Analysis of a Sensitivity Evaluation of the Exterior PV System for a House

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Abstract

The application of photovoltaics (PV) is regarded as an important element for sustainable zero-energy buildings that require energy generation through renewable energy systems. When applying such systems, architects and designers must concern themselves with their integration into the overall scheme of their designs. Thus, in this study, a guideline for design processes including PV modules in new construction is suggested.

This study followed a four-step process. First, design parameters were extracted for an evaluation. The exterior materials and color of a detached house were investigated as evaluation parameters. An investigation focusing on the existing PV literature and the current catalogue of PV modules was then carried out. The color of the PV module was then selected from existing colors. In the second step, an experiment to evaluate reactions to a variety of PV modules and building exterior factors, which the authors refer to as a sensitivity evaluation, was carried out using computer graphics (CG). In the third step, the characteristics of the sensitivity evaluation were analyzed by means of a factor analysis. The cognitive structure formulated during the sensitivity evaluation was also examined through a factor analysis. Fourth, the evaluation characteristics of the categories of the respective parameters were analyzed through a multi-regression method (HAYASHI I). Finally, a method of applying PV modules to the exterior of the house was proposed.

Further various and specific studies considering characteristics that should be taken into account by designers when applying PV modules as design elements should also be performed.

Keywords: sensitivity evaluation; BIPV; characteristic of the sensitivity evaluation; design elements

1. Introduction

1.1 Aim

Recently, the concept of environmental design and energy-savings in architecture has received increasing attention in Korea. As one sign of the growing emphasis being placed on these issues, environmental design and energy-savings have become targets of governmental management through institutional devices.

After 1990, the exterior colors used in architecture became an object of regulatory attention. Thus, colors used in landscapes and architecture are now managed by local governments by means of consultation. The national Korean government established the "landscape regulations" in 2007. These regulations were framed to help local governments to manage landscaping systematically. Then, "architecture basis regulations" were established in 2008. These regulations toughened guidelines for the exterior architectural design of public buildings.

At present, regulatory concern has focused on energy-saving architecture. After the Korean government declared 'Low Carbon and Green Growth,' many related regulations were established.

Indeed, the application of PV systems is regarded as an important element for sustainable zero-energy buildings, which require their energy to be generated through renewable energy systems. However, the appearance of building-integrated PV (BIPV) systems is not always pleasing, as some consider them to have an undesirable machine-like and high-tech look. Such negative views of the appearance of PV systems may deter architects and designers from including this relatively new technology in their designs.

Existing studies on color in architecture and building energy have been conducted in their respective fields. Studies on the sensitivity response of color in architecture were conducted by Yildirim et al., Kwallek and Lewis, Rosenstein, Tzeng and Wang, and Yildirim. Kim and Lee conducted research regarding the color adaptation for an interactive VR
Model. Hatakeyama et al.\textsuperscript{7) }studied the changing appearance of color in architecture, while Manav\textsuperscript{8) }studied color sensitivity in relation to illuminance. On the other hand, there are other studies that dealt with the effect of a building's color surface on its thermal performance. Bansal et al.\textsuperscript{9) }studied the effect of external surface color on the space temperature of a building and Synnefe et al.\textsuperscript{10) }investigated the effect of reflective coatings on lowering the surface temperatures of buildings and other surfaces of the urban environment. Cheng et al.\textsuperscript{11) }presented experimental results regarding the effect of envelope color and thermal mass on indoor temperatures which reveals that the use of lighter surface color and thermal mass can dramatically reduce maximum indoor temperatures.

Several studies concerning these issues have been conducted as follows. Hamza et al. analyzed the effect of the new 'Part L: Conservation of Fuel and Power' of the building regulations on architects, engineers and others when they undertook a construction project in the UK\textsuperscript{12) }. Bae and Lee's paper\textsuperscript{13) }explained a score of respective design elements for environmental performance research and presented an integrated environmental evaluation method as a decision-making tool for a multi-criteria design alternative. In Hagemann's paper\textsuperscript{14) }, through two examples of PV in a building, the energy consumption characteristics were analyzed in five steps: preliminary design drawings, detail drawings, final production drawings, the building process, and the use of the building. Kurakawa explained the PV systems in the urban environment\textsuperscript{15) }. In his paper, the area of the PV module of the buildings and the total optimization of the area were investigated by analyzing examples in a zoned residential zone, a business zone and an industrial zone. Also, Kann et al. suggested data as a reference for architects when designing buildings using 50 examples\textsuperscript{16) }.

