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Sustainable Optimization of Mold Heating: A Dual Approach with SWARA and MARCOS Methods

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Highlights

- Energy efficiency in manufacturing FRP via hot pressing method is investigated.
- Installed combinations are determined by assessing the sunlight duration in the factory's region.
- These combinations have been evaluated using MCDMs under 4 different headings.
- The best alternative is chosen as a 40 kWh battery and a 25 kW solar panel option.

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Abstract

There are many methods and raw materials used in the manufacture of Fiber Reinforced Plastics (FRP) by hot molding, such as Sheet Molding Compound (SMC), Bulk Molding Compound (BMC), and Prepreg fabrics. In most applications, it is common practice to insert the new dough into the mold without cooling it, then re-press and cure. Placing the mold in the dough without cooling causes the surface of the molded product to cure faster than the inner region, resulting in a structurally discontinuous structure in the product. Therefore, in more professional production, the mold is lowered to around 120 ºC and the dough is poured into the mold at this stage. However, this increases energy consumption and carbon emissions for the heating and cooling phases. This study investigated the energy efficiency of the production of FRP using the hot-pressing process. At the end of this study, by using alternative energy methods in the manufacturing processes, results such as investment costs, depreciation costs, reductions in bills, and carbon emissions were achieved. To find the best alternative from these results, the criteria weights were determined using SWARA, and the alternatives identified were ranked using the MARCOS method. As a result of this ranking, the best alternative was determined to be a 40 kWh battery and a 25 kW solar panel option among the solar panel power and battery capacity alternatives.

1. INTRODUCTION

Numerous products in simple or complex shapes have been used for daily life and/or manufacturing for thousands of years. These products range from toys to electronic tools, from tools used in the automotive industry to tools used in the maritime industry, from tools used in agriculture to tools used in attack and defense [1]. Due to its consequences on both the producer and the consumer, environmentally friendly and energy-efficient processes and auxiliary machineries are chosen in the casting industry, which is one of the top industries where the most energy is required per ton of product manufactured [2]. Molding is one of the most fundamental and crucial casting processes. Different molding processes and manufacturing methods are also required by the usage of various goods as raw materials [3]. A large part of the products used today is produced using thermoset plastic and thermoplastic raw materials, with the injection molding method, the foundations of which were laid by the Hyatt brothers in the late 1800s [4]. Energy efficiency in this industry is highlighted since the heating and cooling operations of molds are used to make these items. Especially when the recent studies are examined, it focuses on energy efficiency in the heating and cooling stages of the molds. In this regard, the energy crisis that has begun to be experienced in the world and especially the climate changes in the world due to global warming are the leading factors for these studies [5].

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Processes involving both heating and cooling of the mold in manufacturing have mostly been studied in plastic injection molds. When the studies on this subject are examined, Wang et al. [6] worked on finding the optimum positions of the heating channels on the mold to quickly increase the surface temperature to the desired temperature and performed optimization studies with finite element analysis. Hsieh et al. [7] worked on both heating and cooling of stretch blow molding (SBM) machines used in pet bottle manufacturing, increasing product quality and reducing energy consumption by 10%. Yao et al. [8] and Wang et al. [9] studied the rapid heating and cooling of the mold surface. Liang [10] worked on cooling channel optimization for cooling the mold surface. Guilong et al. [11] studied energy efficiency and manufacturing efficiency by using different materials for mold heating and cooling. Rashid et al. [12] studied heating and cooling fluids as well as heating and cooling channels in order to reduce mold heating and cooling costs.

Wang et al. [13] worked on using the same channels for cooling by adding liquid between the cartridge resistances and the slot in the mold in injection molds. Park et al. [14] studied the geometry of cooling channels in order to reduce the cycle time in injection molds. Bolatturk et al. [15] and Feng et al. [16] studied the production and optimum design of mold cooling channels in complex geometries. Wang et al. [17] made an optimization study using Lagrangian polynomials for the heating and cooling processes of the mold. Zhao et al. [18] examined the results of electrical heating and cooling in the rapid heat cycle molding method and studied the energy consumption and surface quality of the products. Chang et al. [19] worked on heating the mold surface with halogen lamps. Jansen [20] worked on the analytical modeling of the heaters placed in the mold.

Multi-criteria decision-making methods (MCDM) are tools that enable the most appropriate selection for the purpose in systems where more than one qualitative or quantitative objective function or criterion is effective [21]. Although there are many methods in the literature, within the scope of this study, the Stepwise Weight Assessment Ratio Analysis (SWARA) method, which is used to determine the importance coefficients of the criteria, and the Measurement of Alternatives and Ranking According to the Compromise Solution (MARCOS) method, which is used for ranking the alternatives, is discussed. Tus and Adalı [22] examined fuzzy SWARA and fuzzy MARCOS methods to evaluate the best option for the green supply chain operations. Das and Chakraborty [23] tried to identify the best solutions to obtain improved performance and minimalized environmental effects for a green dry milling processes using SWARA-CoCoSo methods.

