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Does Reduction of Material and Energy Consumption Affect to Innovation Efficiency? The Case of Manufacturing Industry in South Korea

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Abstract: "Reduction of material and energy consumption" (RMEC) exists as a major objective of innovation and it is proved to affect positively to innovation performance from previous literature. Though innovation should be measured in efficiency rather than performance itself, however, the relationship between material and energy reduction on innovation efficiency is still unanswered. In this paper, we analyzed the effect of RMEC on innovation efficiency considering both innovation inputs and outputs. We utilized data of 388 manufacturing enterprises in Korea, and performed data envelopment analysis (DEA) and tobit regression analysis. According to the result, firms show difference by industry type in terms of innovation efficiency and RMEC. Moreover, the effect of RMEC on innovation efficiency turned out to be negative. The result indicates a possibility that input used for innovation might overweigh the output yielded when firms pursue innovation for the RMEC.

Keywords: material and energy consumption; innovation objective; innovation efficiency; data envelopment analysis (DEA); tobit regression analysis

1. Introduction

The importance of sustainable innovation has been grown for both practitioners and researchers for several years [1,2]. Recent studies discovered that sustainability-related motivations, such as preventing harmful effect on environment, improving safety for workers, and reduction of material and energy consumption (RMEC), have become major objectives of innovation from diverse countries [3–5]. RMEC, which is a key component of sustainability, turned out to be major objective of innovation in diverse countries [6].

Literature not only identified that sustainability exists as innovation objective, but also discovered the effect of such objective on firm performance. Most studies focus on the positive effect of sustainability. Sustainable innovation is positively correlated with both financial and non-financial performance, including profitability, growth, competitive advantage, and others [7–13].

The performance of innovation, however, should be measured with considering innovation input and output altogether rather than the output itself. Innovation input is not converted automatically into performance as innovation is not a linear process, and accordingly, innovation efficiency should be measured. Nevertheless, most studies until now have not considered innovation efficiency but rather the output itself in their research on the effect of sustainability on innovation performance. Moreover, practitioners might pursue sustainable innovation without considering the cost and effort required to achieve innovation outcome.

In this paper, we examined the relationship between the RMEC as innovation objective and efficiency, considering both inputs and outputs of innovation. It is believed that the study fills up the academic gap between material and energy reduction and innovation efficiency, and also suggests appropriate innovation strategy with considering inputs required for innovation to practitioners. We utilized 388 samples of Korean manufacturing enterprises from 2016 Korean Innovation Survey (KIS) data. The research methods are twofold; first, we performed data envelopment analysis (DEA) to estimate innovation efficiency, and second, tobit regression analysis was adopted to investigate potential effect of material and energy consumption as innovation objective on innovation efficiency.

The paper is presented as follows: Section 2 explains the main theoretical background, followed by Section 3, which clarifies the data and research methods used. The result of the study is elaborated in Section 4, and finally, Section 5 gives managerial implications, limitations, and suggestions for the future research.

2. Theoretical Background

2.1. Material and Energy Reduction as Innovation Objectives

The reason for pursuing innovation could be various [14,15]. The objective of innovation is different from one firm to another, depending on firms' innovation patterns, environment, size and others [16]. Most previous studies focused on cost reduction, and quality improvement as motivation of innovation [17–19]. Others also found that firms perform innovation to shorten the response time, to gain non-tradable assets, and to enhance knowledge [20–22].

While literature identified that economic-related reasons are the main objectives of firms struggling to achieve successful innovation, recent studies also pointed out that sustainability-related purposes exists as major innovation objectives as well, such as to lower the negative influence on environment, to improve working conditions on health, and even to reduce material and energy consumption [3–6]. With increasing interest in sustainable innovation, objectives related to sustainability also have become major objectives for firms pursuing innovation.

