QUANTITATIVE DESCRIPTION OF THE QUALITY OF DAYLIGHT ELECTROLUMINESCENSE (dEL) IMAGES AGAINST DARK ROOM EL IMAGES

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ABSTRACT: In this study, we present a robust comparison between EL/dEL images taken with an InGaAs camera, and "golden images" taken under optimal conditions with a Si camera in the dark, which serves as the benchmark. We study the correlation of EL/dEL data quality correlated with the golden image, considering different acquisition parameters and electrical current panel modulations. A key contribution of this work is the correlation of the SNR25 metric, recently introduced by our group, with pixel-by-pixel metrics used to assess image similarity using the Structural Similarity Index (SSIM). Our findings indicate that the quality of dEL images is reliable, showing a satisfactory correlation with data obtained through dark room EL. This analysis was conducted by comparing the structural correlation pixel by pixel (SSIM), demonstrating that dEL data has a very high correlation, indicating that both methods provide the same information about the panel. Furthermore, we found a correlation between the SNR25 metric and the SSIM, allowing us to use this metric as a proxy to assess the quality of the dEL images taken on the field. The results of this research validate the use of dEL imaging for practical applications.
Keywords: Daylight Electroluminescence, InGaAs cameras, image quality

1 INTRODUCTION

The exponential growth of photovoltaic solar energy production in recent years has established it as a leading green alternative for energy production, hence making the research in this field a priority. Ensuring the reliability and longevity of solar panels is crucial for their optimal operation and to prevent power losses. This makes the characterization and description of solar panel defects a key area of research. Electroluminescence (EL) has emerged as an invaluable technique in this context. It provides spatial information about various detrimental defects in solar modules, thereby contributing to the overall assessment of panel health and efficiency.

Traditionally, high-resolution Si cameras have been used to perform dark room EL, which necessarily given the technical aspects of Si sensor cameras must be performed in a dark room to remove all the light sources besides the electroluminescence from the photovoltaic (PV) module. However, this method requires no-light conditions, posing a challenge for inspecting photovoltaic modules in solar power plants requiring dismounting the solar panels and transport to a dark room for inspection or conducting inspections at night, which lead to production losses and are logistically complex. Despite its limitations, dark room EL with Si cameras remains the standard method for characterizing solar panels post-manufacturing. Recently, daylight electroluminescence (dEL) using InGaAs cameras has emerged as a promising alternative for on-site inspections. However, dEL requires a filtration process to suppress ambient light, which can potentially reduce the quality of the obtained information. The lower resolution of InGaAs cameras and potential quality degradation due to filtration processes are not entirely assessed. Hence, it is necessary to have a robust quantitative comparison of dEL images with those obtained in dark environments.

The InGaAs camera Characteristics makes a technically viable equipment for dEL given the high quantum efficiency on the spectral range PV modules EL emits light. This makes that with small amounts of optic equipment the camera can obtain the information in shorts spam of time, the usual combination is a SWIR optic lens and bandpass filters centered around 1150 nm, with several different bandwidth capable of obtaining data.

Different parameters have been defined to quantify the quality of dEL images [1]. Among these, very recent asynchronous schemes for dEL have been proposed [2, 3], which have the potential to significantly reduce the time required for acquisition and inspection.

The aim of this work is to quantify the quality of the information recovered from dEL images obtained with our asynchronous method and to validate the use of our quality metric described below as a proxy to inform us about how reliable the information recovered from dEL is. For this, we first obtain "golden images" under the best possible conditions in a dark room, which serve as a standard. These images are used to measure against the daylight electroluminescence (dEL) images and also the images taken in a dark room with the same configuration as in dEL. To filter the light that is not emitted by the panels, we use an asynchronous scheme where the panel is modulated using sinusoidal or square pulses and the quality of the resultant images calculated in terms of the SNR25 metric. This process is described in detail in [2]. The obtained images are then compared against the "gold standard" using robust algorithms to extract a metric that measures how similar the images are. We use a combined metric, called similarity index, that is able to detect differences in the structure, focus, grain and sharpness of the images. This index is then ccompared with the quality metric of the images (SNR25), allowing us to correlate this index with the quality of the information in the panel in a robust way.

