

Energy efficiency improvement solutions for Iran's ceramic tile industry with fuzzy Delphi method

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ABSTRACT

Energy efficiency is a matter of immense importance for a wide variety of sectors, and especially industry as the driver of economic growth. Ceramic tile manufacturing is a basic industry that has turned into a nucleus of industrial development in some countries. However, this industry is extremely energy intensive. Iran has a strong ceramic tile industry consisting of a significant number of manufactories with notably high production output and export. Given the energy-intensity of this industry, it can considerably benefit from energy efficiency improvement measures. In this study, first, a number of potential solutions for improving energy efficiency in Iran's ceramic tile industry were identified by reviewing the subject literature and surveying a group of experts. The fuzzy Delphi method was then used to identify and ultimately prioritize 22 appropriate solutions from technical, managerial and production process standpoints for the said purpose. The results showed that the highest-priority solutions for energy efficiency improvement in the ceramic tile industry are Implementation of regular maintenance program of facilities and equipment, Adjusting the air in the kilns and burners, and Replacing electro motors according to the load of slurry mixers, and the lowest-priority solutions for this purpose are Insulation of transmission and distribution routes (steam and hot water pipes), Implementation of lighting management system in the factory, and Installation of heat exchangers to recover wasted heat (exhaust gases and the kiln's cooling system).

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1. Introduction

Energy has played a key role in the evolution of human life and technology over the course of history. Energy is a primary requirement for economic growth, technological development, and even research at the national level and a fundamental input that enables nations to compete at the global level [1]. However, the

steadily increasing energy demand has raises some concerns about forthcoming energy supply problems, energy waste, environmental impacts, and climate change and global warming [2]. The sharp rise in energy demand also has some implications for the economic prosperity of countries. Given the profound impacts of efficiency on the economic performance of countries, efficiency improvement is believed to be as the best strategy for boosting economic growth without overdependence on production inputs, including energy. It has been shown that

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energy efficiency improvement not only boosts gross domestic product (GDP) and competitiveness, but also improves public welfare and allows a country to effectively resolve its energy supply-demand problems and reduce its greenhouse gas emissions [3].

Energy consumption analysis provides useful information to policy makers and planners to improve energy efficiency [4]. According to energy statistics, over the last three decades, industrialized countries have experienced a decline in energy demand growth despite maintaining their GDP growth [5]. However, this is not a global trend. With the current rate of global population growth, the industrial sector is expected to become the world's biggest energy consumer in the next decade. The limitations of existing energy sources on the one hand and the steadily growing demand on the other hand have made it extremely important to discuss and address the existing and impending energy problems. One approach to energy management is to identify the origins of energy waste in each sector and adopt appropriate measures to eliminate the problem. The biggest energy consumer sector of each country tends to be its industrial sector, which also tends to have the highest energy waste. The methodology whereby the factors of energy waste in this sector are identified and analyzed is known as energy audit.

Tiles and other such ceramic objects have been among the earliest human discoveries and creations thanks to the abundance of raw materials and ease of production. Tile making and tiling as an industry and art have been a major component of the architecture of many countries, including Iran. In some countries, this industry has been a core part of the economy throughout history and has served as the nucleus of modern industrial development. The importance of this industry goes beyond technical and economic aspects and extends to social and even political dimensions. The world's biggest producers of ceramic tiles are Asian countries [1].

The challenges of the ceramic tile industry can be divided into three categories: raw materials, machinery-equipment, and human resources. Problems of the first and third categories include poor mining efficiency due to technological deficiencies and poor labor

efficiency. The raw materials used in ceramic tile manufacturing are mostly mineral and non-metallic materials that are processed by heating and shaped into the desired geometry. The said heating is done inside high temperature kilns and usually takes a long time to finish [6]. A few stages of ceramic tile manufacturing consume some amounts of electrical energy; these include raw material transport (for example to mills), blending, pressing, and molding. However, the manufacturing process also requires significant amounts of thermal energy for its endothermic reactions in the stages that involves chemical transformation of materials, including drying and firing. These two stages account for most of the energy consumption of the manufacturing process [7]. So, the ceramic tile industry can be called an energy-intensive industry [8-9]. For example, Ruivo et al. (2021) in their study investigated that the ceramic manufacturing sector accounted for 28% of industrial energy consumption in 2019 [10]. In some studies, thermal energy loss in ceramic tile production processes has been reported to be more than 80 to 95% [6, 11]. The amount of energy consumed in the ceramic tile manufacturing process is also a major production cost item, thus greatly affecting the final price of the product [6]. This further highlights the importance of energy audits and optimization in this industry. In this industry, energy efficiency can be improved by replacing old machinery, equipment and technologies with new ones, modernizing and automating production lines, and especially using high efficiency kilns [12]. Energy efficiency improvement via technological strategies is essential for the future of this industry not only for economic reasons but also as a response to existing and emerging energy and environmental crises. Most of the energy consumed in the ceramic tile industry comes from fossil fuels, which is a problem for many countries that have committed to reduce their greenhouse gas emissions. In Iran, the ceramic tile industry is extremely wasteful in its energy use, which can be attributed to the relatively low price of energy in the country, use of outdated and worn out equipment and machinery, sanctions (which makes it difficult to import new technologies and machinery), and how much this product is exported abroad.