Most of this earlier work investigated efficiency improvements, application methods and the necessity of the application of PV in architecture. In contrast, there has been little regard for the guidelines concerning architectural designs.

Therefore, the aim of this study is to determine the appropriate materials that designers can use when integrating a PV system into the design of a detached house. Thus, a sensitivity evaluation of an exterior composition was carried out.

1.2 Process

This study followed a four-step process. The first step was to extract the parameters for the evaluation. The exterior materials and color of the detached house were investigated as evaluation parameters. An investigation focusing on existing literature and on the current catalogue of available PV materials was also carried out. The appropriate color for the PV module was then selected from among existing colors. In the second step, an experiment to evaluate reactions to a variety of PV modules and building design factors, which the authors will refer to here as a sensitivity evaluation, was carried out using computer graphics (CG). In the third step, the characteristics of the sensitivity evaluation were analyzed using a factor analysis. Fourth, the evaluation characteristics of the categories of respective parameters were analyzed using a multi-regression method (HAYASHI I). Finally, an approach for applying PV modules to the exterior of the house was proposed.

2. Sensitivity Evaluation Experiment

A sensitivity evaluation experiment was carried out using CG to facilitate an understanding of evaluation tendencies regarding variations in the design parameters for the deployment of a PV module on a detached house.

The specific methods are given below.

2.1 Evaluation parameters

The evaluation parameters were determined as the colors of the PV module and of the roof and walls, as well as the materials of the roof and walls of the detached house. Six evaluation parameters were considered: the area on the house where the PV module was applied, the color of the PV module, the color of the roof, the material of the wall, the hue of the wall, and the tone of the wall. In this paper, all parameters have to be orthogonal relative to each other. They are used as independent items in the field of design and thus have been considered as orthogonally relative in most papers. Therefore, here they are dealt with as orthogonally relative.

First, the PV module was deployed over two different percentages of the roof area. In some instances, the PV module was deployed over 100% of the roof area, while in others it was deployed over 60% of the roof area.

Four colors for the PV module were used. In general, PV modules are produced in dark blue or dark purple blue or black. However, it is possible to produce PV modules in a variety of colors, if necessary. Dark blue PV modules offer the best efficiency. In addition to the more common colors listed above, PV modules are also produced in gray, green, yellow-red, and yellow.

In this study, PV modules of four different colors were used: blue (2.5PB 4/4), yellow-red (2.5YR 4/6), yellow (5Y 6/6) and green (5G 5/4).

When 60% of the roof area was covered by the PV module, asphalt shingles were applied to the remaining area of the roof. The colors of the asphalt shingles were selected by referring to an existing survey and to the sales volume of colors in production. Four colors of shingles were selected: a chromatic color with a middle value (N6.5), grayish brown (2.5Y 5/2), brown (5YR 4/2), and green (7.5GY 4/4).

Three parameters (materials, hue, and tone) were selected for the exterior wall. Various materials can be used for the exterior walls of a house, and for this
study, three types were selected: brick, siding (including wood siding and vinyl siding), and paint.

The color of each material was selected by referring to a catalogue of the respective materials, their sales volumes and existing literature about them. For brick, the hues of R and YR with high value/low chroma and middle value/middle chroma were selected. For siding, the hues of YR with middle value/low chroma and middle value/middle chroma were chosen. In addition, siding in a hue of blue with a high value/middle chroma and an achromatic color of siding with a high value were selected. Of course, a wide variety of colors can be and have been used as paint colors for housing; however, in this study, five paint colors were selected: R (2.5R 9/2), YR (10YR 9/2), Y (5Y 9/2), GY (5GY 9/2) and B (10B 9/2). Table 1 presents the specific colors of the respective wall materials chosen for use in this study.