This work is a first step to enable robust large-scale solar panel daylight inspections by leveraging the speed of

InGaAs cameras by establishing a robust methodology for quantifying the quality of dEL images. This marks a significant step forward in the practical application of daylight electroluminescence technology.

2 METHODOLOGY

The analysis is performed in several PV modules of reflective back sheet and PERC cell technologies, the panels coming from three different manufacturers. They were all known to display cracks of several types on EL inspection. For each module, an area of four adjacent cells was selected to be imaged depending on the quantity and variety of existing failures. (The area was marked with four 1140 nm infrared emitters.)

Two different cameras were used for the imaging: a Sony ILCE-7SM3 12.1 MP CCD camera, whose IR filter had been removed, together with a Sony FE 35mm F1.8 lens and a Hoya R72 infrared filter ... a First Ligh C-RED 2 Lite 640x512 (~0.3 MP) InGaAs camera along with a Kowa LM16HC lens and a Salvo Technologies 1160nm FWHM bandpass filter. Both cameras ... placed at the top of a prism-shaped aluminum structure, which was tall enough for them to catch the whole area. It also served as a stand for a Musou Black IR Flock Sheet to cover the space up completely. This was used for dark room images to ensure the best possible conditions given its absorption rate of more than 99.5% of light in near-infrared ranges. It should be noted that the panels may lit the scene otherwise, and non-emitting regions of the panels will show some illumination from the background light. The dark room images were taken then in the darkest room as possible to avoid these artifacts. Musou Black Paint was also applied to remaining inner elements. The structure could easily be attached to any module by means of a four-bar movable frame designed to be fixed to its long sides. This ensures that the cameras are collecting the images in the exact same position, which later helps in the image comparison process.

Fordark room measurements an Aim-TTi CPX400DP DC power supply was used to inject an electric current to the. modules equal to its short circuit current first, Isc, and one-tenth that value afterwards. For each configuration, the Sony ILCE-7SM3 camara with a Silicon sensor was used to produce a high resolution EL image, the so called "golden image" (shutter speed of 30', F1.8 and ISO 80) while the C-RED 2 Lite provided one single image which is the average of a image stack captured at 300 FPS (shutter speed of 3.33"), with its lens aperture completely open. Pictures of the module disconnected were also taken for the background subtraction performed during the subsequent processing. On the other hand, daylight imaging implied taking the modules outdoor and powering them. For this aEA-PSI 91500-30 power supply was used, which allows for current modulation creating custom square and sinusoidal waves with a peak-to-peak amplitude of Isc and frequencies 12 Hz was applied to capture 400 images at 300 FPS again.

The first stepnecessary to ensure data comparability, requires crop and align both images to the same overlapping region of interest (ROI). However, since the Sony is an HD image (3MPix) and the C-RED is a 0.33Mpix, we need to rescale the low resolution image to high res and vice versa. Then we need tomorph images to correct for misalignments warping perspective. This two steps are performed simultaneously using the warpPerspective function included in the CV2 python library, using a LANCZOS4 interpolation algoritm.

Before comparing we also perform an equalization process of the imagesconsisting on applying a contrast limited adaptive histogram equalization with a kernel of 8x8 pixels, perform normalization on the image and rescale the data to uint16.

Finally, a custom image similitude algorithm is bused to calculate the similarity index SI between an image and its "golden image". As mentioned before, this algorithm uses different metrics. First we quantify the structural similarity of the images, for this we use a variation of the Structural Similarity Index SSIM which considers the spatial correlation and pixel intensity analysis [4]. There are several approaches of application of the SSIM in this work we use the Multiscale SSIM (MS-SSIM) described in [5], and implemented in the skimage.metrics python package. We use three scales with weights [0.9, 0.08,0.02] to skew the result towards the smaller detail. The gaussian sigma is keep minimal to ensure small cracks are not blur (0.05) and the image kernel is 3x3 so again we are more sensitive to small local changes. Typically, the similarity index is calculated as the average of the MS-SSIM for all pixels, but here we are much more interested on preservation of small details, so we only compute the average of lowest decile, i.e. the worst 10% of the pixels in the image.This is our $index1$. Quality of an image is also defined by the local sharpness, i.e. how well we distinguish borders. For this we compare the high frequency part (upper decile) of the power spectra of the images. $Index2$ is the ratio of fft upper part of the image and the golden image. Another quality metric is the defocus of the image. For this we perform a relative comparison comparing the normalized Tenengrad sharpness [ref: https://ieeexplore.ieee.org/document/8980980]. The index is again calculated from the ratio of the Tenengrad sharpness, but we use a log10 of the ratio and call it $ndex3$.To compute the relative noise of the images, i.e. the grain of the image we use the variance of the Laplacian of each image, and we create a relative comparison as the ratio of this metric in log10 scale again ($index4$), then our similarity index (SI) is created from all the previous quality indexes:

$$SI = |index1 \times \sqrt[3]{index2 \times index3 \times index4},$$

3 RESULTS

The following datasets were obtained using the following parameters with the two cameras mentioned above over 6 photovoltaic modules: 1. Sony dataset taken in dark room using 30'' acquisition time, aperture F1.8, gain (ISO) 80, 3Mpix(4256x2848) resolution, 2. First light (FL) taken in dark room using 3.3" acquisition time, 300 fps, aperture F("max"), gain medium, 0.3Mpix(640x512) resolution, 3. FL taken in daylight using 3.3" acquisition time, 300fps, aperture F("min"), gain medium, 0.3Mpix(640x512) resolution. Also, daylight dataset is divided into 5 sets testing for different modulation parameters as follows: Sin wave EL 4,8,12 hz and identically with square wave and finally 1 last daylight set with all the modulation parameters mentioned above and variating fps in the range of (600-60). These parameters are summarized in the table 1.

Dataset				
	SI Camera	InGaAs Camera		
	drEL	dEL		drEL
		HZ sin+sqr@300fps	FPS sqr@12hz	300fps
QPLUS	X	4, 8, 12	NA	X
CANADIAN X2	X	4, 8, 13	NA	X
GLC X2	X	4, 8, 14	NA	X
CANADIAN	X	4, 8, 15	40,60,80,100,200, 400,500,600	X

Table 1. Acquired datasets for the experiment

Several degradation tests were performed over each image to test the performance of the comparison algorithm the results of this test are presented in figure 1. The following degradation test were performed over Sony high resolution images: resolution degradation by averaging pixels, resolution degradation adding random noise, degradation by pixel erosion and degradation by defocusing.

We can observe in figure 1 that the decrease in similarity decrease steady according to degradation indicating that the similarity algorithm recognizes the degradation of the images proportional to the amount of degradation applied to the data used.

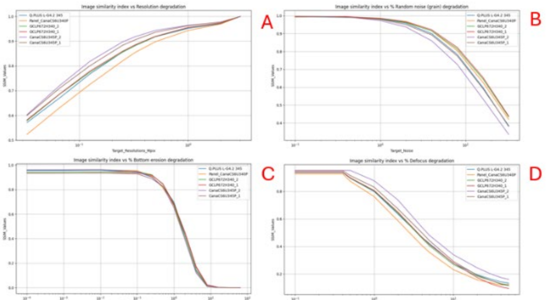


Figure 1. Similarity index algorithm test downgrading high resolution images and then testing against the original image A) Resolution degradation, B) Random Noise degradation, C) Erosion degradation and D) Defocus degradation

An original vs degraded image comparison is presented as colormap is presented in figure 2, the sample panel is the GCLP672H340_1. We can observe the main difference are observed in the definition of the borders of the fingers.

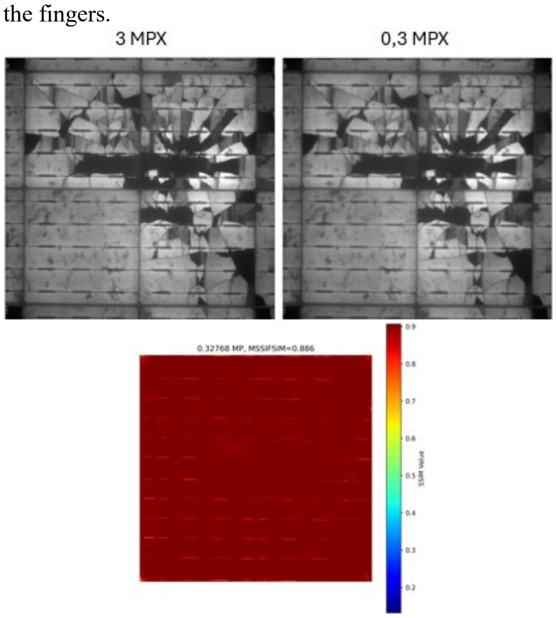


Figure 2. Original resolution 3Mpx vs degrading resolution 0.3Mpx, SI colormap shows that degradation affects the similarity at the borders