Yucenur and Ipekci [24] used H-SWARA and WASPAS methods to determine the most suitable location for the structure, which is used to generate energy by using the current in the sea, by taking into account various criteria such as technical suitability, environmental impact and social acceptability. Maghsoodi et al. [25] studied the selection of the most suitable renewable energy method for a particular region using H-SWARA and MULTIMOORA methods. Karaaslan et al. [26] used the AHP-MARCOS method for the regional evaluation of renewable energy resources in Turkey. Wu et al. [27] revealed the opportunities, threats, strengths and weaknesses in green mining with SWOT analysis, and these criteria were weighted with the AHP method and then they ranked the alternatives using the MARCOS method. Engin et al. [28] and Albayrak [29] examined the use of MCDM in the analysis of renewable energy alternatives. Al Mutairi et al. In their study on optimization of strategies used for the development of renewable energy resources for Iran [30] and Saudi Arabia [31], they used SWOT analyzes and different types of MCDM. Hosseini Dehshiri [32], on the other hand, optimized the economic and environmental effects of the use of different types of hybrid energy sources in the city of Isfahan by using MCDM with HOMER software.

The motivation of this study is the lack of applying any MCDM for the manufacturing of the mold heated FRP process. In this study, energy efficiency was studied by using solar panel and battery combinations, which are alternative energy sources, in heating the molds. Annual invoice cost, carbon emission value, investment cost, and depreciation periods were calculated by using different solar panels power and battery combinations with different capacities. The importance rates of these criteria were asked to ten decision makers with theoretical and practical experience and the weights of the criteria were calculated by the SWARA method. By using the weights of these criteria, the best alternative was found by sorting the battery and solar panel alternatives with the MARCOS method.

2. MODEL AND FORMULATION

In this study, the heat cycle of composite materials manufactured by hot press was studied in Figure 1. For the calculations, a double-sided steel mold with a surface area of 1x0.5 m and a thickness of 0.1 m was taken as an example. The curing temperature of this mold was determined as 5 minutes at 175 ºC, and the temperature of placing the product in the mold was determined as 120 ºC. When the mold temperature reaches 120 ºC, the raw material is put into the mold and pressed. The mold temperature increases to 175 ºC and wait for 5 minutes, the mold is lowered to 120 ºC and the product is taken out and the process is repeated in this way.

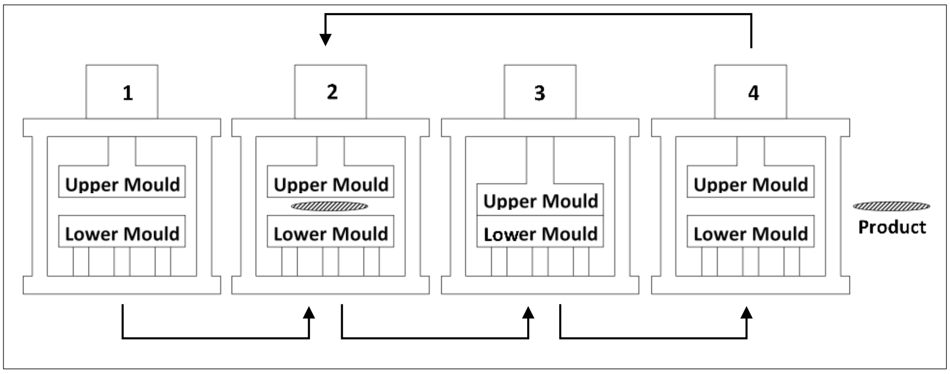

Figure 1. *The mold heated FRP production process*

$$Q = m\ c\ \Delta T \tag{1}$$

$$Q = \alpha\ A_s\ (T_s - T_\infty) \tag{2}$$

where Q is the amount of heat energy taken in or given out [kJ], m the mass of the mold to be heated [kg], c the specific heat [kJ/kg.°C], ΔT the temperature difference [°C], α the heat transfer coefficient [W/m^2.°C], A_S furnace surface area [m^2], T_S denotes mold surface temperature [°C], T_∞ ambient temperature [°C].

Equation (1) is used to calculate the amount of energy required to heat the mold and to calculate the amount of energy required to be withdrawn from the mold for cooling. Equation (2) uses to calculate the natural heat transfer between the mold and the medium. The characteristics of the mold to be used as an example in this study are given in Table 1.