Table 1. The Colors of the Respective Exterior Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Colors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick</td>
<td>7.5R 8/2, 10R 5/6, 10YR 9/2, 7.5YR 6/6</td>
</tr>
<tr>
<td>Siding</td>
<td>10YR 8/2, 5YR 6/6, 10B 8/4, N 8.5</td>
</tr>
<tr>
<td>Paint</td>
<td>2.5R 9/2, 10YR 9/2, 5Y 9/2, 5GY 9/2, 10B 9/2</td>
</tr>
</tbody>
</table>

2.2 Evaluation Object

Evaluation objects were created by using a Color Image Processor as shown in Fig.2.

The target evaluation objects were model detached houses with gable roofs. The backgrounds of the scenes containing the model houses were a grayish achromatic color with a middle value to prevent the subjects from being influenced by the background color of a given scene.

The detailed procedures of the creation of objects are as follows: 1) The detailed images of each category were made using the respective parameters. 2) Eleven hundred and fifty-two images were made for every case. 3) Similar images were included as objects. At that time, the authors checked whether there were missing parts in the respective categories. 4) Finally, 128 scenes were used as evaluation objects.

2.3 Subjects

The subjects in this study consisted of graduate and undergraduate students in a department of architecture who had normal perception of light and color and who had visual acuity of better than 1.0 with or without corrective lenses.

These experiments were conducted with 40 subjects. However, a group of experts was included, consisting of about 30 subjects. Therefore, this experiment was carried out by 32 subjects.

Table 2. Composition of the Subjects

<table>
<thead>
<tr>
<th>Gender</th>
<th>Males: 18, Females: 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degree</td>
<td>Graduates: 12, Undergraduates: 20</td>
</tr>
<tr>
<td>Total</td>
<td>32</td>
</tr>
</tbody>
</table>

2.4 Evaluation Adjectives

Evaluation adjectives were extracted from a previous related paper. The evaluation adjectives were distributed on three axes based on the Osgood theory: evaluation, potency, and activity. Fifteen pairs of adjectives were selected as evaluation adjectives, as shown in Table 3.

Table 3. Evaluation Adjectives

<table>
<thead>
<tr>
<th>Harmonious</th>
<th>Inharmonious</th>
<th>Desirable</th>
<th>Undesirable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural</td>
<td>Unnatural</td>
<td>Unique</td>
<td>Common</td>
</tr>
<tr>
<td>Comfortable</td>
<td>Uncomfortable</td>
<td>Dignified</td>
<td>Common</td>
</tr>
<tr>
<td>Stable</td>
<td>Unstable</td>
<td>Brilliant</td>
<td>Ordinary</td>
</tr>
<tr>
<td>Chic</td>
<td>Unchic</td>
<td>Bright</td>
<td>Dark</td>
</tr>
<tr>
<td>Up-to-date</td>
<td>Old-fashioned</td>
<td>Warm</td>
<td>Cool</td>
</tr>
<tr>
<td>Neat</td>
<td>Disordered</td>
<td>Soft</td>
<td>Hard</td>
</tr>
<tr>
<td>Familiar</td>
<td>Unfamiliar</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.5 Experimental Method

The experiment was carried out using CG. The validity of these experiments was verified in a previous paper.

Fig.1. Examples of Objects

Fig.2. The Experimental Scene

Because colors are highly sensitive to lighting conditions, all experiments were performed under the same illuminance condition in which the color palettes were selected. Subjects were given a ten-minute adaptation period in a darkened room and then a one-minute adaptation to the scene. A time of
approximately two and a half hours was required to finish the experiment for each subject. Fig.2. presents the scene shown to subjects during the experiment.

The semantic differential method (SD method) was used for the sensitivity evaluation.

**2.6 Analysis Method**

The data were analyzed using the statistical program SPSS/PC+. Fifteen pairs of adjectives were scored from 1~7. The mean, dispersion and standard deviation of each evaluation adjective were obtained. A factor analysis was conducted by principal component analysis using Varimax rotation. The eigen values were all over 1.0. In addition, the multi-regression method was utilized with the HAYASHI I (multi-regression method) program.

**3. Analyzing the Characteristics of the Sensitivity Evaluation of the Exterior Composition**

**3.1 Factor Analysis**

In this study, a sensitivity evaluation of six parameters (the percentage of area covered by the PV module, the color of the PV module, the color of the roof, the material of the wall, the hue of the wall, and the tone of the wall) was carried out for a detached house with a PV system using 15 evaluation adjectives. A factor analysis was used to evaluate the data. It was found that there were three main evaluation factors (Table 4.).