The next step is an analysis of the dark room EL between high resolution SI-camera and low resolution InGaAs camera, and between high resolution and low resolution Si-camera image. The similarity index colormap comparison and original images are shown in figure 3. In this analysis we want to observe what degradation parameters are comparable to the low-resolution image. We can observe that the structural index shows that there are more losses than just resolution as observed in figure 4. A complete analysis of degradation is presented in figure 5, notice where the similarity index cut is the amount of degradation required to obtain the InGaAs score with our different degradation algorithms.

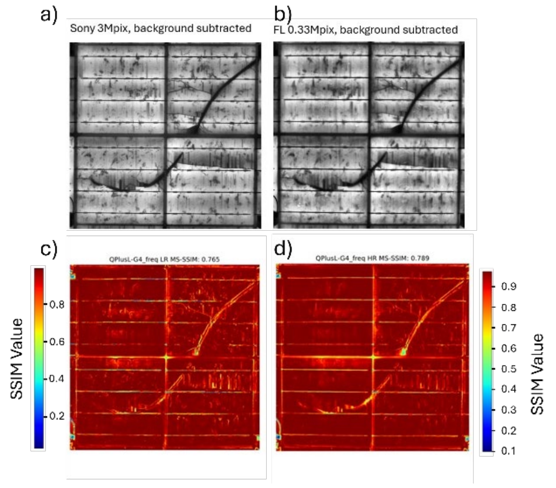


Figure 3. high resolution and low resolution InGaAs camera image presented in a) and b) respectively, c) is the low resolution vs a) similarity index and d) is the high resolution b) similarity index vs degraded resolution b)

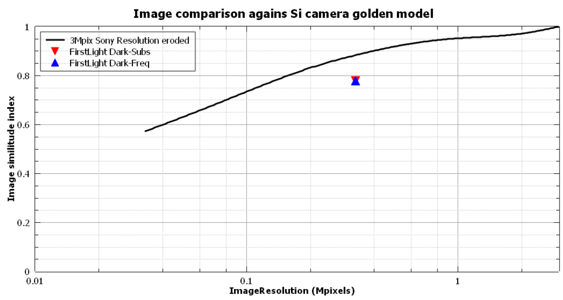


Figure 4. Degraded high resolution image curved and FL low resolution images similarity index

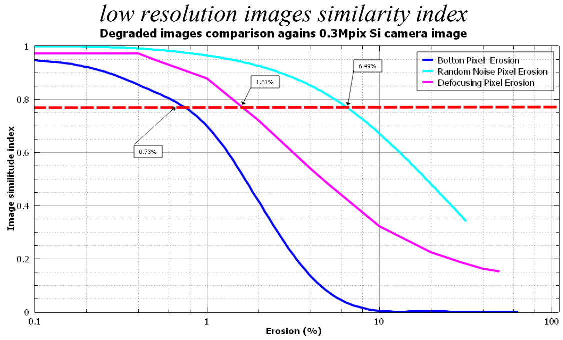


Figure 5. Different degradation methods over high resolution Si-camera curves presented against Similarity index value against InGaAs camera vs high resolution similarity index

These results show that the image obtained with FL

InGaAs camera does not vary only because of the resolution but due to several factors as seen in figure 5.

Once this is assessed we can finally compare drEL Si-camera, drEL InGaAs and dEL InGaAs. For the case drEL are processed with the same method as the dEL using background takes as off-state modulation shuffling them in an orderly manner. index color map between Si camera and dEL are presented in figure 6.