As a result, the energy consumption of the Iranian ceramic tile industry is significantly higher than the global average. Thus, improving the energy efficiency of the Iranian ceramic tile industry can be expected to offer major economic and environmental benefits. This study aimed to investigate the variety of technical, managerial and production solutions that can be realistically implemented to improve the energy efficiency of the Iranian ceramic tile industry through consultation with a panel of experts and ultimately identify the most effective solutions for this purpose.

The unique contribution of this study compared to other researches is the following: To identify solutions to improve energy efficiency in the tile and ceramic industry, a comprehensive approach is included; The process, production equipment and management of energy consumption at the level of tile and ceramic factories have been investigated. Also, the application of the fuzzy Delphi method with the aim of identifying solutions to improve energy efficiency has rarely been used in other researches in this field.

The following points indicate the novelty of the present study:

- Providing solutions with the aim of improving energy efficiency and focusing on the critical points of energy consumption in the ceramic and tile industry,
- Using the opinions of tile and ceramic industry experts for to identify solutions,
- Using the Fuzzy Delphi method to identify and prioritize Energy efficiency solutions.

This paper is organized as follows: In Section 2 introduces a review of the relevant literature. In Section 3, presents how we adopt the methodology, Fuzzy Delphi and Statistical population and sample. In Sections 4, presents the Results that Identifying effective solutions for energy efficiency improvement in the ceramic tile industry. The discussion is presented in Section 5. Finally, the concluding is included in Section 6.

2. Literature review

Efficiency is a general term with multiple definitions and measures in economics. For a production process, efficiency can be generally

defined as the ratio of useful output produced to the total amount of input consumed in the process. Likewise, energy efficiency can be described as the ratio of useful output (production) to the total input energy. Thus, increasing energy efficiency means consuming less energy to produce the same level of output or producing more output with the same amount of energy [13]. Energy efficiency in the industrial sector has been subject of many studies. In one study, Liu (1995) investigated the energy efficiency of the cement industry three scenarios: using high-cost, state-of-the-art precalciner kilns; moderate-cost advanced vertical kilns; and low-cost vertical kilns without advanced technology and proposed some solutions for increasing the energy efficiency in this sector [14]. Zabihi et al. (2006) proposed a number of practical solutions for optimizing electrical energy consumption in a cement factory based on an energy audit [15]. In a study by Rastgoftar et al. (2006) on the energy consumption in the ceramic tile industry, after reviewing the ceramic tile manufacturing processes and methods, they discussed the energy carriers used in different stages of this industry and the areas in which there is potential for energy saving [16]. In the research carried out by Chu et al. (2009) on the drivers of energy efficiency in China, they used an economic growth model to identify the determinants of energy efficiency, ultimately finding that energy efficiency is related to the share of industry in GDP, share of public sector in gross domestic product, and share of electricity in total energy consumption. They also stated that for better energy efficiency, the country's industrial development structure should shift from industry to service and its energy consumption structure should shift to clean energies [17]. Fazeli Vissari et al. (2016) provided a roadmap for energy optimization in the Iranian ceramic tile industry. For this purpose, these researchers first examined the state of the country's ceramic tile industry and compared it with the global competition, and then formulated some solutions for optimizing energy consumption in the industry accordingly [18]. Hadipour Zimsar et al. (2018) conducted a research on increasing energy efficiency in the tea processing industry. They identified the factors affecting energy efficiency in the tea industry by asking the managers of tea production units. the factors

were divided into three broad categories of technical, managerial-policy, and knowledge-skill. They also introduced the most important factors for improving energy efficiency in tea production factories in Gilan province [19]. In a study by Oyebanji et al. (2022) on the subject of energy efficiency and environmental deregulation in Greece, findings showed that improving energy efficiency has great environmental benefits in the form of CO₂E reduction. They also proposed a number of innovative policies for controlling carbon emissions by increasing energy efficiency in Greece. According to this study, the adoption of low-carbon circular economy with high resource efficiency can boost environmental protection, strengthen green growth, create new jobs, and reduce unemployment in Greece [20]. Li (2022) investigated the factors of energy efficiency in seven emerging economies from 2004 to 2020 using the Method of Moments Quantile Regression (MMQR). The results of this study showed that financial inclusion, economic growth, globalization, human capital and composite risk were important factors of energy efficiency in all quantities [21]. Shah et al. (2022) examined the trends and determinants of energy efficiency in South Asian countries, stating that energy efficiency is the most efficient solution for addressing increasing energy demand. They also investigated the role of energy efficiency and productivity growth in the ecological improvement of South Asia and evaluated the determinants of energy efficiency change (efficiency change or technological change) in different South Asian countries. The results of this study showed that the main determinant of energy efficiency growth is technological change rather than efficiency change. These researchers also reported that the average energy efficiency from 2001 to 2010 has been significantly different from 2011 to 2019. Their results ultimately showed that energy efficiency and productivity in South Asia have decreased over the course of the studied period, a trend that they attributed to inefficiency in energy conversion, extensive resource utilization, and low production growth [22].