Table 1. *Mold specifications*

Mold dimensions	1m x 0.5m x 0.1m (2 pcs.)
Mold weight	350 kg
Mold material	Mold steel
Mold density	7250 kg/m^3
Specific heat	0.45 kJ / kg.°C
Total surface area with mold open	0.8 m^2
Total surface area with mold closed	0.4 m^2
Heat transfer coefficient	17 W/ m^2 °C

The SWARA method [33] is a MCDM used to determine the importance coefficients of the criteria. Scoring or rating processes of different alternatives can be determined by taking expert opinions, using objective methods, subjective methods and integrated/composite methods. The average of these evaluations is taken and the weight values of the criteria are calculated by using the Equations (3)-(5) given below in order

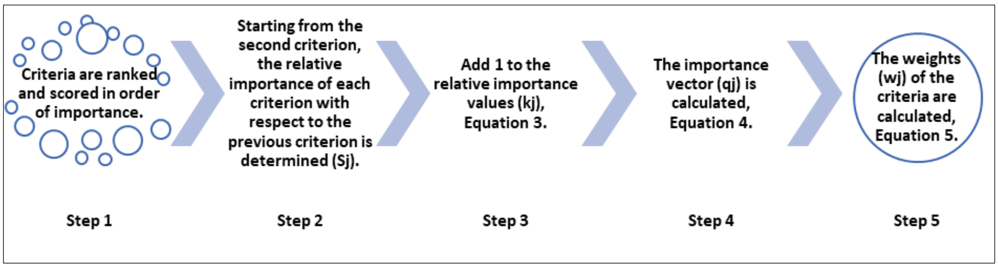

Figure 2. *SWARA Method Steps*

$$k_j = \begin{cases} 1, & j = 1 \\ S_j + 1, & j > 1 \end{cases} \tag{3}$$

$$q_j = \begin{cases} 1, & j = 1 \\ \frac{q_{j-1}}{k_j}, & j > 1 \end{cases} \tag{4}$$

$$w_j = \frac{q_j}{\sum_{k=1}^{n} q_k}. \tag{5}$$

The MARCOS method is also one of the MCDM used for ranking alternatives [34]. The criteria whose weights are calculated in the SWARA method are used in the MARCOS method to determine the best alternative. The calculation steps in the MARCOS method are given in Figure 3 and the Equations (6)-(9) used in these calculations are given below

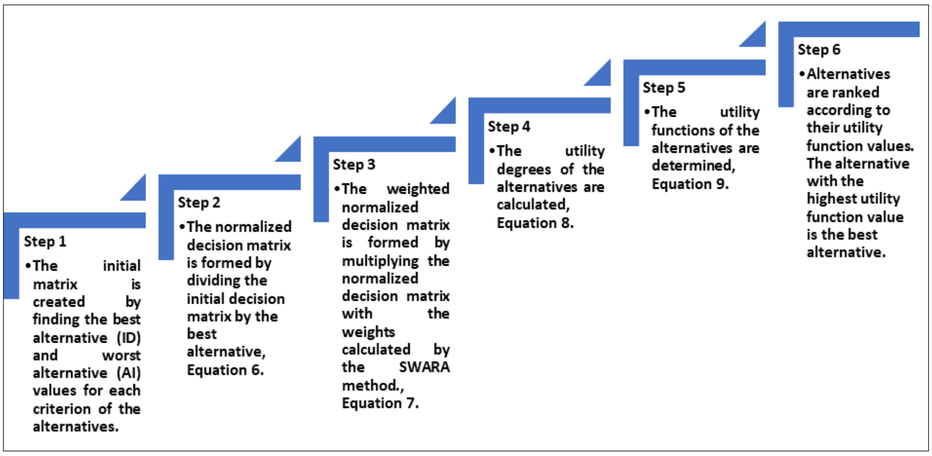

Figure 3. *MARCOS method steps*

$$n_{ij} = \frac{x_{ij}}{x_{ID}}\ for\ benefit\ types, n_{ij} = \frac{x_{iD}}{x_{Ij}}\ for\ cost\ type \tag{6}$$

$$v_{ij} = n_{ij} * w_j \tag{7}$$

$$K_i^- = \frac{S_i}{S_{AI}};\ \ K_i^+ = \frac{S_i}{S_{ID}};\ \ S_i = \sum_{j=1}^{m} v_{ij} \tag{8}$$

$$f(K_i) = \frac{K_i^- + K_i^+}{1 + \frac{1 - f(K_i^+)}{f(K_i^+)} + \frac{1 - f(K_i^-)}{f(K_i^-)}};\ \ f(K_i^+) = \frac{K_i^+}{K_i^+ + K_i^-};\ \ f(K_i^-) = \frac{K_i^-}{K_i^+ + K_i^-}. \tag{9}$$

3. RESULTS AND DISCUSSION

Considering the mold properties given in Table 1 in the sample study, the energy and power requirements consumed according to the flow chart in Figure 1 are given in Table 2.

