POLITECNICO DI TORINO

Master's Degree in Computer Engineering

Energy Management for IoT

Lab 2 - Report

Energy efficient image processing

Dario Castagneri
277967

A. Y. 2020-2021

Table of contents

Introduction

The goal of the experience is the analysis of how image manipulation techniques can be used to trade off image quality and reduce energy consumption in emissive displays. The analysis includes considerations regarding image power consumption with respect to distorsion before and after manipulations. All the required equalization and processing, implemented by using MATLAB scripts, are applied uniformly to the entire set of the provided images and to six further personal images. The additional images, whose preview is shown in *figure 1*, include screenshots of black and white editors, internet pages and a full red image.

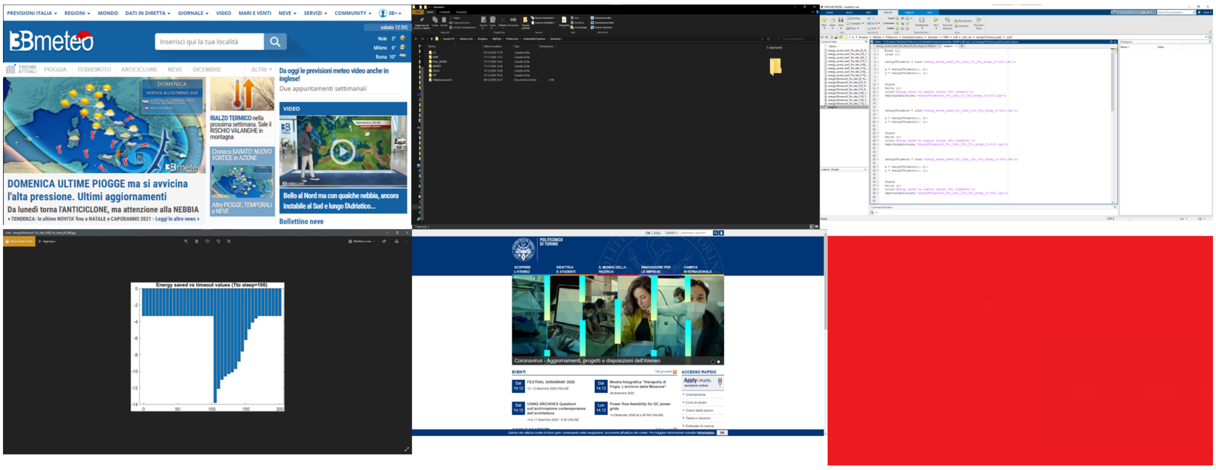


Figure 1 - Additional images

Image manipulations

Power consumption estimation

The power consumption of an image is computed using a model that emphasizes an energy-color dependency. The model defines the requested power to show an image as the sum between the power of each image pixel and a baseline power. The correspondent formulas are shown below.

$$P_{pixel} = w_R * R^\gamma + w_G * G^\gamma + w_B * B^\gamma \qquad P_{image} = w_0 + \sum_{i=1}^{n} P_i(R, G, B)$$

Distorsion estimation

There exist different mathematical models to estimate distortion between images. For this experience, two models are used, the first is based on euclidean distance, the second on Mean Structural Similarity Index. The euclidean model is applied in the LAB color domain and deals with the pixel distance between the original and the distorted images. On the other hand, the MSSI model involves measures of brightness, contrast and structural distortion. However, both models do not take into account how the human eye can perceive differences between two similar images. For this reason, a further empirical evaluation and comparison with human perception is provided.

Experimental results

Color reduction

Color reduction is an example of a pixel-oriented transformation technique. For this reason, it is expected an increment in power savings as the color reduction increases. The manipulation is applied to each image RGB value with a sweep of 10% for each iteration up to a 100% reduction. The average results regarding power savings and distortions on the entire set of images are shown in *figure 2*.