The literature contains a number of studies on the subject of energy efficiency in ceramic tile manufacturing and the methods of improving energy efficiency in this industry.

Some of the more notable studies in this field are mentioned below.

In a study by Cassani (2010) on energy recovery from kiln, spray dryer, and mill, it was stated that roller kilns account for most of the thermal energy waste in ceramic tile manufacturing [23]. Introducing a definition for “waste heat” in industrial processes, Bending et al. (2013) stated that the kilns used in ceramic tile manufacturing are extremely inefficient and waste a major part of their energy input through stacks and coolants [24]. In a study by Mezquita et al. (2014), they stated that a major part of thermal energy consumed in the production of ceramic tiles is wasted in the firing stage, and roller kilns, which are the type of kiln most widely used in this stage, are fueled by natural gas and tend to waste over 50% of their energy input through stacks and coolants. These researchers proposed a method based on adjusting certain kiln operating parameters for energy saving in the kiln by making part of the cooling gas return to the firing chamber instead of being released into the atmosphere [11]. In the study conducted by Ciacco et al. (2017) on the energy consumption of the Brazilian ceramic tile industry, they stated that this industry has a prominent position in the Brazilian economy and a notable contribution to the country’s GDP, but also accounts for approximately 1.9% of the total energy consumption in Brazil and 5.8% of all energy consumed in the Brazilian industrial sector (2014 statistics). They added that the energy consumed in this industry is prominently fossil fuel, mainly natural gas. After quantifying the energy consumption of the ceramic tile manufacturing process by using experimental data from each stage of the process, they found that approximately 56% of all energy used in the entire manufacturing process is consumed in the firing and sintering stages, 30% in the atomization stage, and 14% in drying. They also reported that manufacturing ceramic tiles by the wet process consumes four times more energy than using the dry process [25]. Manrique et al. (2018) analyzed the barriers to the implementation of energy efficiency measures in Colombia’s ceramic tile industry. This study reported that the greatest barriers to the implementation of said measures are hidden costs followed by corporate values.

This study also found a positive correlation between potential energy savings, the degree of obsolescence of equipment, and the overall barrier to the implementation of energy efficiency measures. The results also showed that the identified barriers can be overcome by devising some programs for reducing uncertainty in the adoption of new technologies [1]. In their review of energy efficiency developments, technologies and strategies in the ceramic industry, Castro Oliveira et al. (2020) stated that since heat-based manufacturing processes tend to have extremely high energy loss, they can significantly benefit from waste heat recovery (WHR) strategies. They recommended a number of actions for improving energy efficiency in ceramic tile manufacturing, which include using high-efficiency burners, recycling hot air from kilns to other processes, installing heat exchangers, and using gas turbines for combined heat and power generation [26]. In a study by Türkmen et al. on the sustainability of the ceramic tile industry in Turkey, they compared the environmental impacts of current manufacturing process under four scenarios: 1- heat recovery for use in the drying process, 2- improving combustion efficiency, 3- producing thinner ceramic tiles to minimize energy and material consumption, and 4- a combination of all other scenarios. They analyzed the implications of each scenario for each stage of ceramic tile production and estimated the impact on sustainability [27].

3. Methodology

This study classifies as applied research (considering the expected benefits for stakeholders, especially policymakers and industry owners), subscribes to a constructivist research philosophy, and is a descriptive survey in terms of research objectives and methodology. The data collection methods used in the study were survey and review of literature and documents. Taking a mixed research approach, the study used a combination of qualitative and quantitative methods. The goal of the study was to identify effective solutions for improving energy efficiency in Iran's ceramic tile industry. In the course of the study, first, a library study was performed to explore

relevant literature and documents and then the fuzzy Delphi method was used to survey a group of experts in order to generate a list of effective solutions for improving energy efficiency in the ceramic tile industry. In the end, the identified solutions were prioritized. The schematic diagram of the research model for identifying effective solutions for energy efficiency improvement in Iran's ceramic tile industry is presented in Fig. 1.

3.1. Fuzzy Delphi

The Delphi method is a decision-making tool and a qualitative method of forecasting based on the consensus of a group of experts [28]. It was first introduced by Dulkey and Helmer in 1963. The original version of the method, known as classic Delphi, has several problems including high cost, difficulty to reach convergence in expert opinions, and the high probability of some expert opinions to be ignored. In 1985, Murray, Pipino, and Gigch introduced the fuzzy Delphi theory to not only resolve these problems but also reduce ambiguities and conflicts. In this method, the opinions of experts are converted into triangular fuzzy numbers. More specifically, the maximum and minimum values determined by experts make up the two endpoints of triangular fuzzy numbers. The fuzzy Delphi method has several advantages over the classic Delphi, which include encouraging unbiased responses, requiring fewer surveys, better performance in receiving feedbacks, and better statistical analysis of opinions. In this study, the opinions of experts were turned into triangular fuzzy numbers so that they could be analysed by the fuzzy Delphi method. Therefore, the maximum and minimum values of the expert opinions were considered as the boundary points of fuzzy triangular numbers [29]. For the triangular fuzzy number $Z = (l, m, u)$, the membership function is in the following form:

$$\mu_z = \begin{cases} 0, & x < l \\ \frac{(x-l)}{(m-l)}, & l < x < m \\ \frac{(m-x)}{(m-u)}, & m < x < u \\ 0, & x > u \end{cases} \quad (1)$$