Table 2. *Power requirements of process*

<table>
<tr><th rowspan="2">Stage</th><th rowspan="2">Operation</th><th colspan="4">Bottom Mold</th><th colspan="4">Upper Mold</th></tr>
<tr><th>Temperature (℃)</th><th>Energy consumption (kJ)</th><th>Time (min)</th><th>Required power (kW)</th><th>Temperature (℃)</th><th>Energy consumption (kJ)</th><th>Time (min)</th><th>Required power (kW)</th></tr>
<tr><td>1</td><td>Operation</td><td>25</td><td>0</td><td>0</td><td>0</td><td></td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>1-2</td><td>Manufacturing preparation</td><td>25-120</td><td>15884</td><td>10</td><td>26</td><td rowspan="3">25-175</td><td rowspan="3">25754</td><td rowspan="3">21</td><td rowspan="3">20</td></tr>
<tr><td>2</td><td>The upper and lower molds are started to be heated.</td><td>120</td><td>29</td><td>1</td><td>0</td></tr>
<tr><td>2-3</td><td>When the lower mold reaches 120℃, composite raw material is placed inside and the upper mold continues to be heated.</td><td>120-175</td><td>9201</td><td>10</td><td>15</td></tr>
<tr><td>3</td><td>Lower and upper molds are removed up to 175℃</td><td>175</td><td>230</td><td>5</td><td>1</td><td>175</td><td>230</td><td>5</td><td>1</td></tr>
<tr><td>3-4</td><td>Mold temperatures are kept constant at 175℃ and curing is complete.</td><td>175-120</td><td>8360</td><td>10</td><td>14</td><td>175</td><td>612</td><td>10</td><td>1</td></tr>
<tr><td>4</td><td>The mold is opened and the lower mold temperature is lowered to 120℃</td><td>120</td><td></td><td>1</td><td>0</td><td>175</td><td>46</td><td>1</td><td>1</td></tr>
</table>

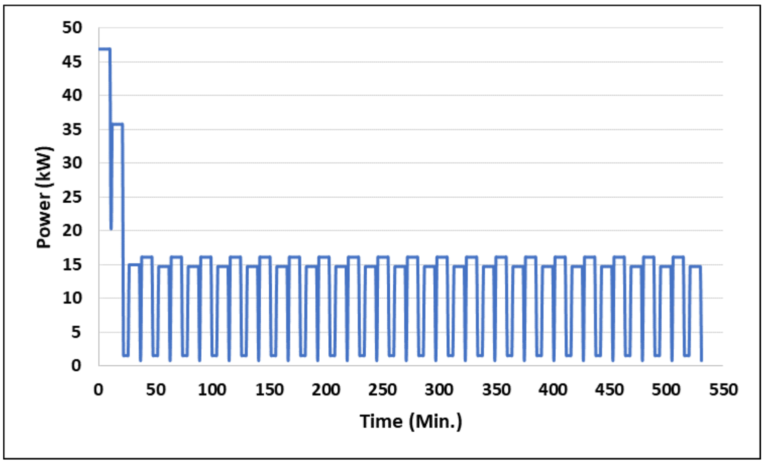

Figure 4. *Daily power demand*

Another criterion that should be known before starting the solar panel application is the duration of the sun. Considering that this application was set up in Istanbul, the amount of sunshine per month according to the data of the Ministry of Energy and Natural Resources [35] and the amount of energy to be produced per unit m^2 of solar panel daily according to these sunshine durations are given in Table 3.

Table 3. *Average sunshine durations* [35] *and solar panel powers*

Month	Sunshine duration [h]	Solar panel energy production [kj/m^2/day]	Month	Sunshine duration [h]	Solar panel energy production [kj/m^2/day]
January	3.46	2491.2	July	11.17	8042.4
February	4.43	3189.6	August	10.14	7300.8
March	5.32	3830.4	September	7.83	5637.6
Aprıl	6.85	4932	October	5.22	3758.4
May	8.61	6199.2	November	3.85	2772
June	10.51	7567.2	December	2.96	2131.2

According to Table 3, the lowest power production with 1 m^2 solar panel was calculated as 2131.2 kJ in December and the highest energy production was calculated as 8042.4 kJ in July. Considering the daily energy consumption, 202 m^2 solar panels are needed for December, while 54 m^2 solar panels are needed for July. In addition to these, when we add the power needs, this turns into a cost optimization problem. In order for the solar panel to be installed in the factory to be used more efficiently, it is necessary to supplement with the battery. The same power is not used continuously throughout the manufacturing process. The proposed hybrid energy sources for the heating of the process is shown in Figure 5.

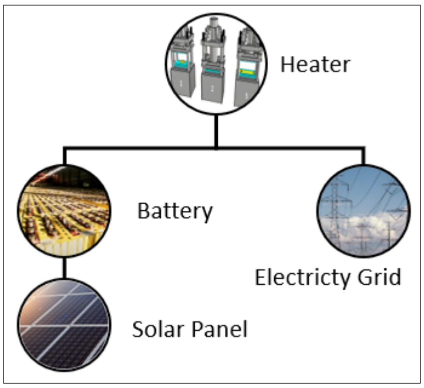

Figure 5. *Proposed hybrid energy source for the heating process*

As can be seen in Figure 2, there are times when 16 kW of power is required, and also sometimes 1 kW is required. When a solar panel is installed based on 16 kW of power, when 1 kW of power consumption is required, 15 kW of energy is not used. Therefore, by adding a battery, this energy can be stored and used when necessary. The data to be used in the study to be conducted are given in Table 4.