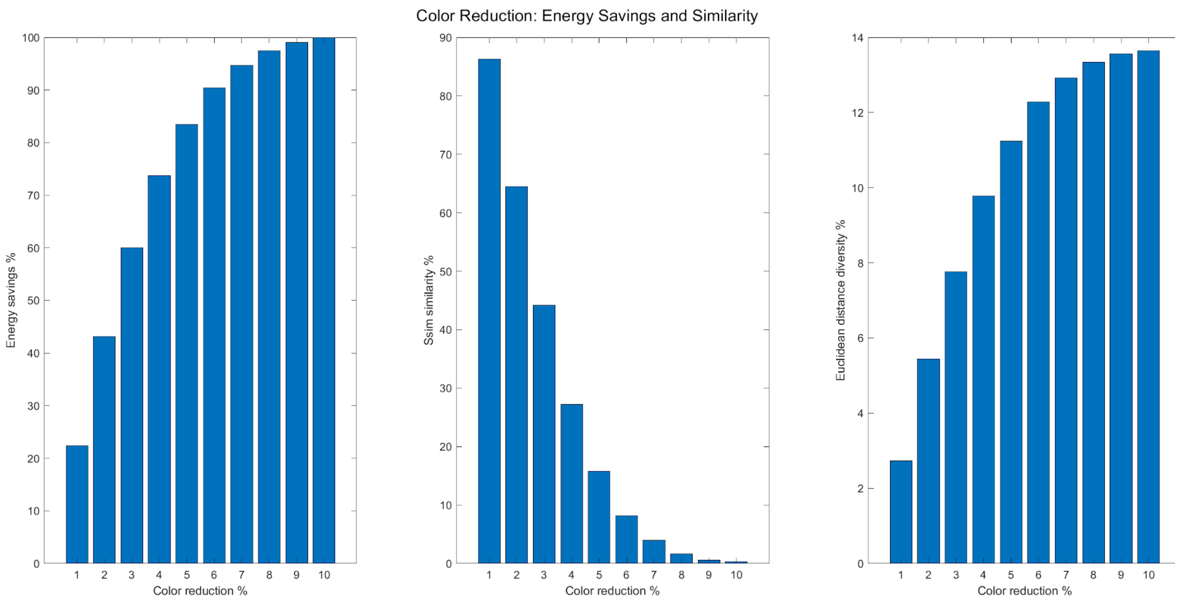


Figure 2 - Average color reduction statistics

In the following, color reduction results are provided and discussed for a sub set of images that have shown significant results.

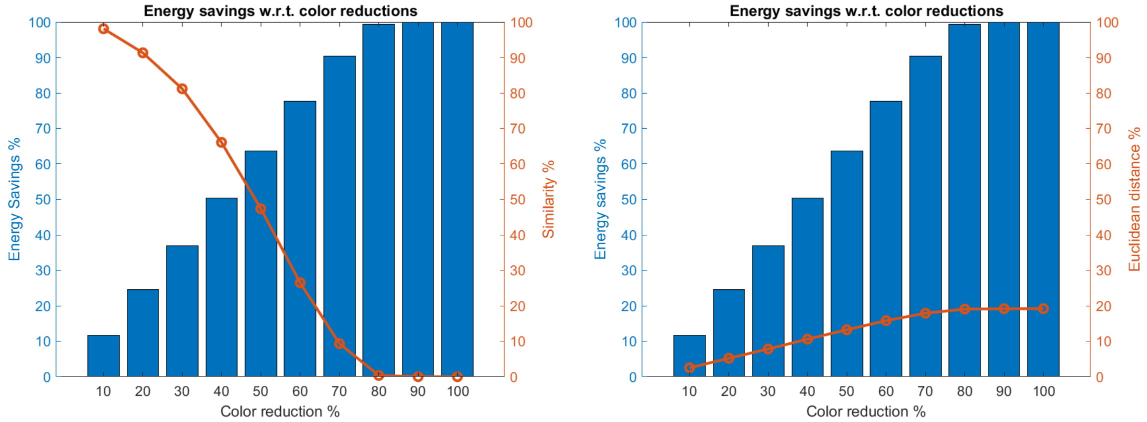


Figure 3 - Color reduction statistics for image (1)

