study with a systematic framework is conducted in an automobile manufacturing plan. Steps involved are analyse, identify problem, suggestion sustainable measures, evaluation, and infer the result. The performance indicator values provide an intricate understanding about the effect of the overall systems' energy efficiency and sustainability.

Comparative study of the alternatives shows that integrated system with renewable energy source is the best technique for many applications based on the feasibility. In this specific case, a conflicting situation arise for the selection of energy efficient sustainable heating after analytical approach, so MCDA TOPSIS method is selected to rank the performance different heating system. It helps us to identify the best feasible measures within a set of predetermined criteria.

This framework will be helpful in reviewing the current procedure, comparing it to alternative methods, and clarifying opportunities for energy conservation, improving energy efficiency, and moving toward sustainability. This study helps to understand the application of MCDA in energy decision making. The result shows that there is a significant scope of improvements can be done to achieve the sustainability goal such as energy efficient system, energy saving thereby reduction in GHG (CO_2) emission, energy cost, maintenance cost, capital investment etc. Also identifies in a feasible situation integration of renewable system with energy efficient system is the best sustainable measure. Renewable energy source with energy efficient that can be recommended as the best sustainable measure in low and moderate temperatures.

This study demonstrates that even minor improvements may lead the industrial system to advance to sustainability goals. Harmful impacts can be predicted & appropriate measures can be taken to prevent the adverse effects, thereby shifting towards industrial sustainability.

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