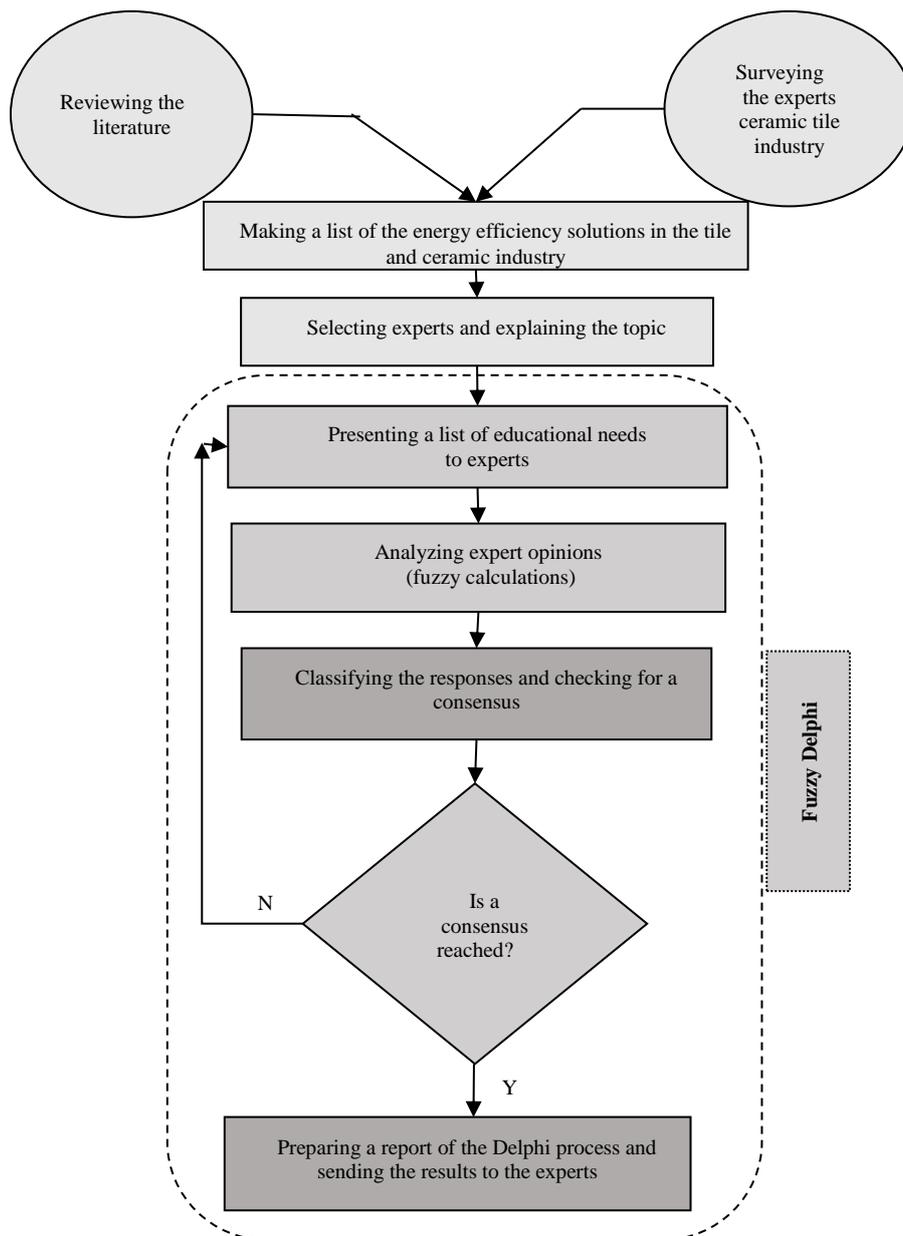


Fig. 1. Research process

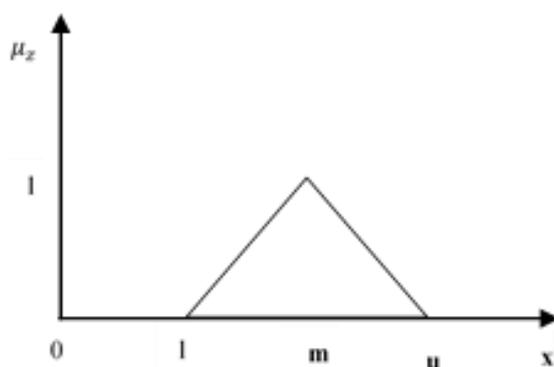


Fig. 2. A triangular fuzzy number

Table 1. Conversion of linguistic variables

Linguistic variable	Fuzzy number(l, m, u)
Very low	(0, 0, 0.25)
Low	(0, 0.25, 0.5)
Moderate	(0.25, 0.5, 0.75)
High	(0.5, 0.75, 1)
Very high	(0.75, 1, 1)