Table 4. *Design values of power systems* [36,37]

Solar panel investment cost	108	\$/m^2
Solar panel power generation	0.2	kW/m^2
Battery investment cost	216	\$/kWh
Grid electricity price	0.27	\$/kWh
Daily energy consumption	430314	kJ
Amount of carbon emission	0.443	kg/kWh

Considering the values given above and monthly sunshine durations, the amount of energy to be produced and consumed during monthly and annual production has been calculated. The variation of the monthly energy drawn from the grid at different solar panel powers is shown in Figure 6 without battery and Figure 7 with 5 kWh battery.

When Figures 6 and 7 are examined, it is shown that the amount of energy drawn from the grid changes according to the power of the solar panel in cases with and without battery. The figure start with January and end with December. Since the sunshine duration reaches its lowest level in these two months, the amount of energy drawn from the grid reaches its maximum in these months. In June, July and August, as the sunshine duration reaches its maximum, the energy drawn from the grid is minimum in these months.

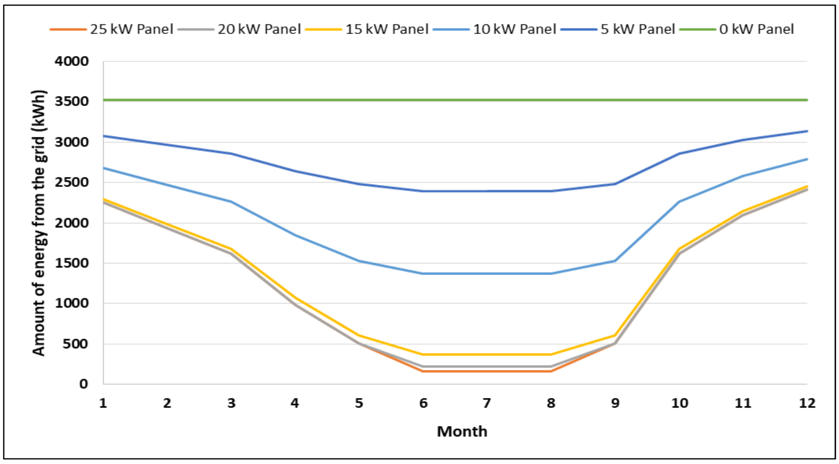

Figure 6. *Amount of monthly energy drawn from the grid without battery*

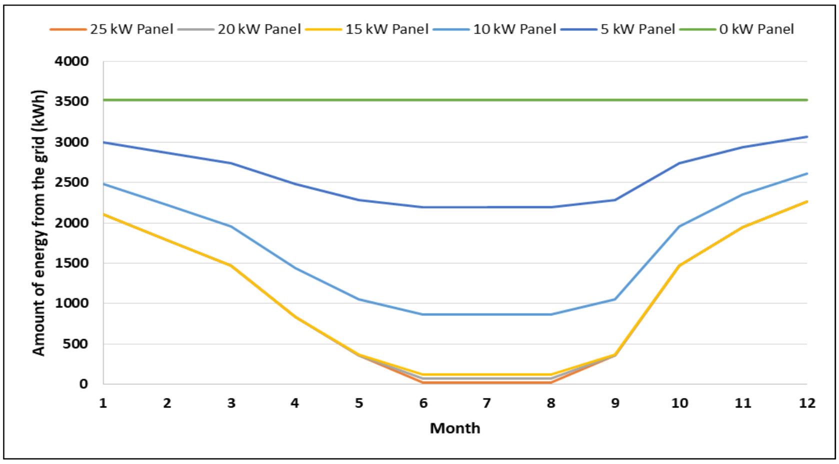

Figure 7. *Amount of monthly energy drawn from the grid 5 kWh battery*

Using the data in Table 4, the amount of energy drawn from the grid and the annual invoice amount for this energy are shown in Figure 8. According to the figure, the invoice amount decreases rapidly until the solar panel power reaches 25 kW and any significant change is observed after 25 kW. There is a linear relationship between the increase in the battery capacity and the decrease in the invoice amount.