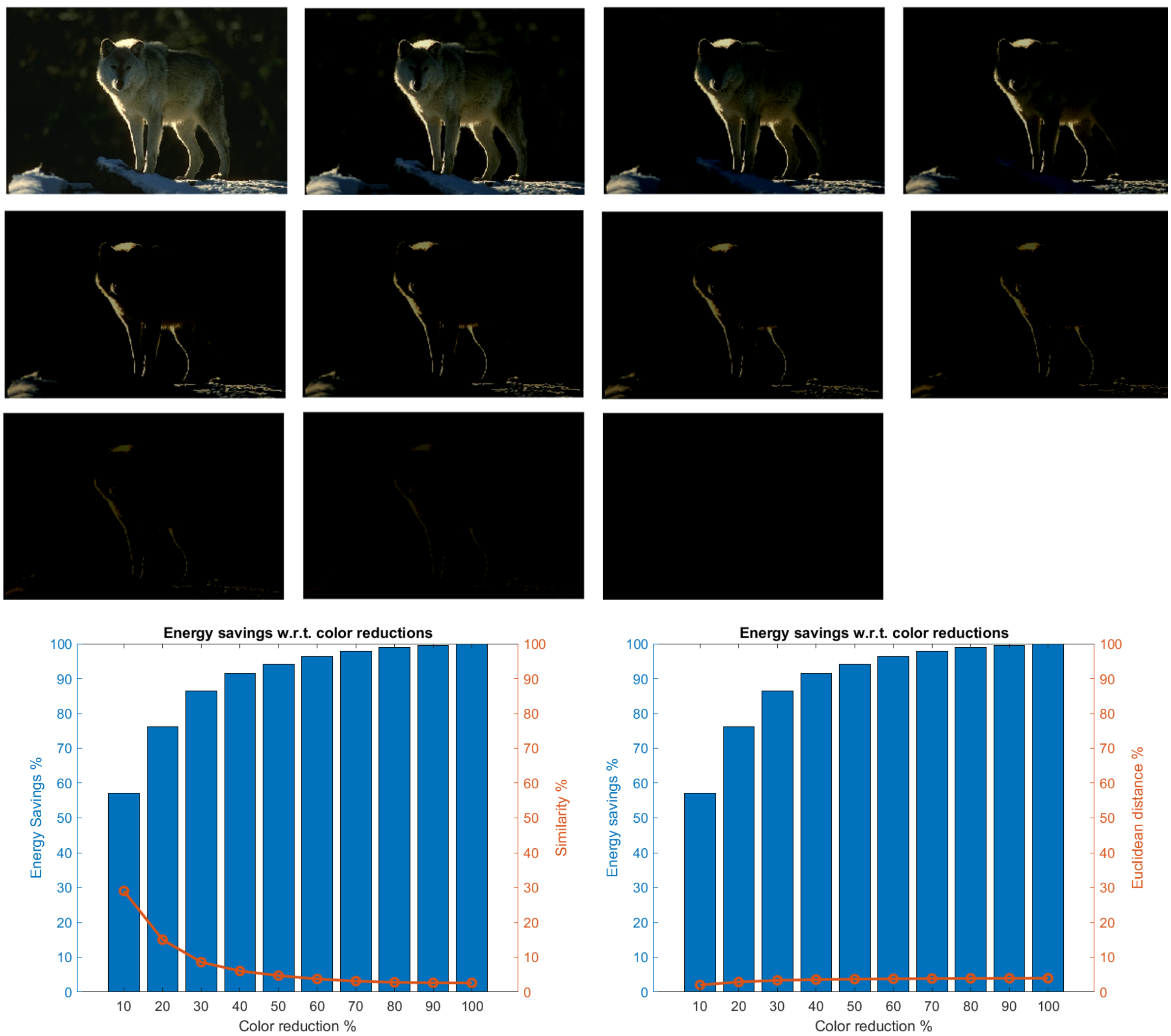


Figure 4 - Color reduction statistics for image (53)

Observations

The expectations regarding both power savings and distortion are confirmed by the average results of the entire set of images, shown in *figure 2*. As a detailed example, the color reduction, the power and distortion statistics regarding *image (1)* are shown in *figure 3*. As expected, being a pixel-oriented transformation technique, color reduction has a very high impact on the power consumption as the color reduction increases. However, as it is evident from *figure 3*, a color reduction set to 30% starts already to become too pervasive. For this reason, especially for very bright images, this kind of manipulation does not preserve the image characteristics in terms of both analytical and empirical point of views. Similar considerations can be made for all the brighter images. On the other hand, for already dark images some additional considerations can be made. As an example, *figure 4* shows color reduction applied to *image (53)*. The resulting image becomes darker and darker, but with less difference in terms of power savings, distorsions and human perception, especially between consecutive steps.

Personal image observations

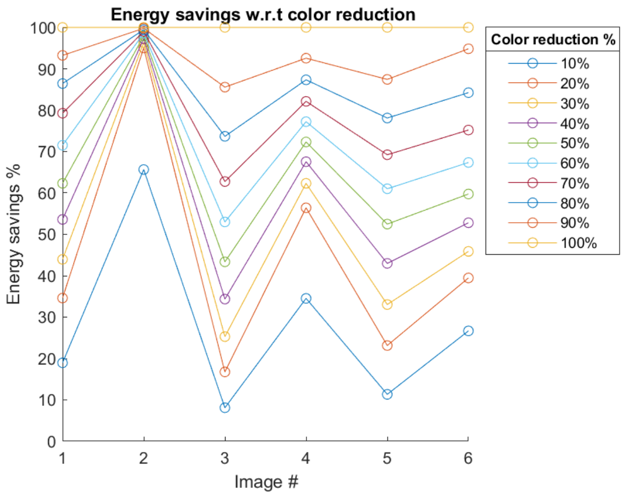


Figure 5 - Color reduction statistics for the additional images

Figure 5 shows the energy savings we have obtained after applying color reduction on the set of personal images. Again it is evident that power savings become higher as the color reduction increases. Interestingly, *image (3)* and *image (5),* the white editor screenshot and the white dominant web page, show the least power savings. The reason is probably related to their white dominant color spectrums. Obviously, all the images have a 100% energy savings when the color reduction, set to 100%, converts the images in their totally black versions.

History equalization

History equalization is not a pixel-oriented transformation technique. It mainly deals with modifications of the image brightness and contrast. For this reason, a conversion of the original image into its HSV version is required. After the equalization has been applied, the image is converted back to the RGB domain. *Figure 6* shows the power consumption and the distorsion evaluations for the entire set of images.