**Table 4. Results of Factor Analysis**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Evaluation Item</th>
<th>Factor Stressing Score</th>
<th>Communality</th>
<th>Factor Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Natural</td>
<td>0.9465</td>
<td>-0.1460</td>
<td>0.1738</td>
</tr>
<tr>
<td>I</td>
<td>Desirable</td>
<td>0.9410</td>
<td>-0.0514</td>
<td>0.2479</td>
</tr>
<tr>
<td>I</td>
<td>Harmonious</td>
<td>0.9379</td>
<td>-0.1554</td>
<td>0.1820</td>
</tr>
<tr>
<td>I</td>
<td>Familiar</td>
<td>0.9326</td>
<td>-0.1040</td>
<td>0.2422</td>
</tr>
<tr>
<td>I</td>
<td>Comfortable</td>
<td>0.9251</td>
<td>-0.1588</td>
<td>0.2723</td>
</tr>
<tr>
<td>I</td>
<td>Stable</td>
<td>0.9068</td>
<td>-0.2452</td>
<td>0.2546</td>
</tr>
<tr>
<td>I</td>
<td>Neat</td>
<td>0.9029</td>
<td>-0.0944</td>
<td>0.0125</td>
</tr>
<tr>
<td>I</td>
<td>Unique</td>
<td>-0.7231</td>
<td>0.5058</td>
<td>0.0589</td>
</tr>
<tr>
<td>I</td>
<td>Brilliant</td>
<td>-0.6436</td>
<td>0.6299</td>
<td>0.1245</td>
</tr>
<tr>
<td>II</td>
<td>Bright</td>
<td>0.1030</td>
<td>0.8675</td>
<td>0.0554</td>
</tr>
<tr>
<td>II</td>
<td>Chic</td>
<td>-0.1446</td>
<td>0.8280</td>
<td>-0.4779</td>
</tr>
<tr>
<td>II</td>
<td>Up-to-date</td>
<td>-0.3137</td>
<td>0.7983</td>
<td>-0.4549</td>
</tr>
<tr>
<td>II</td>
<td>Dignified</td>
<td>0.3668</td>
<td>-0.8021</td>
<td>0.2773</td>
</tr>
<tr>
<td>III</td>
<td>Warm</td>
<td>0.5241</td>
<td>-0.2266</td>
<td>0.7764</td>
</tr>
<tr>
<td>III</td>
<td>Soft</td>
<td>0.6504</td>
<td>0.1031</td>
<td>0.6802</td>
</tr>
<tr>
<td>III</td>
<td>Eigen value</td>
<td>8.0854</td>
<td>5.5846</td>
<td>2.2354</td>
</tr>
<tr>
<td></td>
<td>Contribution Rate</td>
<td>44.9189</td>
<td>31.0258</td>
<td>12.4191</td>
</tr>
<tr>
<td></td>
<td>Cumulative Contribution Rate</td>
<td>44.9189</td>
<td>75.9447</td>
<td>88.3638</td>
</tr>
</tbody>
</table>

Factor I consisted of 'Natural,' 'Desirable,' 'Harmonious,' 'Familiar,' 'Comfortable,' 'Stable,' 'Neat,' 'Unique' and 'Brilliant.' From among these adjectives, 'Unique' and 'Brilliant' showed a negative correlation. Factor I was related to 'the Evaluation' item based on the Osgood theory. The contribution rate of Factor I was 44.92%.

Factor II consisted of 'Bright,' 'Chic,' 'Up-to-date' and 'Dignified.' From among these adjectives, 'Dignified' showed a negative correlation. Factor II is related to 'the Activity' item based on the Osgood theory. The cumulative contribution rate was 75.94%. Factor III consisted of 'Warm' and 'Soft.' The contribution rate of Factor III from among all adjectives was 12.42%.

**3.2 Analyzing the evaluation tendency using the factor scores**

A scatter diagram is presented in Fig.3. and Fig.4. according to the factor scores of the respective evaluation objects.