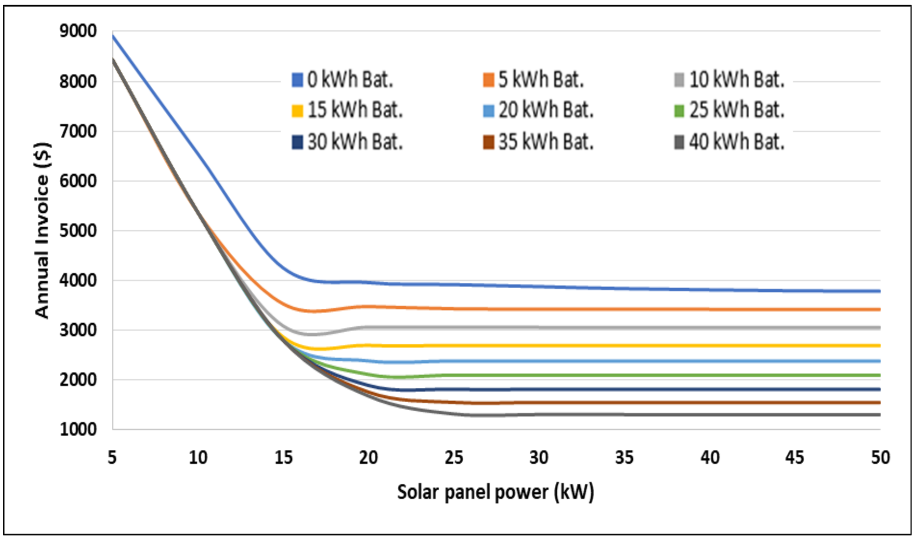

Figure 8. *Annual invoices of solar panels power for different battery capacities*

Considering the decrease in the invoice, the depreciation period according to the investment cost is given in Figure 9. When the figure given is examined, the lowest depreciation period is 12 months, with the combination of a 5 kW solar panel without batteries, followed by a 5 kWh battery with 12.5 months and a 10 kW solar panel.

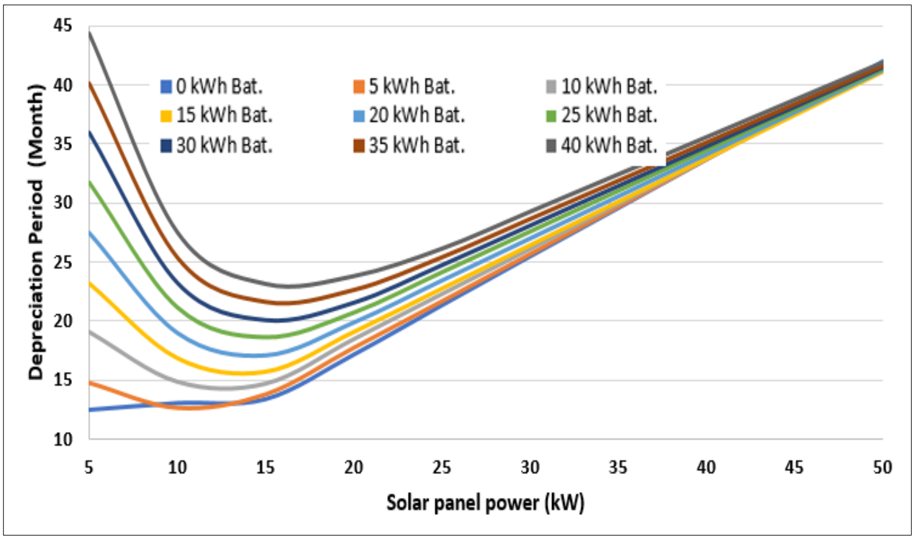

Figure 9. *Depreciation periods of solar panels power for different battery capacities*

Calculated carbon emissions according to the different solar panel power and different battery capacities are shown in Figure 10 giving linear characteristics between variables. Calculated emission values are so close in the same referred stage such as 3.440, 3.438, 3.436, 3.435, 3.434, and 3.433 tons for 25 kW panel power and varying battery capacities. The same results are valid for the varying solar panel power 20-50 kW and 0-40 kWh battery capacities.

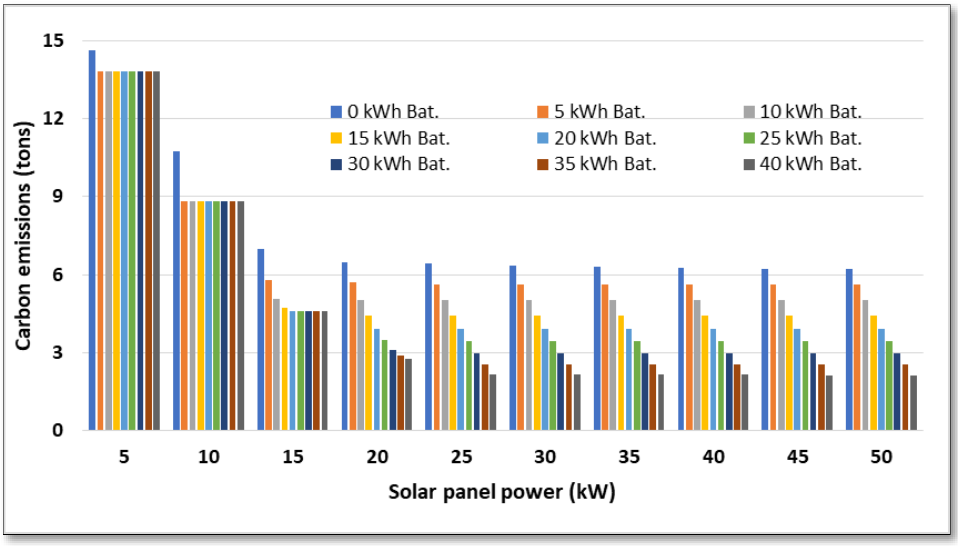

Figure 10. *Carbon emissions of solar panels power for different battery capacities*