The objectives of sustainable innovation could be categorized into several components depending on literature, previous studies included reduction of raw material and energy consumption as key sustainability-related objective in common. Kunapatarawong and Martínez-Ros [11] divided sustainability-related objectives into: (1) reducing material usage, (2) reducing energy usage, (3) mitigating environmental impact, and (4) complying with the environmental requirements, while Shin et al. [23] categorized sustainability-related motivations into three: reduce material and energy, improve environment, and improve safety of workers or environment of their workplace. Moreover, Poussing [24] argued that: (1) reduction of material and energy cost and (2) reduction of environmental impact are two environment-related innovation objectives, and Ulvenblad et al. [25] classified maximization of material and energy efficiency as one of the major sustainable business model archetypes. Reduction of material and energy have turned out to be major objective of innovation in diverse countries [6].

2.2. Material and Energy Reduction and Firm Performance

Studies not only discovered that sustainability exists as a major innovation objective, but also analyzed the relationship between such objective and firm performance. Since RMEC is a major component of sustainability, material and energy reduction has been studied by the name of sustainability in previous literature.

Hojnik and Ruzzier [7] argued that process eco-innovation affect positively on firms' growth and profitability, and Ghisetti and Rennings [8] maintained that reduction in the use of resources and energy is positively correlated with firms' profitability. Chen et al. [9] proved that such green-innovation tends to increase competitive advantage, and Peng and Lin [10] also proved that adoption of green management increases financial and non-financial performance of firms. Moreover, Kunapatarawong and Martinez-Ros [11] argued that green innovation is positively related to employment, and the relationship is stronger in not environmental-friendly industries. González-Moreno et al. [12] also pointed out that environmental oriented innovation affects positively to manufacturing process and logistics. Jugend et al. [13] found that green product development is positively correlated with product portfolio performance and creation of new opportunities.

Studies constantly emphasized the advantage of pursuing sustainability-related objectives, including material and energy reduction. However, studies until now have measured the dependent variable as performance itself without considering resources and/or efforts required for performing innovation.

2.3. Innovation Efficiency

Innovation inputs are not automatically transferred into innovation outputs, as innovation cannot be a linear process, innovation input and output variables should be considered altogether [26]. Innovation efficiency, which is “the ability to translate inputs into innovation outputs” by definition, should be measured when analyzing innovation performance instead of considering output itself [26,27]. Accordingly, diverse studies measured innovation efficiency, and Table 1 summarizes recent literature on innovation efficiency which measured both inputs and outputs of innovation. As Table 1 indicates, most literatures established input variable including expenses and employees required for R&D, and output variable including profits, sales, patents, and other performance-related factors [23,26,28–38]. There is also a rare case that patent was used as input variable [38].

Although it seems that researches have considered innovation efficiency when analyzing firms’ innovation, most of them have not covered the domain of sustainability in their research. That is, though studies on the relationship between sustainability and innovation performance has been vigorous (as further elaborated in Section 2.2), they have focused on performance itself without considering innovation input. Accordingly, a huge gap between sustainability and innovation efficiency exists and it is not fulfilled yet. Though Shin et al. [23] maintained that environmental improvement as innovation objective affects negatively while safety improvement affects positively to innovation efficiency, the relationship between RMEC and innovation efficiency is not verified yet.

Given that sustainability has become major innovation objective and RMEC exists as a key component of sustainability, we investigate the effect of RMEC as innovation objective on innovation efficiency. As studies until now have only looked into the relationship between material and energy reduction and its performance, this paper is believed to broaden the discussion by including input used for innovation and measure innovation efficiency instead of performance itself. The result of the study could suggest great implications to practitioners as well, as the study could notify outcome of innovation with input required when pursuing innovation to reduce material and energy consumption. We name material and energy reduction as “MER” in this paper.