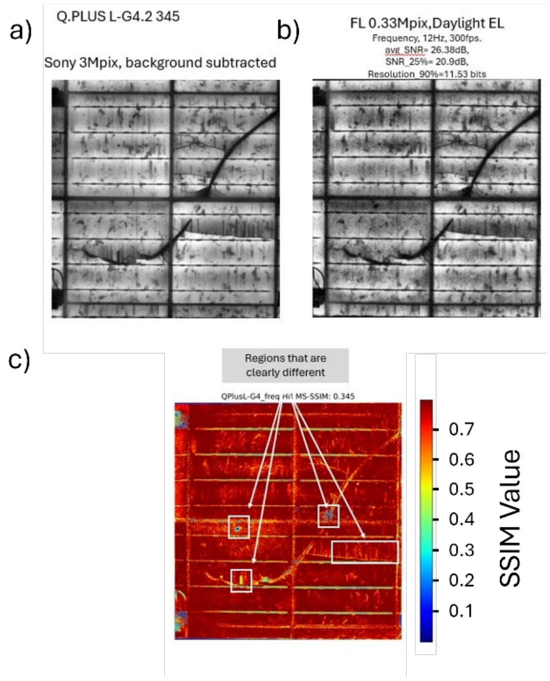
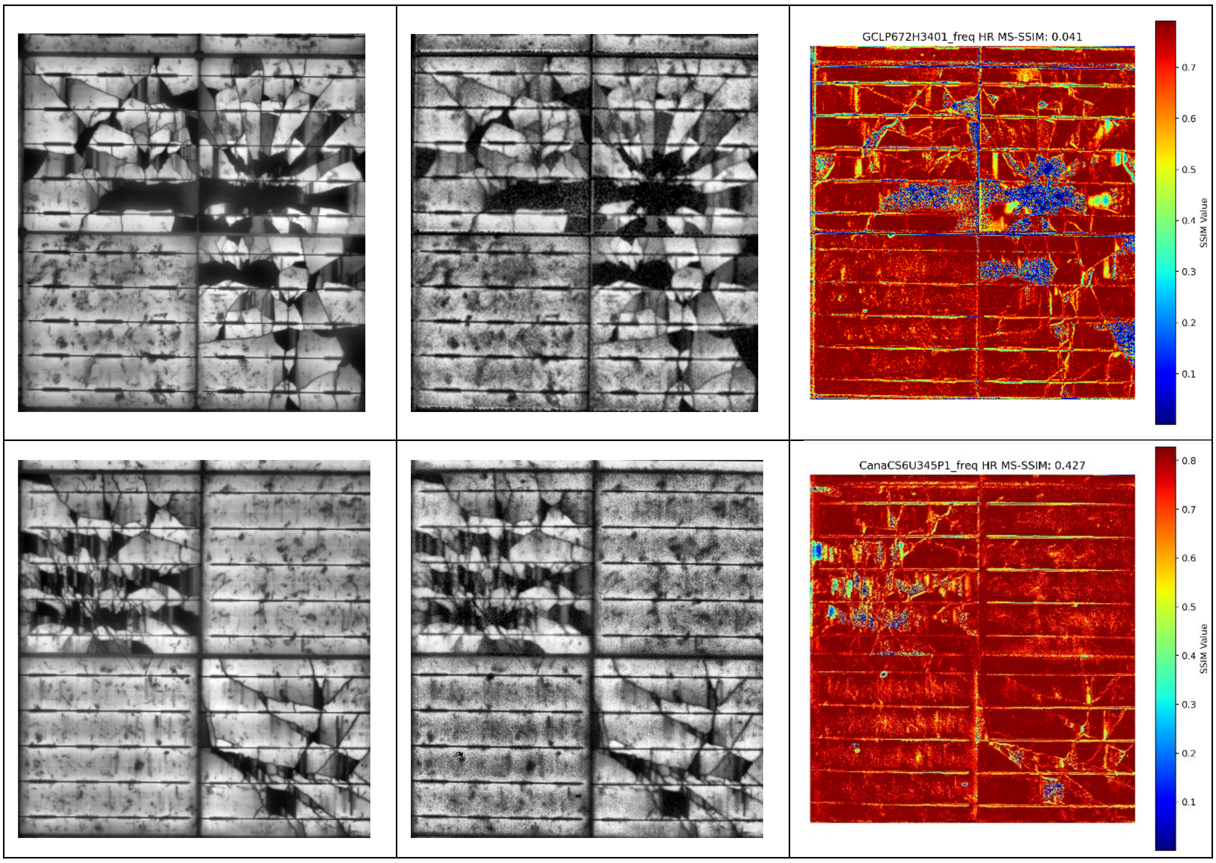


Figure 6. Similarity index comparison and original images a) drEL Si-camera, b) dEL InGaAs and c) colormap similarity index