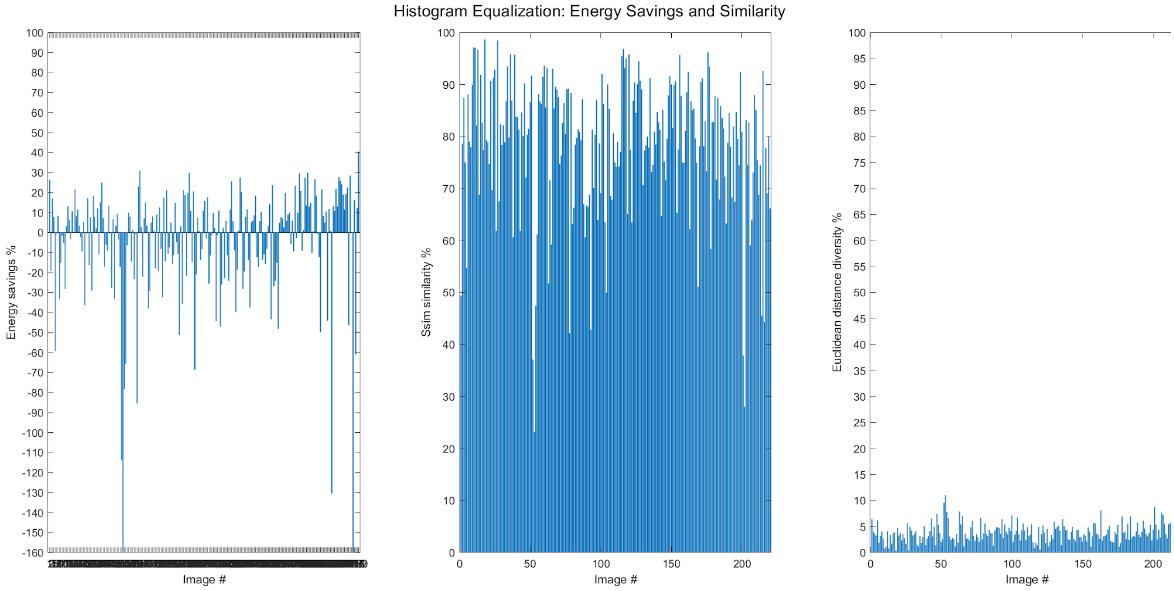
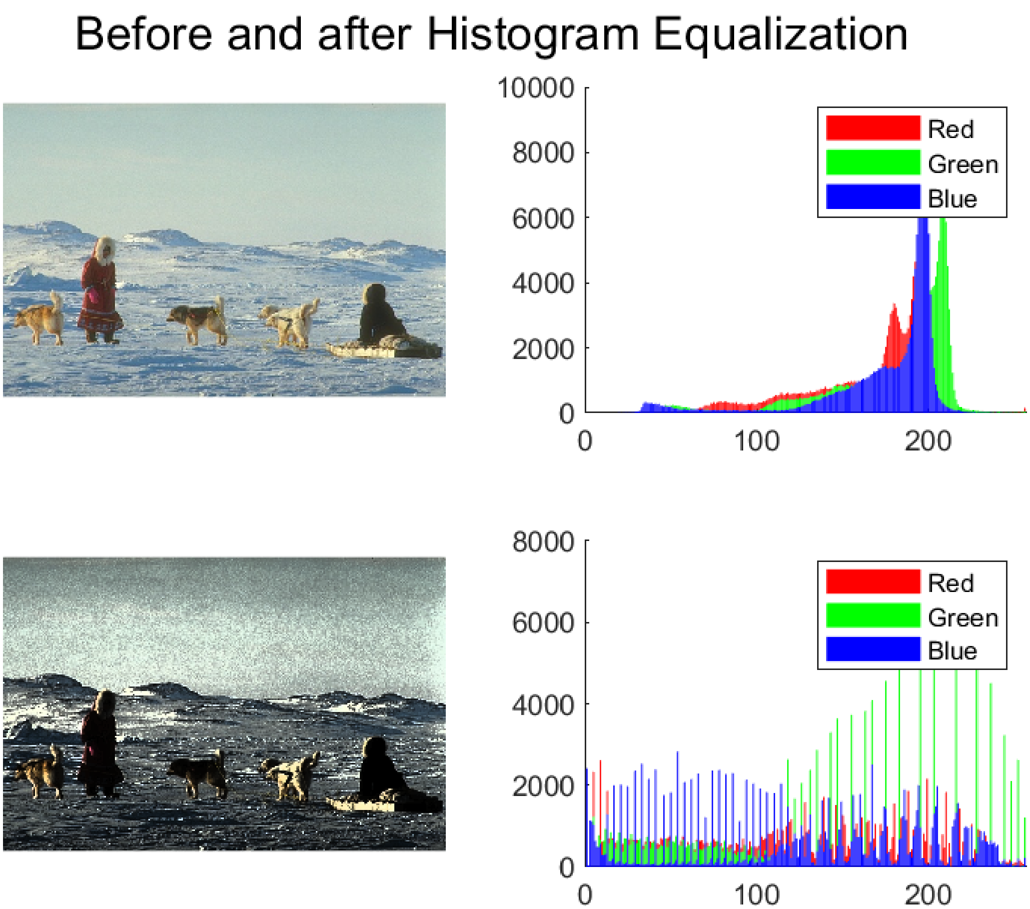


Figure 6 - History equalization statistics for all the images

In the following, history equalization results are provided and discussed for a sub set of images that have shown significant results.