3. Methodology and Model

3.1. Data Envelopment Analysis (DEA) and Tobit Regression Analysis

The method used in this study is data envelopment analysis (DEA), which is based on linear programming (LP). Following Charnes et al. [39], DEA has been used as efficiency analysis technique by diverse studies. DEA is a non-parametric methodology which does not assume a production function form, and it has been widely used to measure the efficiency or productivity by estimating the ratio of outputs to inputs [23,26,28–38]. There are two traditional DEA models, which were developed by Charnes et al. [39] and Banker et al. [40]. DEA model from Charnes et al. [39] assumed constant return to scale (CRS), while variable returns to scale (VRS) model from Banker et al. [40] was developed to overcome the shortcomings of the CRS model by adding a convexity constraint. We carried out the output-oriented model in this study to estimate innovation efficiency of each firm.

Table 1. Studies on innovation efficiency. DMUs: decision making units (adopted from Shin et al. [23]).

Source	Method	DMUs	Input Factors	Output Factors
Shin et al. (2018) [23]	DEA	441 Korean manufacturing companies	(1) R&D employee (2) R&D expense	(1) Patent application (2) Innovation sales
Park (2018) [28]	DEA	1778 Korean manufacturing SMEs	(1) R&D expenditure divided by total sales (2) share of R&D staff in total employment	(1) Percentage of sales from R&D activities
Wang et al. (2016) [29]	DEA	38 Chinese new energy enterprises	(1) Fixed assets (2) Staff wages (3) R&D costs	(1) Total profits (2) Market value
Suh and Kim (2014) [30]	DEA	300 Korean service firms	(1) Number of researchers (2) Investment in IT infrastructure (3) Innovation cost for physical resources	(1) Service innovation (2) Process innovation (3) patents
Cruz-Cázares et al. (2013) [31]	DEA/Malmquist index	415 (first stage)/362 (second stage) Spanish manufacturing firms	(1) R&D capital stock (2) High-skill staff	(1) The number of product innovations (2) The number of patents
Wang et al. (2013) [32]	DEA	Top 65 high-technology firms	(1) Employees (2) Assets (3) Number of researchers (4) R&D expenditures	(1) Market value (2) Return on investment
Claudio et al. (2013) [33]	DEA	3111 observations of 536 Spanish manufacturing firms	(1) R&D capital stock (2) High-skilled staff	(1) New products (2) Patents
Chen and Guan (2012) [34]	DEA	30 Chinese province-level regions	(1) Expenditure on science and technology (2) Number of science and technology personnel (3) Foreign direct investment (4) Expenditure on the import of technology (5) Expenditure on the purchase of domestic technology (6) Value of contractual inflows in domestic technical markets	(1) Gross domestic products (2) Sale of new products (3) Value of exports (4) Annual income in urban residents per capita
Bae and Chang (2012) [35]	DEA	1251 Korean manufacturing firms	(1) Innovation expenditures	(1) R&D personnel (2) The number of registered patents (3) The turnover (4) Operating profits
Guan and Chen (2012) [36]	DEA	22 Countries	(1) Number of full-time equivalent scientists and engineers (2) Incremental R&D expenditure (3) Prior accumulated knowledge stock breeding upstream knowledge production	(1) Added value of industries (2) Export of new products in high-tech industries
Zhong et al. (2011) [37]	DEA	30 Chinese province-level regions	(1) R&D expenditure (2) Full-time equivalent of R&D personnel	(1) Patent applications (2) Sales revenue of new products (3) Profit of primary business
Guan and Chen (2010) [38]	DEA	26 Chinese province-level regions	(1) Internal expenditure of R&D funding (2) Full-time equivalence of scientists and technologists on R&D activities (3) Accumulated patents stock	(1) The value added taxes (2) The value added profits (3) The export value of new products (4) The sale revenue of new products
Hollanders and Celikel-Esser (2007) [26]	DEA	35 Countries	(1) Innovation drivers (2) Knowledge creation (3) Innovation & entrepreneurship	(1) Applications (2) Intellectual property