With the mold used in the study, 20 products are produced per day. Considering that this factory works 365 days, it pays an annual electricity bill of 1602 $ only for this product. In this study, the effect of battery and solar panel power combination on this bill is examined. While calculating the energy from the solar panel, monthly sunshine durations are also taken into account. At the time of the study, the kWh cost of the battery is 216 $/kWh and the solar panel costs 540 $/kW.

The 10 combinations of batteries and panels with the lowest depreciation period according to these costs and invoice amount are given in Table 5. As a result of the study, a total of 90 alternatives were evaluated in 4 different criteria. The evaluation of the table was made according to the depreciation period, but the criteria may differ for the investor. While carbon emissions may be an objective function for one investor, the investment cost may be more important for another. Therefore, it is necessary to analyze MCDM to determine the best alternative.

Table 5. *Depreciation periods*

Battery (kWh)	Solar panel (kW)	Investment cost ($)	Annual invoice ($)	Depreciation period (Month)	Carbon emission (Tons)
0	0	0	11601.99	0.0	19.036
0	5	2700	8909.39	12.0	14.618
5	10	6480	5368.51	12.5	8.808
0	10	5400	6546.37	12.8	10.741
0	15	8100	4252.95	13.2	6.978
5	15	9180	3530.23	13.6	5.792
5	5	3780	8433.60	14.3	13.837
10	15	10260	3086.34	14.5	5.064
10	10	7560	5368.51	14.6	8.808
15	15	11340	2865.20	15.6	4.701

In this study, results were obtained under 4 objective functions as investment cost, annual invoice amount, depreciation period and reduction in carbon emissions in a total of 90 different alternatives. In this study, a total of 10 experts in the field of the importance of the decision maker (DM), with at least a bachelor's degree, were asked and scored out of 100 and the weight results were obtained using the SWARA method, Figure 11.

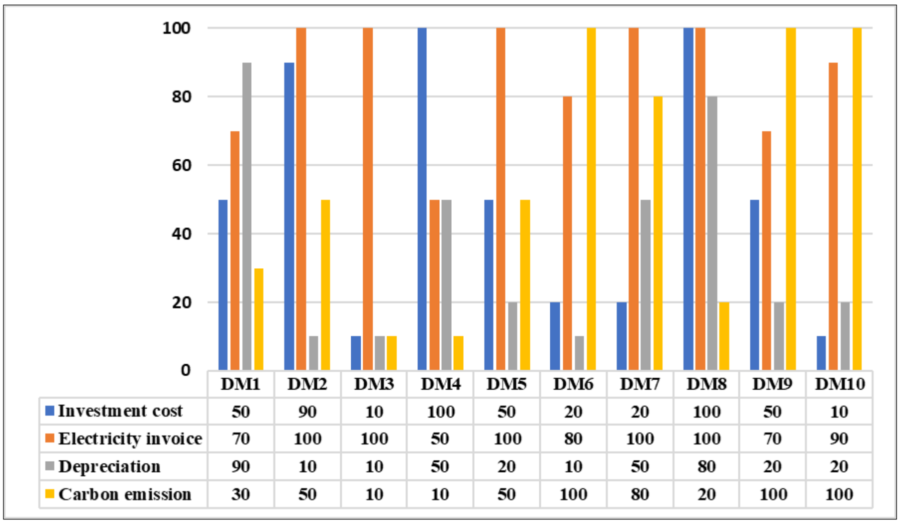

Figure 11. *Decision matrix of the study*

Table 6 presents the calculations by Equations (3-5) for the SWARA method. According to this method, the weight values of the criteria are calculated as 0.387471 for the electricity invoice, 0.284808 for the carbon emission, 0.200766 for the investment cost, and 0.126955 for the depreciation period.

Table 6. *Results of SWARA method*

Criterion	S_j	k_j	q_j	w_j
Electricity Invoice	0	0	1	0.387471
Carbon Emission	0.360465	1.360465	0.735043	0.284808
Investment Cost	0.418605	1.418605	0.518145	0.200766
Depreciation	0.581395	1.581395	0.32765	0.126955
			2.580838	

By using these weight values (w_i), a ranking was made among the alternatives. MARCOS was used as the ranking method. The calculation steps according to this method are given in Table 7, 8 and 9. First of all decision matrix is prepared for calculations in Table 7. This matrix is included all alternatives and specifications (invoice, depreciation period, carbon emission) values. Also, ideal values (ID) and non-ideal values (NID) of this specifications are determined.