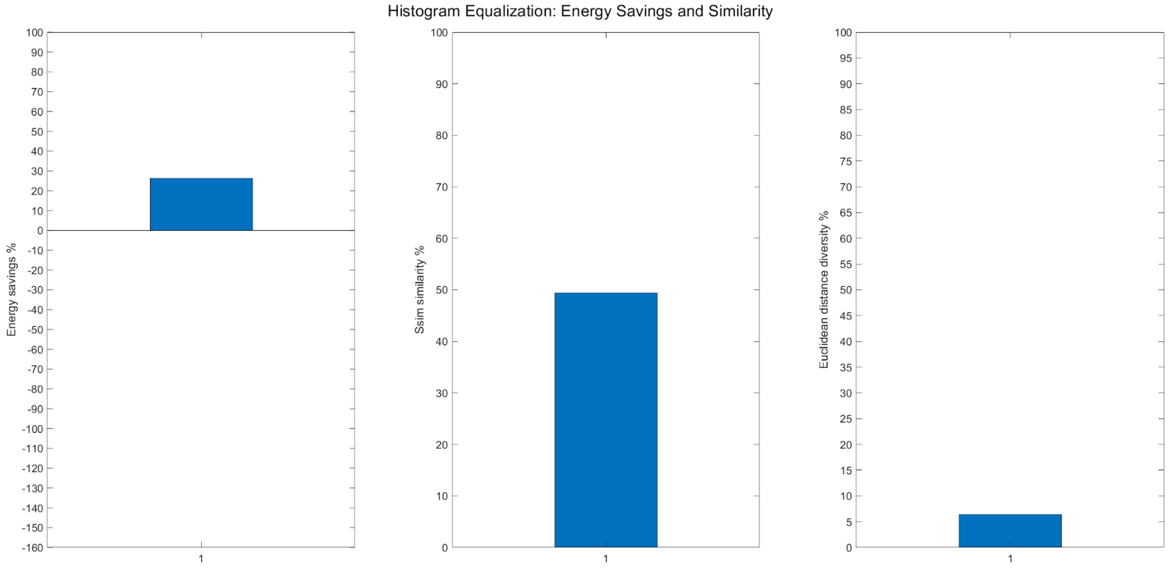
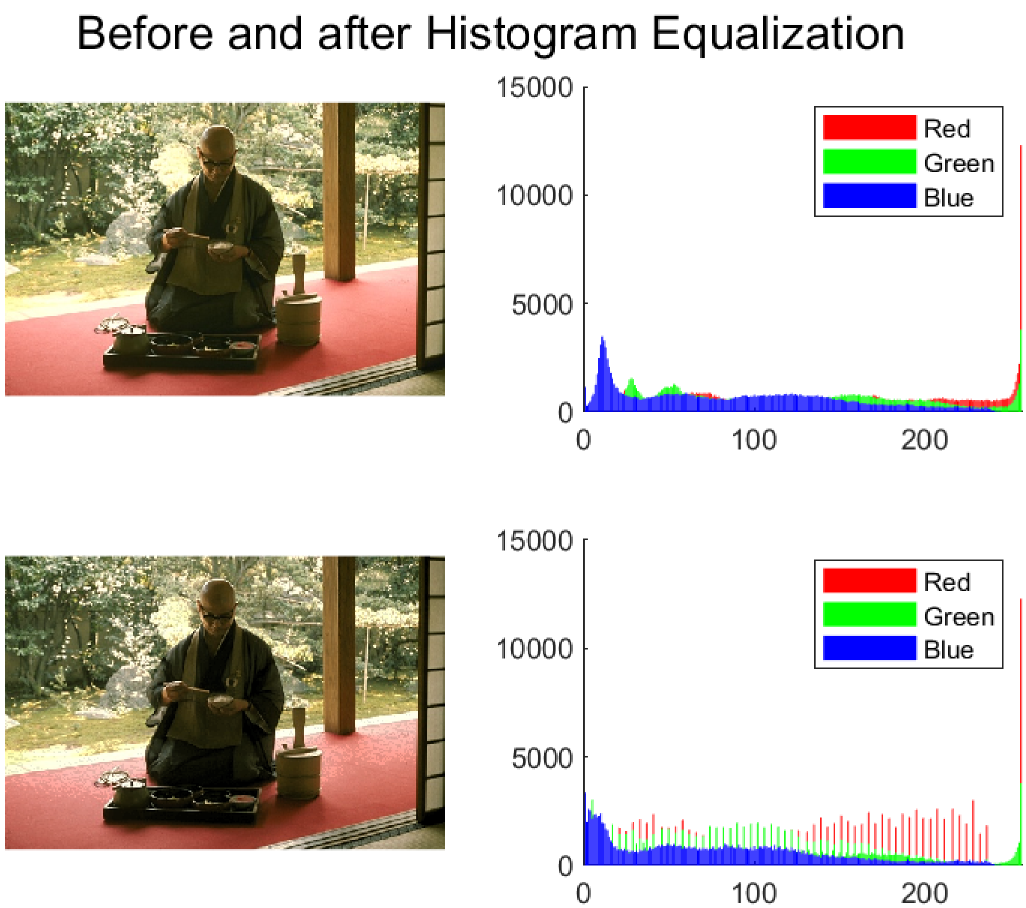


Figure 7 - History equalization statistics for image (1)