We used advanced DEA model to estimate innovation efficiency to overcome several limitations of traditional CRS and VRS model. Since DEA is a non-parametric analysis, there exist many decision making units (DMUs) achieving efficiency score as 1. Therefore, we adopted super efficiency model (SEM) instead to analyze innovation efficiency of DMUs. The methodology was developed by Andersen and Petersen [41] to calculate efficiency without constraining efficiency score not to exceed 1, which enables determining ranking among efficient DMUs. The SEM-DEA model adopted in this study is expressed as below [42]:

$$\max \Phi_o^{VRS-super}$$

$$\text{s.t.} \sum_{\substack{j=1 \\ j \neq o}}^{n} \lambda_j x_{ij} \leq x_{io},\ i = 1,\ 2,\ \ldots,\ m,$$

$$\sum_{\substack{j=1 \\ j \neq o}}^{n} \lambda_j y_{rj} \geq \Phi_o^{VRS-super} y_{ro},\ r = 1,\ 2,\ \ldots,\ s,$$

$$\sum_{\substack{j=1 \\ j \neq o}}^{n} \lambda_j = 1,$$

$$\Phi_o^{VRS-super} \geq 0,$$

$$\lambda_j \geq 0,\ j \neq o.$$

In order to use the average of the efficiency scores, furthermore, the bootstrap DEA proposed by Simar and Wilson [43] was applied in this study. We derived the bootstrap efficiency mean by subtracting the bias following the procedure developed by Kneip et al. [44]:

"Bootstrap efficiency mean = Original efficiency score/(1 + bootstrapped bias/original efficiency)"

After measuring innovation efficiency, we investigated the potential effect of MER on the firms' efficiency level. We established MER as independent variable and set efficiency score measured by SEM as dependent variable when implementing regression analysis. However, the efficiency score is censored by nature as it is limited its lowest value from 0 [45]. When dependent variable is censored, using ordinary least square (OLS) method might produce biased coefficients [46]. Therefore, we performed tobit regression instead to avoid such distortions, following studies which performed tobit regression as a second step after calculating efficiency score [47–49].

3.2. Data and Measurement

We utilized 2016 KIS data on Korean manufacturing firms carried out by the Science and Technology Policy Institute (STEPI). KIS data is suitable for our research, since KIS data includes overall innovation status for the recent three years (2013, 2014 and 2015) of each firm including information of innovation objectives, resources required for innovation, and innovation performance.

However, since the data does not contain the full range of data required for this study, the sample with missing value was removed. Output variable with 0 values were also removed, as they might distort the result when comparing innovation efficiency among companies. Consequently, we extracted 388 samples out of total 4000 and utilized as DMUs in this paper.

To calculate innovation efficiency, we adopted two innovation inputs and two innovation outputs; the inputs were the number of R&D employee and the amount of R&D expense, and the outputs were the number of patent application and innovation sales [23,26,28–38]. To capture R&D employee, we multiplied the number of regular employee with the percentage of R&D employee out of regular employee. R&D expense was measured as total cost of innovation, and patent application was measured as the number of patent application. Total sales and the percentage of innovative product sales out of total sales are multiplied to measure innovation sales. Thus, the variable "innovation sales" is defined as the sales of innovative products. Lastly, to capture the degree of innovation objective "RMEC", we measured the importance of the objective by 4-point Likert scale, from 0 (not relevant) up to 3 (high). The KIS data questionnaire related to the factors used in this study is explained in Table 2, and the sample profile is summarized in Table 3 categorized by Korean standard industrial classification (KSIC). The research model is shown as Figure 1.

Table 2. Questionnaire in Korean Innovation Survey (KIS) data and factors used in the study.

Factors		Questionnaire in KIS Data
Input	R&D employee	The number of regular employee
		The percentage of R&D employee out of regular employee
	R&D expense	Total innovation cost
Output	Patent application	The number of patent application
	Innovation sales	Total sales
		The percentage of innovative products sales out of total sales
Independent	Material and energy reduction	How important is the "material and energy cost reduction" as an objective of performing innovation