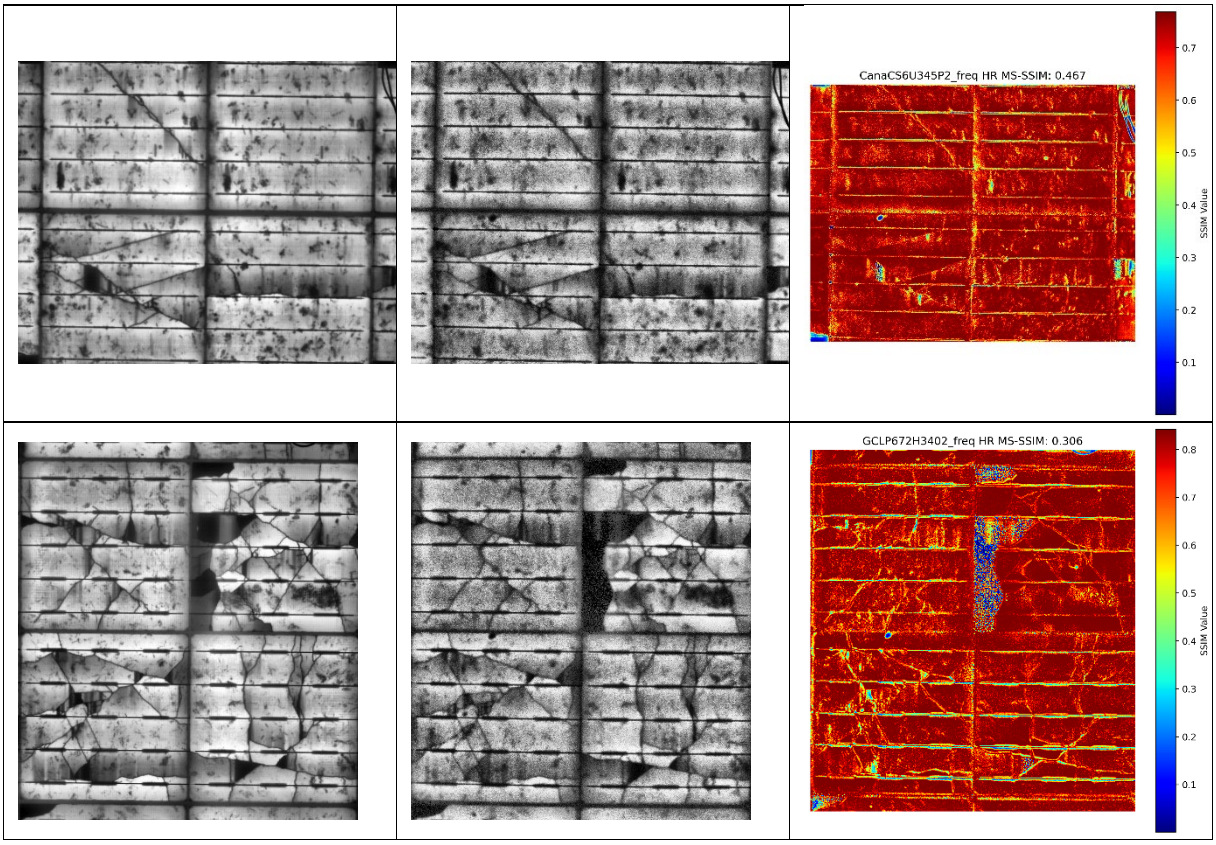


Figure 7. Image comparison between Si DrEL images and dEL images on 4 other panels.

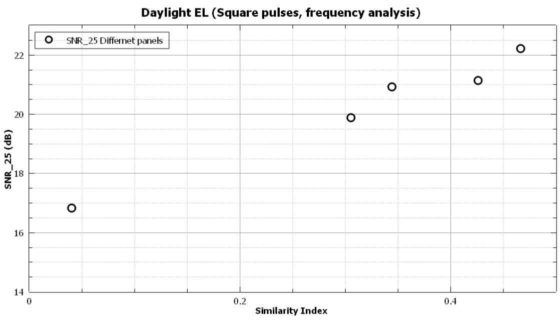


Figure 8. SNR25 vs Similarity index of all the panels, see the correlation blablabla

These results show that the image

4 REFERENCES

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