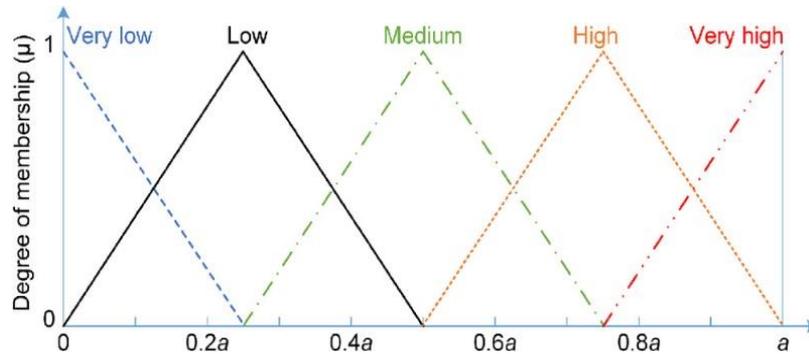


Fig. 3. Relationship of fuzzy numbers with the Likert spectrum

Figure 2 shows a triangular fuzzy number.

The responses were fuzzified through conversion into equivalent fuzzy numbers using the Likert spectrum based on the conversion rules given in Table 1.

The relationship between the fuzzy numbers given in Table 1 and the Likert spectrum is shown in Fig. 3.

Since crisp values are easier to comprehend, the final output of the fuzzy system was converted to crisp values for better interpretability. This operation is known as defuzzification. While there are several methods for defuzzification, this study used Minkowski’s defuzzification formula, which is given in Eq. (2).

$$x = m + \frac{\beta - \alpha}{4} \tag{2}$$

$$A_i = (a_1^{(i)}, a_2^{(i)}, a_3^{(i)}), i = 1.2.3 \dots n \tag{3}$$

$$A_{ave} = (m_1, m_2, m_3) = \left(\frac{1}{n} \sum_{i=1}^n a_1^{(i)}, \frac{1}{n} \sum_{i=1}^n a_2^{(i)}, \frac{1}{n} \sum_{i=1}^n a_3^{(i)} \right) \tag{4}$$

In the above equation, A_i denotes the opinion of expert i , and A_{ave} represents the average of all the expert opinions.

3.2. Statistical population and sample

Considering that over 60% of Iran’s ceramic tile production takes place in Yazd province, which hosts over 100 ceramic tile

manufacturing plants, the geographical scope of the study was limited to this province. Since qualitative studies depend on the opinions of people with expertise in the subject of interest, the study had to use a statistical population comprised of relevant experts. In this study, the statistical population consisted of people with enough experience and knowledge in relation to the ceramic tile industry, especially energy efficiency in this field. The knowledge requirements for experts were (i) having a master’s or higher degree with relevance to energy efficiency/consumption in manufacturing units and (ii) being a university professor with relevant education. The experience requirement for experts was having at least five years of professional work experience in the field of energy efficiency or equally long collaboration with energy audit organizations. Since the experts to be sampled were working in different departments of different organizations at different levels, it was decided to use a non-probability purposive sampling method for selecting experts. Based on the criteria, the panel was formed with 12 experts selected from the organizations that were relevant to the research objectives. Table 2 shows the number, degree, and expertise of people include in the panel of experts of this study.

Table 2. Profile of expert panel members

No.	Degree	Field of education	Occupation
1	PhD	Industrial engineering	Faculty member
2	PhD	Electrical engineering	Faculty member
3	PhD	Industrial management	Faculty member
4	PhD	Mechanical-energy engineering	Faculty member
5	Master's	Industrial engineering	Energy audit expert
6	Master's	Mechanical engineering	Energy audit expert
7	Master's	Electrical engineering	Energy audit expert
8	PhD	Mechanical engineering	Energy inspection company
9	Bachelor's	Energy	Energy inspector
10	Bachelor's	Electrical engineering	Factory manager
11	Master's	Chemical engineering	Factory manager
12	Master's	Mechanical engineering	Quality control manager

4. Results

This study was conducted in two stages. In the first stage, the goal was to identify solutions for improving energy efficiency by reviewing the research literature and surveying experts. In the second stage, the effective solutions for energy efficiency improvement in ceramic tile manufacturing were identified using the fuzzy Delphi method.

4.1. Identification of effective solutions for energy efficiency improvement in the ceramic tile industry using fuzzy Delphi method

In this study, the goal was to identify the variety of technical, managerial and production solutions that can be implemented to improve the energy efficiency of a ceramic tile factory. To achieve this goal, first, the relevant literature was carefully studied and explored to identify the barrier, challenges and potential solutions in relation to energy consumption in ceramic tile manufacturing and generate a list of solutions for improving energy efficiency in this process. Then, a number of interviews were conducted with relevant experts and managers working in different departments of ceramic tile factories. In these sessions, the interviewees were given the prepared list and were asked to share their opinion on the current state of the industry from six points of view: energy organization, energy policy, energy information systems, motivation, progress, and investment. The response given by the experts were used to get a broad picture of the current state of the Iranian ceramic tile industry. Then, a list of potential solutions for moving toward a

more desirable state was prepared. To identify appropriate solutions from a technical standpoint, the results of energy audits and library studies were provided to experts and the best options were identified using the fuzzy Delphi method. In this process, the solutions proposed by each expert were shared with others to determine their merits and limitations. Eventually, 22 appropriate energy efficiency improvement solutions were identified. The solutions are presented in Table 3.