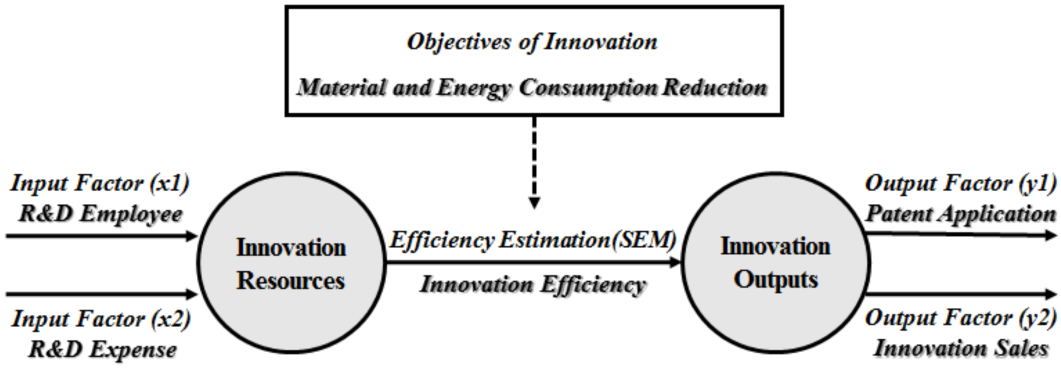

Figure 1. Research model.

Table 3. Sample profile categorized by industry type. MER: material and energy reduction.

Industry Type	No. of Firms	Ave. R&D Employees	Ave. R&D Expense	Ave. Patent Application	Ave. Innovation Sales	Ave. MER
Manufacture of food products	8	12.03	575.00	1.88	7015.00	2.38
Manufacture of beverages	1	30.00	1700.00	1.00	79,800.00	2.00
Manufacture of textiles, except apparel	6	6.75	585.83	2.83	27,985.38	1.83
Manufacture of wearing apparel, clothing accessories and fur articles	1	0.39	50.00	3.00	3250.00	3.00
Tanning and dressing of leather, manufacture of luggage and footwear	1	0.21	20.00	2.00	1620.00	2.00
Manufacture of wood and of products of wood and cork; except furniture	2	2.49	109.50	4.00	1129.65	3.00
Manufacture of pulp, paper and paper products	2	2.62	204.00	3.00	5204.05	2.00
Printing and reproduction of recorded media	2	16.20	400.00	3.50	25,325.95	2.00

Table 3. *Cont.*

Industry Type	No. of Firms	Ave. R&D Employees	Ave. R&D Expense	Ave. Patent Application	Ave. Innovation Sales	Ave. MER
Manufacture of chemicals and chemical products except pharmaceuticals and medicinal chemicals	14	9.98	898.00	7.14	7985.18	2.21
Manufacture of pharmaceuticals, medicinal chemicals and botanical products	6	26.81	1329.67	3.67	19,085.53	2.33
Manufacture of rubber and plastic products	53	7.71	343.79	2.81	14,907.65	2.38
Manufacture of other non-metallic mineral products	8	4.45	543.63	3.75	14,165.06	2.25
Manufacture of basic metal products	7	6.35	315.57	2.00	31,644.59	2.00
Manufacture of fabricated metal products, except machinery and furniture	23	8.67	345.22	3.39	22,929.02	1.70
Manufacture of electronic components, computer, radio, television and communication equipment and apparatuses	31	18.50	1132.00	7.81	15,842.41	1.65
Manufacture of medical, precision and optical instruments, watches and clocks	32	16.79	326.38	4.41	10,449.78	2.34
Manufacture of electrical equipment	38	11.66	602.76	3.26	10,463.06	2.18
Manufacture of other machinery and equipment	122	7.72	579.03	3.65	5320.44	2.51
Manufacture of motor vehicles, trailers and semitrailers	24	14.15	1320.29	4.29	22,745.88	2.00
Manufacture of other transport equipment	3	20.00	1436.67	15.67	30,478.80	2.00
Manufacture of furniture	2	4.41	350.00	8.00	9760.77	2.00
Other manufacturing	2	4.10	65.00	3.00	322.55	3.00

4. Results

The descriptive statistics of variables are summarized in Table 4.

Table 4. Descriptive statistics.