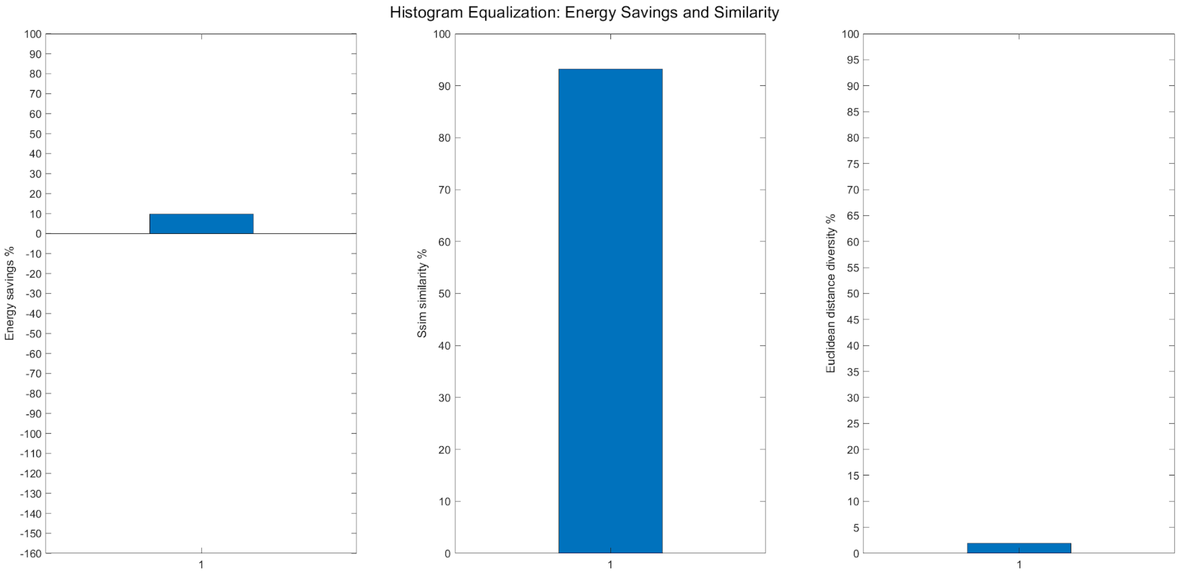
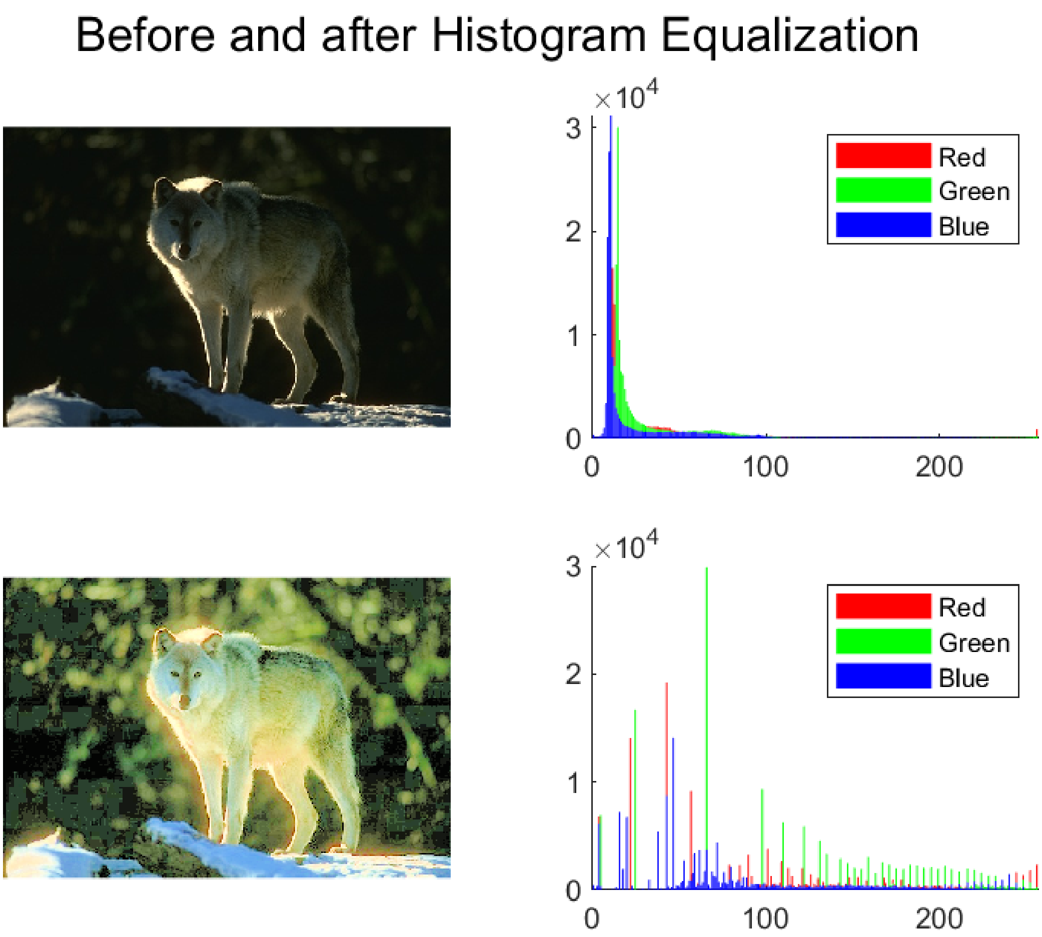


Figure 8 - History equalization statistics for image (117)



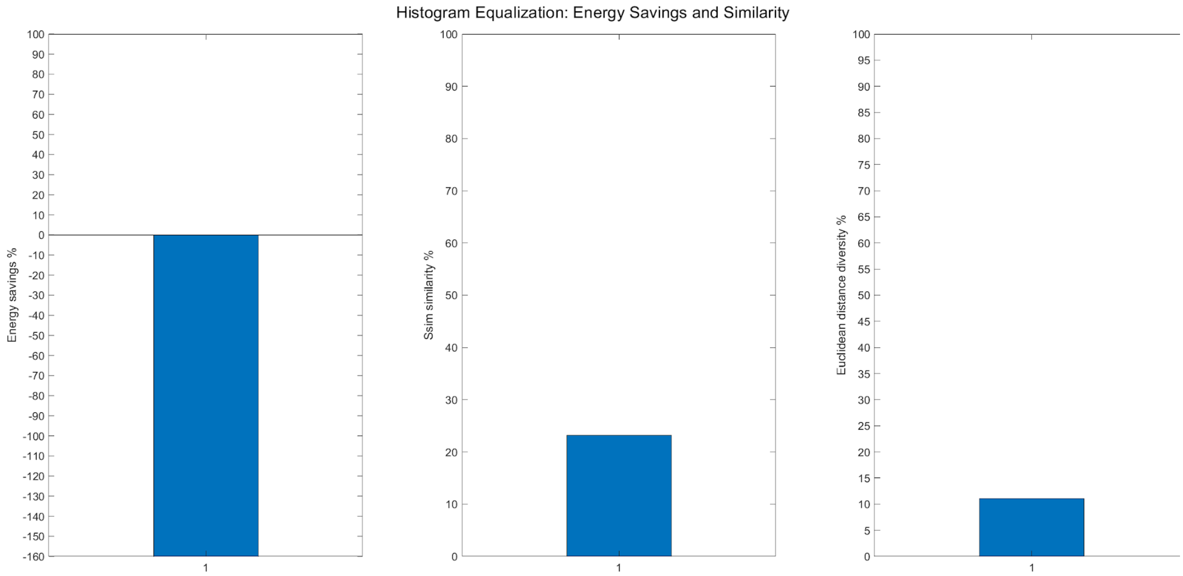


Figure 9 - History equalization statistics for image (53)