4.2. First stage survey

In the first step, the panel members were given the list of suggested solutions and were asked to rate them on a Likert scale. After collecting the opinions, the ratings given to each option were determined and organized. The results of this survey are presented in Table 4.

After determining the frequency of ratings given to each solution, the triangular fuzzy mean and defuzzified mean for each variable were calculated using the Minkowski formula. The results of these calculations are presented in Table 5.

4.3. Second survey

After calculating the defuzzified averages from the first stage, the experts were surveyed for the second time and their responses regarding the degree of importance of each variable based on the five-point Likert spectrum were collected. According to the fuzzy Delphi method, the results of these two surveys should be compared and matched. The results of this survey are given in Table 6.

As in the first stage, after counting the number of responses given to each Solution, their triangular fuzzy mean for each variable was computed and the result was defuzzified by the Minkowski formula. The results of this step are provided in Table 7.

After performing these calculations for both surveys, it was necessary to examine the difference between the defuzzified means of research variables in the two stages. This difference is given in Table 8.

Table 3. energy efficiency improvement solutions extracted from the related literature

No.	Solutions	group	REF
1	SO1 Using speed and power controllers in alternating compressors	Technical	[25, 30]
2	SO2 Separation of electricity consumed by each part by installing a separate meter in the power supply path	Managerial	[25, 31]
3	SO3 Power factor correction by installing capacitors for main consumers	Technical	[32]
4	SO4 Increasing the load factor of the factory by reducing the demand and reducing the consumption simultaneity factor	Managerial	experts' opinion
5	SO5 Reducing losses in the compressed air production and distribution system	process	[10, 30, 33]
6	SO6 Improving the efficiency of compressors by reducing the inlet temperature	Technical	[10, 34]
7	SO7 Implementation of regular maintenance program of facilities and equipment	Managerial	[1, 35]
8	SO8 Installing air curtain systems or automatic doors	Technical	[36]
9	SO9 Implementation of lighting management system in the factory	Managerial	[37, 38]
10	SO10 Insulation of transmission and distribution routes (steam and hot water pipes)	Process	[39]
11	SO11 Insulation of heat exchangers, boilers and spa expansion sources	Process	[39]
12	SO12 Proper loading of transformers and AC motors	Managerial	[40]
13	SO13 Management of electricity consumption during peak hours (presses, ball mills, stone crushers and glazers)	Managerial	experts' opinion
14	SO14 Soft starters in ball mill electro motors using power controllers	Technical	[41]
15	SO15 Replacing electro motors according to the load of slurry mixers	Process	[1, 40, 42]
16	SO16 Installation of heat exchangers to recover wasted heat (exhaust gases and the kiln's cooling system)	Process	[33, 24, 31, 34, 39]
17	SO17 Replacement of roller furnaces with tunnel furnaces	Technical	[6, 11, 23, 24, 34, 39]
18	SO18 Adjusting the air in the kilns and burners	process	[11, 33, 31, 34, 27]
19	SO19 Process control and kiln's firing cycle	Process	[11, 23, 31, 27]
20	SO20 Adjust kiln's thermocouples	Managerial	[31]
21	SO21 Sealing pores between the rail wall and wagon in the kilns	Technical	[39]
22	SO22 Improving the efficiency of kiln fan electro motors	Managerial	[1, 33]

Table 4. Results of counting the responses given in the first survey

Solutions	Very high	High	Moderate	Low	Very low
SO1	2	3	4	2	1
SO2	3	2	3	2	2
SO3	1	2	2	4	3
SO4	2	3	2	3	2
SO5	3	4	2	2	1
SO6	2	4	2	2	2
SO7	4	3	2	2	1
SO8	2	2	3	4	1
SO9	1	2	5	2	2
SO10	1	2	4	2	3
SO11	1	1	4	4	2
SO12	2	3	3	3	1
SO13	3	3	3	2	1
SO14	2	1	4	3	2
SO15	2	3	4	2	1
SO16	2	3	1	4	2
SO17	3	4	2	2	1
SO18	1	5	3	2	1
SO19	0	4	2	3	3
SO20	1	3	5	2	1
SO21	1	4	4	2	1
SO22	3	3	2	3	1