Variables	Minimum	Maximum	Average	St.dev	Median
R&D employee	0.00	134.40	10.60	13.70	6.00
R&D expense	20.00	3689.00	619.82	760.81	300.00
Patent application	1.00	130.00	4.06	7.75	2.00
Innovation sales	106.00	140,000.00	12,320.45	18,752.89	5021.25
Material and energy reduction	0.00	3.00	2.25	0.79	2.00

A 2×2 matrix with innovation efficiency of each industry and the innovation objective of MER as the x and y axes, respectively, is constructed as shown in Figure 2. The first quadrant indicates the industry with high innovation efficiency and high importance of MER as innovation objective. Industries with low efficiency with high importance of MER objective will locate in the second quadrant, while industry group with low MER motivation and low innovation efficiency will be located in the third quadrant. Finally, industries that achieved high level of innovation efficiency with low MER motivation belong to the fourth quadrant.

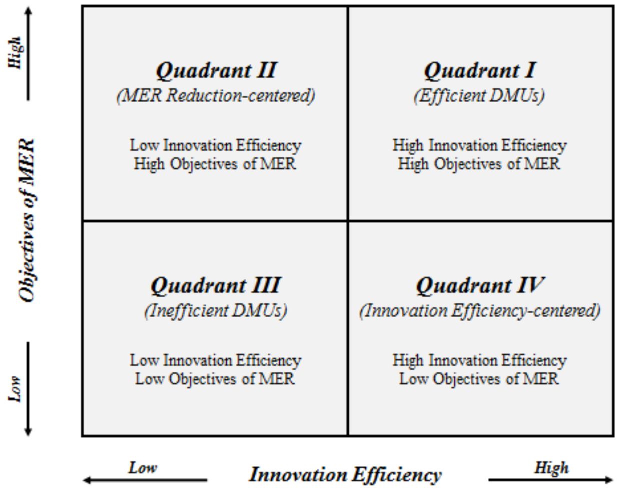

Figure 2. Innovation efficiency and MER objective matrix.

In order to determine the location of each industry within four quadrants given from Figure 2, bootstrap DEA was performed 2000 times following Simar and Wilson [43], and the results are summarized in Table 5. Table 5 elaborates the number of samples, the average of the bootstrap mean values, and the average of the objectives of MER by industry groups. Figure 3 shows the 2 × 2 matrix for each industry group after excluding the industries with less than 10 companies, as industry characteristics represented by only a few enterprises might be biased.

Table 5. Bootstrap DEA results.

Industry Type	No. of Firms	Ave. Innovation Efficiency	Ave. MER
Manufacture of food products	8	0.04	2.38
Manufacture of beverages	1	0.11	2.00
Manufacture of textiles, except apparel	6	0.27	1.83
Manufacture of wearing apparel, clothing accessories and fur articles	1	0.47	3.00
Tanning and dressing of leather, manufacture of luggage and footwear	1	0.73	2.00
Manufacture of wood and of products of wood and cork; except furniture	2	0.18	3.00
Manufacture of pulp, paper and paper products	2	0.16	2.00
Printing and reproduction of recorded media	2	0.14	2.00
Manufacture of chemicals and chemical products except pharmaceuticals and medicinal chemicals	14	0.14	2.21
Manufacture of pharmaceuticals, medicinal chemicals and botanical products	6	0.05	2.33
Manufacture of rubber and plastic products	53	0.22	2.38
Manufacture of other non-metallic mineral products	8	0.16	2.25
Manufacture of basic metal products	7	0.14	2.00
Manufacture of fabricated metal products, except machinery and furniture	23	0.22	1.70

Table 5. *Cont.*

Industry Type	No. of Firms	Ave. Innovation Efficiency	Ave. MER
Manufacture of electronic components, computer, radio, television and communication equipment and apparatuses	31	0.07	1.65
Manufacture of medical, precision and optical instruments, watches and clocks	32	0.20	2.34
Manufacture of electrical equipment	38	0.14	2.18
Manufacture of other machinery and equipment	122	0.10	2.51
Manufacture of motor vehicles, trailers and semitrailers	24	0.18	2.00
Manufacture of other transport equipment	3	0.10	2.00
Manufacture of furniture	2	0.16	2.00
Other manufacturing	2	0.41	3.00