Observations

It is clear that histogram equalization may have positive or negative consequences based on the intrinsic characteristics of the image. For bright images, it generally reduces power consumption with negative results in measured distorsion. As an example, *figure 7* shows a very distorted *image (1)*. In other less bright images, like *image (117)*, the power consumption is reduced and the distorsion remains limited as *figure 8* shows. Different observations can be made for originally very dark images for which histogram equalization is particularly deleterious for both distortion and power consumption. As an example, *figure 9* shows how *image (53)* becomes particularly bright, resulting in a higher power consumption and distortion from both mathematical models and empirical sides.

Personal image observations

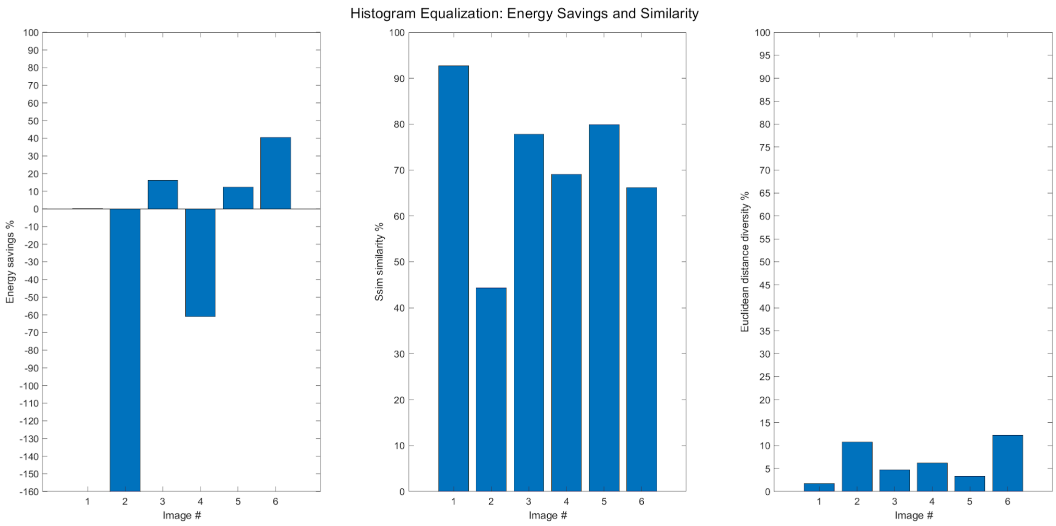


Figure 10 - Histogram equalization statistics for the additional images

Figure 10 shows the energy savings and the distorsions we obtain after applying histogram equalization on the set of personal images. As happened for the average results, histogram equalization shows very different results according to the color spectrum of the image. *Image (1)* has no benefit from the equalization. The white dominant images, *image (3)* and *image (5),* show similar results. In both cases, we have a limited amount of energy savings and a SSIM similarity around 80 %. For the black dominant images, *image (2)* and *image (4),* histogram equalization does not show any benefits. In fact, it increases the power consumption and lowers similarities, especially for *image (2).*

Luminance reduction

As color reduction, also luminance reduction is a pixel-oriented transformation technique. The manipulation is applied in the image HSV space with a sweep of 10% for each iteration up to a 100% reduction. *Figure 8* shows the average results regarding power consumption and distorsions for the entire set of images.