Table 7. *The initial decision matrix*

			Decision Matrix			
Alternative	Battery (kWh)	Solar panel (kW)	Investment cost ($)	Annual invoice ($)	Depreciation period (Month)	Carbon emission (Tons)
ID			2700	1302	12.51	2.136
A1	0	5	2700	8909	12.51	14.618
A2	5	5	3780	8434	14.80	13.837
A3	10	5	4860	8434	19.03	13.837
A4	15	5	5940	8434	23.26	13.837
.	.	.	.	.	.	.
A87	25	50	32400	2093	41.34	3.434
A88	30	50	33480	1808	41.46	2.967
A89	35	50	34560	1544	41.66	2.534
A90	40	50	35640	1302	41.94	2136
NID			35640	8909	44.40	14618

The normalized decision matrix given in Table 8 was calculated using Equation (6). Since the criteria are cost type criteria, the cost type of Equation (6) was used. Then, using Equation (7), the weighted normalized decision matrix was calculated by multiplying the normalized values with the weights calculated in the table.

Table 8. *The normalized and the weighted normalized decision matrixes*

	Normalized Decision Matrix				Weighted Normalized Matrix			
Alternative	Investment cost	Annual invoice	Depreciation period	Carbon emission	Investment cost	Annual invoice	Depreciation period	Carbon emission
ID	1.0000	1.0000	1.0000	1.0000	0.2008	0.3875	0.1270	0.2848
A1	1.0000	0.1461	1.0000	0.1461	0.2008	0.0566	0.1270	0.0416
A2	0.7143	0.1544	0.8455	0.1544	0.1434	0.0598	0.1073	0.0440
A3	0.5556	0.1544	0.6576	0.1544	0.1115	0.0598	0.0835	0.0440
A4	0.4545	0.1544	0.5381	0.1544	0.0913	0.0598	0.0683	0.0440
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
A87	0.0833	0.6222	0.3027	0.6222	0.0167	0.2411	0.0384	0.1772
A88	0.0806	0.7200	0.3018	0.7200	0.0162	0.2790	0.0383	0.2051
A89	0.0781	0.8432	0.3003	0.8432	0.0157	0.3267	0.0381	0.2401
A90	0.0758	1.0000	0.2983	1.0000	0.0152	0.3875	0.0379	0.2848
NIDI	0.0758	0.1461	0.2818	0.1461	0.0152	0.0566	0.0358	0.0416

Using Equations (8)-(9), respectively, the values given in Table 9 were calculated and ranked according to their Ki values.

Table 9. *The ranking of the alternatives.*

Alternative	K-	K+	T	fk+	fk-	Ki	Rank
A1	2.8542	0.4260	3.2802	0.4940	0.0737	0.2249	42
A2	2.3756	0.3545	2.7302	0.4112	0.0614	0.1540	63
A3	2.0022	0.2988	2.3011	0.3466	0.0517	0.1084	78
A4	1.7647	0.2634	2.0280	0.3054	0.0456	0.0838	84
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
A86	2.8416	0.4241	3.2657	0.4918	0.0734	0.2228	43
A87	3.1723	0.4734	3.6457	0.5491	0.0819	0.2799	29
A88	3.6086	0.5386	4.1472	0.6246	0.0932	0.3661	21
A89	4.1586	0.6206	4.7793	0.7198	0.1074	0.4928	12
		Maximum	5.77				

According to this ranking method, the most ideal alternative is calculated as a 40 kWh battery and a 25 kW solar panel option. The depreciation period of this criterion is calculated as 26.09 months, the invoice amount is 1317 $, the investment cost is 22140 $ and the carbon emission is 2.160 tons.

4. CONCLUSION

Due to the increasing energy costs and climate changes in the world, countries have started to work more on the energy efficiency. In this study, the energy efficiency in the manufacturing of fiber reinforced plastics (FRP) produced by the hot press method was investigated that has been studied how long it takes for companies that manufacture with hot molds to depreciate their investment if the molds are heated by solar power. Solar panel and battery combinations that can be installed are calculated considering the sunshine duration in the region where the factory is located. These combinations have been evaluated under four different outputs as change in annual electricity cost, change in carbon emission, investment cost and depreciation period.

In order to find the most suitable alternative among the calculated values, SWARA and MARCOS methods, which are among the MCDM, were used. In calculating the criteria weights, 10 decision makers were asked about the importance levels of the criteria. Then, criterion weights were calculated with the SWARA method. By using these criteria weights, the most suitable alternative was determined with the MARCOS method. As a result, the optimum alternative is chosen as a 40 kWh battery and a 25 kW solar panel option that has 26.09 months depreciation period, 1317 $ the invoice amount, 22140 $ the investment cost, and 2.160 tons the carbon emission.

The effects of the using different kinds of combined green or renewable energy sources and the effects of the alternative MCDMs for the different FRP production processes on the mentioned outputs can be evaluated in the future studies.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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