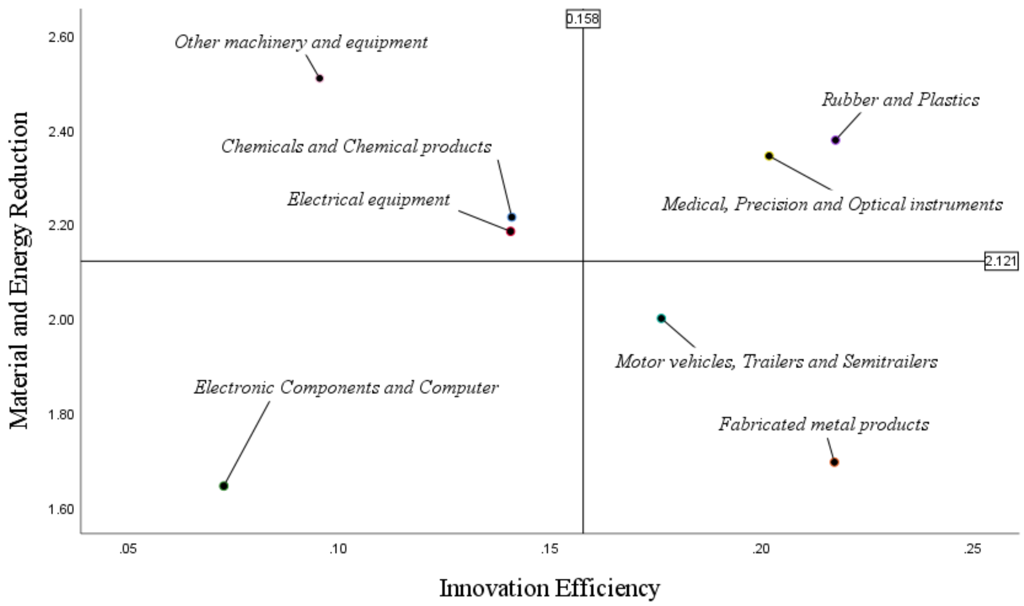

Figure 3. 2 × 2 matrix categorized by industry type.

According to Figure 3 below, the manufacturing industry has different characteristics in terms of innovation efficiency and innovation objective "RMEC". Manufacture of rubber and plastics products and manufacture of fabricated metal products (except machinery and furniture) turned out to achieve the highest innovation efficiency, while manufacture of electronic components, computer (visual, sounding and communication equipment) has the lowest. Meanwhile, manufacture of other machinery and equipment performs innovation to achieve MER the most, while manufacture of electronic components, computer does not engage in innovation for MER. Overall, manufacture of rubber and manufacture of plastics products and medical, precision and optical instruments belong to the first quadrant, whereas manufacture of electronic components, computer belongs to the third quadrant.

Establishing innovation efficiency calculated from SEM as dependent variable, we carried out tobit regression analysis to investigate potential effect of MER as innovation objective on the efficiency. The result is summarized in Table 6.

Table 6. Tobit regression for MER on innovation efficiency.

Dependent Variable: Innovation Efficiency	Coefficient	Standard Error
(Intercept)	0.399 *	0.078
MER	−0.067 **	0.033
Log-sigma	−0.670 ***	0.036

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

The regression analysis proved that MER has significant negative effect on innovation efficiency. The result is surprising that diverse literature pointed out the benefits of reducing material and energy consumption, such as increasing competitive advantage, profitability, and firm performance [7–13]. Given that the literatures consider outputs only, however, this study does not contradict the previous studies but rather indicate the possibility that input used for innovation might overweigh the output yielded.