In Fig.3., Factor II is presented on the X axis and Factor I is presented on the Y axis. Therefore, the evaluation object for the 'Bright' and 'Chic' images is presented on the right side, while that of the 'Natural' and 'Desirable' images is arranged on the top.

For the evaluation adjectives related to Factor I, the evaluation adjectives were highly rated for the PV module deployed over 100% of the roof area. The adjectives group of Factor I was not greatly affected by the materials of the wall. The adjectives related to Factor I were rated highly for the hue of YR with a high value/low chroma.

For the adjectives related to Factor II, the tone of the exterior wall had a strong influence on the evaluation. The tone of high value/low chroma was particularly highly rated.

In Fig.4., the factor scores for Factor I and Factor III are plotted. Factor III is presented on the X axis while Factor I is presented on the Y axis. Therefore, the evaluation objects of 'Warm' and 'Soft' images are presented on the right side, while those of 'Natural' and 'Desirable' images are arranged on the top.

In Factor III, the hue of the exterior wall greatly influenced the evaluation. The hues of R and YR were highly rated, whereas the hue of B received a low rating.
4. Analysis of the Influence on Sensitivity Evaluation

The multi-regression method was carried out to interpret the specific evaluation tendencies connected with particular parameters and categories.

4.1 Analysis of the Effects of Evaluation Parameters

In Table 5., the evaluation tendencies are analyzed according to the Partial Correlation Coefficients of the six evaluation parameters.

The hue of the exterior wall had the most influence as an evaluation parameter, with the tone of the wall second.

Whether an overall design image was rated by participants as having an appearance that was 'Familiar,' 'Stable,' 'Neat,' 'Brilliant,' or 'Warm' was greatly influenced by the color of the PV module. Whether an image was viewed as 'Unique' was affected mainly by the color of the roofing shingles.

The evaluation adjectives 'Chic' and 'Up-to-date' were primarily dependent on the exterior materials of the wall. The percentage of roof area over which the PV module was applied did not greatly influence the evaluation.

4.2 Analysis of the Effects of Categories

In Table 6., the effects of the categories of the six evaluation parameters are summarized. An analysis of these figures indicates that the multiple-correlation coefficient was over 0.7 for most adjectives.

The evaluation adjectives related to Factor I were primarily dependent on the hue of the wall, as indicated in Fig.3. For the adjectives of 'Desirable' and 'Comfortable,' the evaluation objects were greatly influenced by the PV module deployed over 100% of the roof area. For images rated as 'Unique' and 'Brilliant,' the PV module deployed over 60% of the roof area was mainly affected.

Among the PV modules, the hue of Y was highly rated. When housing materials were analyzed, both siding and paint were strongly associated with images described as 'Bright,' while brick was associated with images rated as 'Dignified.'

In terms of the hue of the exterior walls, those of YR was rated highly for most adjectives and the hues of GY and B were highly rated as 'Unique' and 'Brilliant.'

For the tone of the exterior walls, having a high value/low chroma was rated highly for most adjectives and having a middle value/middle chroma was rated highly as 'Unique' and 'Brilliant.'

Table 7. presents the results of the analysis of the adjectives related to Factor II and Factor III.

The PV module deployed over 60% of the roof area was rated highly for the adjectives related to Factor II.

Table 6. presents the results of the analysis of the evaluation adjectives related to Factor I and Factor II. For the adjectives related to Factor II, the PV module deployed over 60% of the roof area was associated with images rated as 'Bright,' 'Chic,' and 'Up-to-date.' The PV module deployed over 100% of the roof area was associated with images rated as 'Dignified.'

In terms of the color of the PV module itself, the hue of R was closely associated with images rated as 'Bright,' the hue of B with images rated as 'Chic' and 'Up-to-date,' and the hue of Y with images rated as...(continued)
For the color of the roof, images described as 'Bright,' 'Chic' and 'Up-to-date' were closely associated with an achromatic color and images rated as 'Chic' and 'Up-to-date' were associated with the hue of G. Images described as 'Dignified' were associated with the hue of YR with a dark tone.

In the evaluation of the exterior wall materials, the descriptor 'Bright' was closely associated with brick. The descriptors 'Chic' and 'Up-to-date' were closely associated with paint and the descriptor 'Dignified' was closely associated with brick.