Table 5. Average views of experts in the first survey

Solutions	Triangular fuzzy mean (m, α, β)	Defuzzified mean
SO1	(0.563, 0.333, 0.771)	0.672
SO2	(0.542, 0.333, 0.729)	0.641
SO3	(0.375, 0.188, 0.604)	0.479
SO4	(0.500, 0.292, 0.708)	0.604
SO5	(0.625, 0.396, 0.813)	0.729
SO6	(0.542, 0.333, 0.750)	0.646
SO7	(0.646, 0.417, 0.813)	0.745
SO8	(0.500, 0.271, 0.708)	0.609
SO9	(0.458, 0.250, 0.688)	0.568
SO10	(0.417, 0.229, 0.646)	0.521
SO11	(0.396, 0.188, 0.625)	0.505
SO12	(0.542, 0.313, 0.750)	0.651
SO13	(0.604, 0.375, 0.792)	0.708
SO14	(0.458, 0.250, 0.667)	0.563
SO15	(0.563, 0.333, 0.771)	0.672
SO16	(0.479, 0.271, 0.688)	0.583
SO17	(0.625, 0.396, 0.813)	0.729
SO18	(0.563, 0.333, 0.792)	0.677
SO19	(0.396, 0.208, 0.646)	0.505
SO20	(0.521, 0.292, 0.750)	0.635
SO21	(0.542, 0.313, 0.771)	0.656
SO22	(0.583, 0.354, 0.771)	0.688

Table 6. Results of the counting of responses given in the second survey

Solutions	Very high	High	Moderate	Low	Very low
SO1	1	4	4	1	2
SO2	3	2	1	3	3
SO3	2	2	4	1	3
SO4	3	2	3	3	1
SO5	2	4	4	2	0
SO6	3	2	3	1	3
SO7	5	3	2	2	0
SO8	3	0	4	5	0
SO9	2	0	4	3	3
SO10	1	3	3	3	2
SO11	1	2	4	5	0
SO12	3	3	2	3	1
SO13	4	3	2	1	2
SO14	2	3	3	3	1
SO15	3	3	5	0	1
SO16	2	1	2	4	3
SO17	4	3	1	3	1
SO18	2	5	3	2	0
SO19	1	4	2	3	2
SO20	2	5	3	1	1
SO21	2	2	5	1	2
SO22	3	4	1	3	1

Table 7. Average views of experts in the second survey

Solutions	Triangular fuzzy mean (m, α , β)	Defuzzified mean
SO1	(0.521, 0.313, 0.750)	0.630
SO2	(0.479, 0.292, 0.667)	0.573
SO3	(0.479, 0.292, 0.688)	0.578
SO4	(0.563, 0.333, 0.750)	0.667
SO5	(0.625, 0.375, 0.833)	0.740
SO6	(0.521, 0.333, 0.708)	0.615
SO7	(0.729, 0.479, 0.875)	0.828
SO8	(0.521, 0.271, 0.708)	0.630
SO9	(0.396, 0.208, 0.604)	0.495
SO10	(0.458, 0.250, 0.688)	0.568
SO11	(0.479, 0.229, 0.708)	0.599
SO12	(0.583, 0.354, 0.771)	0.688
SO13	(0.625, 0.417, 0.792)	0.719
SO14	(0.542, 0.313, 0.750)	0.651
SO15	(0.646, 0.417, 0.833)	0.750
SO16	(0.396, 0.208, 0.604)	0.495
SO17	(0.625, 0.396, 0.792)	0.724
SO18	(0.646, 0.396, 0.854)	0.760
SO19	(0.479, 0.271, 0.708)	0.589
SO20	(0.625, 0.396, 0.833)	0.734
SO21	(0.521, 0.313, 0.729)	0.625
SO22	(0.604, 0.375, 0.792)	0.708

Table 8. Difference between the defuzzified means in the two stages

Solutions	Defuzzified mean from the first stage	Defuzzified mean from the second stage	Difference
SO1	0.672	0.630	0.042
SO2	0.641	0.573	0.068
SO3	0.479	0.578	0.099
SO4	0.604	0.667	0.063
SO5	0.729	0.740	0.010
SO6	0.646	0.615	0.031
SO7	0.745	0.828	0.083
SO8	0.609	0.630	0.021
SO9	0.568	0.495	0.073
SO10	0.521	0.568	0.047
SO11	0.505	0.599	0.094
SO12	0.651	0.688	0.036
SO13	0.708	0.719	0.010
SO14	0.563	0.651	0.089
SO15	0.672	0.750	0.078
SO16	0.583	0.495	0.089
SO17	0.729	0.724	0.005
SO18	0.677	0.760	0.083
SO19	0.505	0.589	0.083
SO20	0.635	0.734	0.099
SO21	0.656	0.625	0.031
SO22	0.688	0.708	0.021

Table 9. Ranking of the effective solutions

Rank	Solutions	Rank	Solutions
1	SO7	12	SO1
2	SO18	13	SO8
3	SO15	14	SO21
4	SO5	15	SO6
5	SO20	16	SO11
6	SO17	17	SO19
7	SO13	18	SO3
8	SO22	19	SO2
9	SO12	20	SO10
10	SO4	21	SO9
11	SO14	22	SO16

Table 8 shows the difference between the results of the first and second stage surveys. As can be seen, the difference between the defuzzified means of the two stages was less than 0.1, indicating the completion of the survey process as per the instructions of the fuzzy Delphi method. In other words, these results showed the consistency of the outcomes of the first stage and the second stage, suggesting that the experts have reached a consensus regarding energy efficiency solutions in the ceramic tile industry and the second stage can be stopped. This means that the experts reached relatively the same understanding of energy efficiency solutions and could approve them as effective solutions for the said purpose.

Considering the research objective, the next step was to prioritize the identified solutions. This prioritization was performed based on the defuzzified means obtained for the variables in the second stage of the survey. The results of this prioritization are presented in Table 9.