5. Conclusions

5.1. Discussion and Implications

Up until now, studies constantly have maintained the positive effect of sustainability-related innovation objectives on innovation performance. Sustainability-related motivation of firms to pursue innovation could affect positively to firms' growth, profitability, and competitive advantage [7–9]. Moreover, logistics and manufacturing process of firms could be improved by pursuing sustainability-related innovation [12]. The benefits that firms could earn from sustainability is not limited only on firms' financial performance, but non-financial performance such as satisfaction of customers could also be increased when firms adopt green innovation [10].

The result of this study, on the contrary, pointed out that the RMEC could affect negatively on firms' innovation efficiency. Given that RMEC is a key component of sustainability, the result is seemed to be counter the previous studies. However, as this study measured innovation efficiency with considering both innovation inputs and outputs, not performance itself, this study suggests brand new implications to academics and practitioners rather than supplementing or contradicting existing literature.

According to previous studies, RMEC, which is a key component of sustainability, has become an essential objective for firms' successful innovation. Though innovation efficiency should be measured, again, however, previous researches did not consider effort and/or cost used for pursuing innovation but rather measure output only.

We measure innovation efficiency instead of performance itself, with considering two innovation inputs and two innovation outputs; inputs are the number of R&D employees and innovation cost, while outputs are the number of patent application and sales of innovative products. The tobit regression analysis proved that the effect of material and energy reduction on innovation efficiency is negative. By suggesting 2×2 matrix categorized by industry type, moreover, we identified different characteristics of industries in terms of innovation efficiency and reduction of material and energy as innovation objective.

The study suggests a few implications to previous researches and potential future studies on the effect of sustainability-related innovation objectives. While studies mostly argued that firms should become sustainable to achieve higher level of innovation performance, this paper points to the possibility that such behavior does not always guarantee advantages or even hinder innovation. However, one should interpret carefully that it does not contradict the previous literature, but rather points out the inputs used for innovation could be far outweigh compared to the actual outputs earned. As the study also identified the matrix categorized by industry type, it helps deeper understanding that huge difference exist in terms of material and energy reduction and innovation efficiency.

The study also gives several practical implications to managers at firms. First, we found the characteristics of manufacturing industries in terms of innovation efficiency and RMEC as innovation objective. From the result, managers at manufacturing firms could realize in which quadrant each industry belongs to, and establish appropriate innovation strategy with comparing competitors in the same industry. Second, the effect of RMEC turned out to have significant negative influence on innovation efficiency. It suggests to the managers that they should not perform innovation to reduce such consumption blindly, but rather consider deliberately the input they use to achieve certain amount of innovation output.

5.2. Limitations and Directions of Future Research

Though this study suggests both academic and practical implications, several limitations could be pointed out. First, the objective "RMEC" could be divided into two, reduction of material consumption, and reduction of energy consumption, following Guan et al. [16]. This study added up two objectives into one, because the data we used asks two objectives with a single questionnaire. If future research measures two objectives separately and analyzes the relationship between each of two objectives and innovation efficiency, the implication suggested could be very important.

Due to the nature of the DEA analysis, moreover, the efficiency value tends to decrease as the input element grows. Accordingly, we have not seen how efficiency values are distributed under the number of R&D employee and the R&D expenses used as input factors in this study. Future studies need to look at the effects of these variables using a methodology other than DEA.

The size of the sample used could also be pointed out as a limitation. We used only 388 samples out of 4000 manufacturing companies, since samples with missing values were excluded from the analysis. Consequently, the number of industry types examined is only 22, and the number plotted in the matrix in terms of innovation efficiency and MER as objective was limited to 8. Utilizing datasets including sufficient samples of each industry is believed to enable precise comparison among all industries, and we leave it to the future research.

Recent studies showed that material and energy consumption is not an issue only for the field of sustainability. Previous literature looked into the methods of managing energy consumption, such as "demand response" which is a tactic for managing electrical loads of users [50]. Moreover, material and energy consumption is also considered as a key performance indicator in the research field of production technology [51–53]. Future research on the efficiency of such research field which includes the issue of material and energy consumption is believed to suggest great implications as well.

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