For wall hues, the descriptors 'Bright,' 'Chic' and 'Up-to-date' were closely associated with achromatic walls. Images with walls in the hue of YR were highly rated as 'Dignified.'

In terms of the tone of the walls, the images containing high value/low chroma were associated with the descriptors 'Bright,' 'Chic' and 'Up-to-date,' while images with the middle value/middle chroma were often rated as 'Dignified.'

The adjectives related to Factor III were evaluated as follows.

Images containing a PV module covering 100% of the roof and in the hue of Y were highly associated with the descriptors 'Bright,' 'Chic' and 'Up-to-date,' while images with the middle value/middle chroma were often rated as 'Dignified.'
materials of the wall were highly rated in the case of brick. The color of the wall was estimated highly by the hue of YR with a high value/low chroma.

5. Conclusions

In this study, factors for designers to consider when integrating PV modules as an exterior component of their designs were analyzed. The results are as follows.

1) The most important factor to consider in an exterior design was the hue of the wall, followed by the tone of the wall. The hue of the wall and the tone of the wall strongly affected whether an image was rated as 'Familiar,' 'Stable,' 'Neat,' 'Brilliant' or 'Warm.' The color of the roof was an important determinant of whether an image was considered 'Unique,' and the exterior materials used for the walls must be considered for a design to be considered 'Chic' or 'Up-to-date.'

2) Designs associated with the descriptors 'Natural,' 'Desirable,' 'Harmonious,' 'Familiar,' 'Comfortable,' 'Stable' and 'Neat' were likely to have PV modules that covered 100% of the roof area and to include the color Y.

For designs with a PV module covering only 60% of the roof area, having the color Y on the roof was highly rated. The hue of YR with a dark tone was closely associated with images regarded as 'Harmonious' and 'Familiar.' The inclusion of an achromatic color of roof in design was associated with the resulting image being described as 'Comfortable' and 'Stable.' In terms of exterior wall materials, the use of paint was associated with images rated as 'Natural,' 'Harmonious,' 'Familiar,' 'Stable' and 'Neat,' while brick was highly associated with images rated as 'Desirable' and siding was associated with images described by participants as 'Natural.' In terms of wall colors, the hues of YR and Y with a high value/low chroma were highly regarded.

3) The method for achieving an exterior design likely to be viewed as 'Unique' and 'Brilliant' is as follows. A PV module in the color of R that covers less than 100% of the roof area should be applied on a roof that is the color of YR in a light tone. Siding in the color of GY or B in a middle value/middle chroma should be applied as the exterior wall material.

For the expression of a design likely to be viewed as 'Bright,' 'Chic' and 'Up-to-date,' a PV module should be applied over less than 100% of the roof surface and the exterior color of the house should be achromatic or of a hue with a high value/low chroma. For a design likely to be considered 'Bright,' a PV module in the color of R should be applied, the color of the roof should be achromatic, and brick should be used as the wall material. To create a design likely to be considered 'Chic' and 'Up-to-date,' a PV module the color of B should be applied, the roof should be the color of G, and paint should be used for the exterior walls.

4) To create a design that is 'Dignified,' 'Warm' and 'Soft,' a PV module that covers 100% of the roof should be applied and the color of the PV module should be Y.

To achieve a 'Dignified' design, the color of YR with a dark tone should be utilized on the roof, brick should be applied as an exterior material, and the hue of YR with a middle value/middle chroma should be applied on the walls. To give a 'Warm' and 'Soft' impression, the area of the PV module should be kept below 100%, and an achromatic color should be used on the roof. The use of brick was commonly associated with an image of 'Warm,' while the use of paint and chroma were commonly associated with an image of 'Soft.' The use of the hues Y, YR, and R with high value/low chroma had a strong effect on the perception of an image of 'Soft.'

In this study, a guideline for integrating PV modules into exterior and architectural designs is suggested from a design point of view. Further studies considering specific characteristics for designers to consider when applying PV modules should also be performed.

Acknowledgments

This work was supported by the Energy Efficiency & Resources of the Korea Institute of Energy Technology Evaluation and Planning (No.2012T100100065) and by the Human Resources Development Project of the Korea Institute of Energy Technology Evaluation and Planning (No.20114010203040) grant funded by the Ministry of Knowledge Economy.

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