After analyzing technical, managerial and production (equipment and facilities) solutions for improving energy efficiency in the ceramic tile industry based on expert opinions using the fuzzy Delphi method, the 22 solutions were prioritized as shown in Table 9. According to the opinion of experts, the highest-priority solutions for energy efficiency improvement in the ceramic tile industry are: Implementation of regular maintenance program of facilities and equipment, Adjusting the air in the kilns and burners, and Replacing electro motors according to the load of slurry mixers. Also, the lowest-priority solutions for energy efficiency improvement in this industry are: Insulation of transmission and distribution routes (steam and hot water pipes),

Implementation of lighting management system in the factory, and Installation of heat exchangers to recover wasted heat (exhaust gases and the kiln's cooling system).

5. Discussion

The results of this research are comparable to existing findings in several aspects. Firstly, it shows that the optimization of energy consumption can influence the economy of manufacturing units, especially in the ceramic tile industry, which is consistent with the findings of Liu (1995), Patterson (1996), RastGoftar and Shaygan (2006), Chu et al. (2009), Oyebanji et al. (2022), Li (2022) and Shah (2022). Also, some of the energy efficiency solutions identified in this study are in line with the findings of other studies. For example, Cassani (2010) identified roller kilns as the components with the highest thermal energy waste in the process of ceramic tile manufacturing. Similarly, one of the solutions recommended in the present study was to replacement of roller kilns with tunnel kilns. Another recommended solution was consistent with the finding of Bending et al. (2013) regarding the low efficiency of kilns used in the production of ceramic tiles, which causes energy waste through stacks and coolants. Also, Mezquita et al. (2014) reported that most of the thermal energy consumed in the production of ceramic tiles is wasted in roller kilns, stacks and coolants, which is consistent with the solutions that involve replacing roller kilns with tunnel kilns and recovering waste heat from combustion exhaust gases through heat exchanger and from hot air exiting the kiln's cooling system. The identified solutions that involve regular maintenance and changing

and replacing worn out equipment are consistent with Manrique et al.'s (2018) identification of the old age of equipment and the lack of renovation as barriers to energy efficiency in Colombia's ceramic tile industry. Some of the solutions are also similar to those proposed by Castro Oliveira et al. (2020) such as using high-efficiency burners, recycling hot air from kilns to other processes, and installing heat exchangers. In the study of Türkmen et al. (2021), one of the scenarios they considered for improving the sustainability of ceramic tile production in Turkey was to improve combustion efficiency, which is similar to the solutions identified in the present study about optimizing the combustion process and heat recovery and insulation. Some of the identified solutions are also consistent with Shah et al.'s (2022) identification of technological change as the main determinant of energy efficiency growth in South Asian countries. Therefore, most of the identified solutions appear to be more or less in line with the findings of previous studies.

6. Conclusion

In the modern era, efficiency improvement is increasingly viewed as a primary driver of economic growth. With the straining of the world's energy supplies and the waste of considerable amounts of energy in different sectors, many countries have chosen to pay and draw more attention to the subject of energy efficiency. In many countries, the industry sector is the biggest consumer of energy. Energy, as a fundamental and usually expensive input, tends to become a major determinant of the final price of product. Therefore, optimizing energy consumption in energy-intensive industries can greatly contribute to their economic prosperity. In recent decades, Iran's ceramic tile manufacturing has grown into a sprawling industry, sometimes exhibiting the highest export growth in the industry sector. However, ceramic tile manufacturing is rightfully believed to be an extremely energy-intensive industry. Thus, any improvement in the energy efficiency of this industry can offer extensive economic benefits and may even lead to the production of higher quality products. In this study, we first identified a number of solutions for improving energy efficiency in Iran's

ceramic tile industry by reviewing the subject literature and surveying a group of experts. The list of realistic energy efficiency improvement solutions was then provided to the experts for discussion, and after several meetings, they were asked to opine on these solutions from technical, managerial and production process standpoints. Next, the fuzzy Delphi method was conducted in two stages and ultimately experts reached consensus on 22 solutions that they believed to be appropriate for improving energy efficiency in the ceramic tile industry. Finally, these solutions were prioritized based on their importance. The results of this study in terms of effective solutions for energy efficiency improvement in Iran's ceramic tile industry are presented in Table 9. According to this prioritization, the highest-priority solutions for energy efficiency improvement in the ceramic tile industry are Implementation of regular maintenance program of facilities and equipment, Adjusting the air in the kilns and burners, and Replacing electro motors according to the load of slurry mixers, and the lowest-priority solutions for this purpose are Insulation of transmission and distribution routes (steam and hot water pipes), Implementation of lighting management system in the factory, and Installation of heat exchangers to recover wasted heat (exhaust gases and the kiln's cooling system).

Future studies are recommended to analyze the economic feasibility of the solutions identified in this study in terms of investment requirements and return on investment following energy efficiency optimization to determine the most cost-effective solutions. It is also recommended to evaluate these solutions based on a number of criteria at the factory level and rank them using multi-criteria decision-making methods to allow industry owners to choose the best option.

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