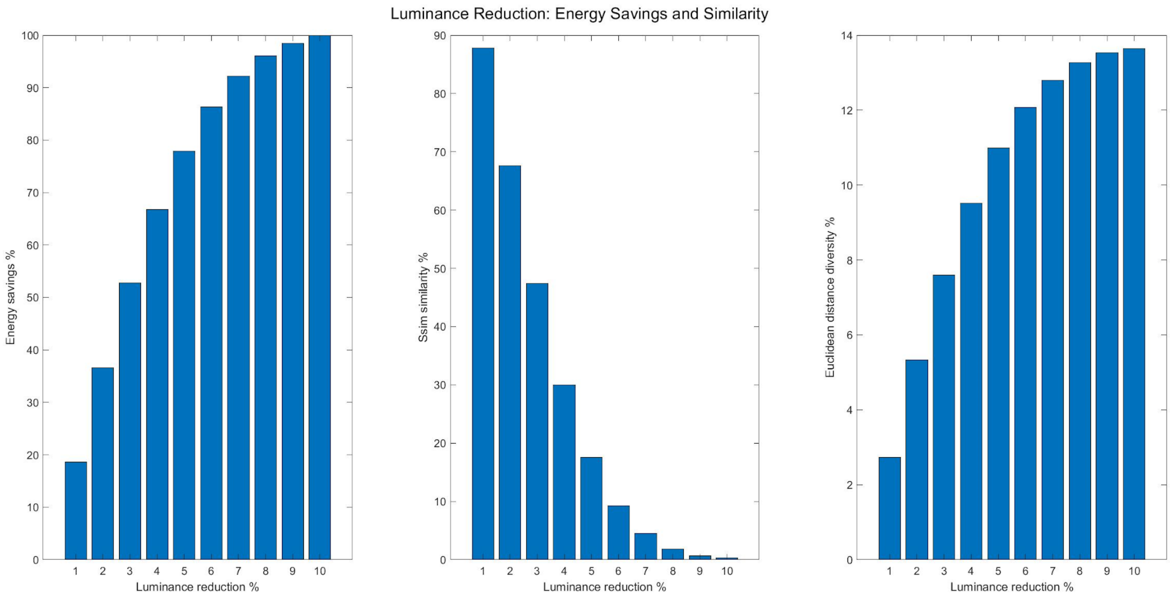


Figure 11 - Average luminance reduction statistics

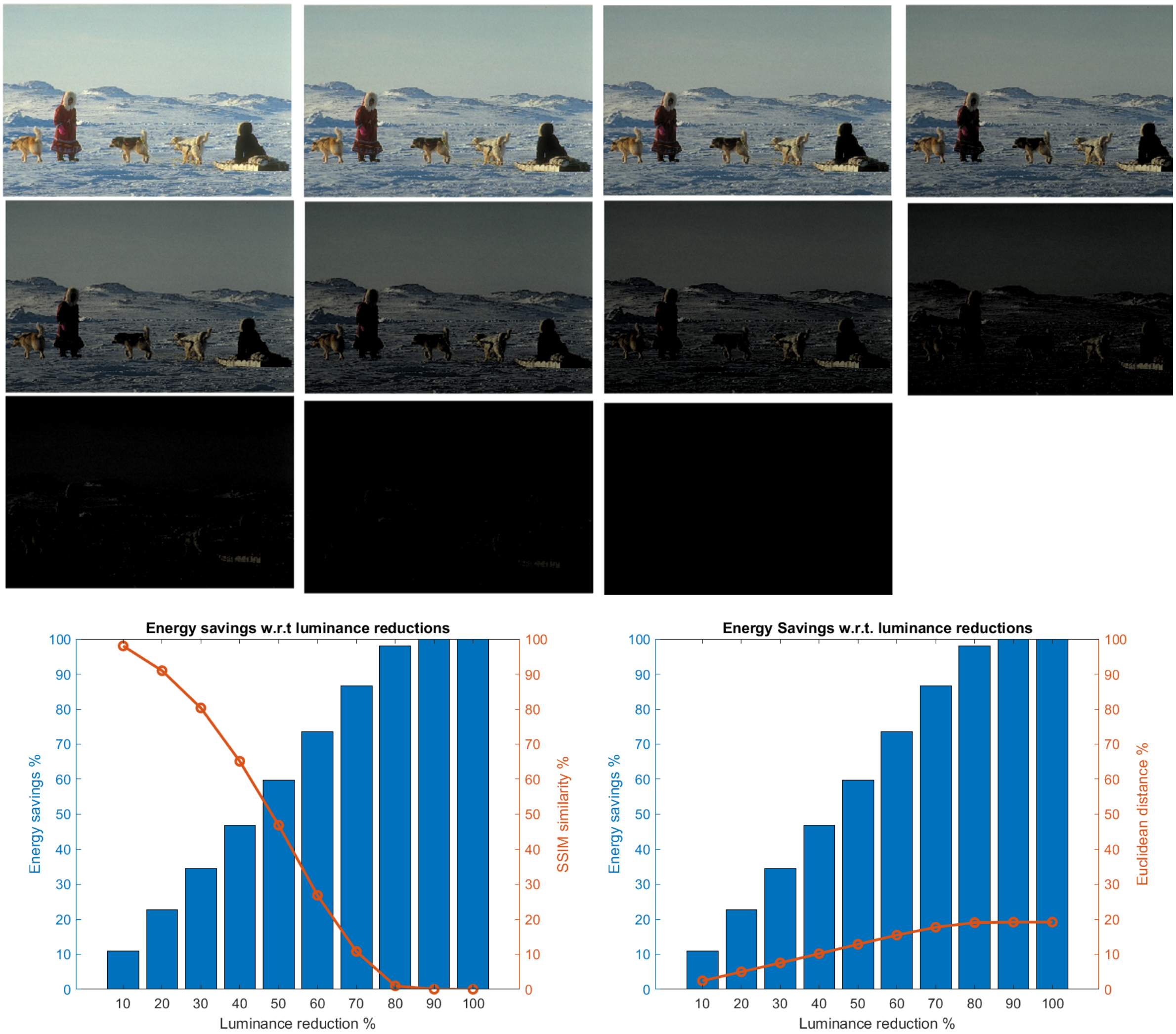


Figure 12 - Luminance reduction statistics for image (1)

Observations

From an empirical point of view, luminance reduction shows similar results with respect to color reduction. However, as experimental results show, there are some minor differences in both power consumption and distortion. In particolar, the power consumption and the MSSIM are slightly lower for color reduction. Nonetheless, that is not true for the entire set of images. As an example, in *figure 12*, luminance reduction is applied to *image (1)*. In this case, the power savings graph shows slightly different results with respect to the average ones. Specifically, the luminance reduction power saving is slightly smaller with respect to the color reduction one, even if the distorsions level are very similar. From a visual point of view, for high levels of color and luminance reduction, the image becomes totally dark. For this reason, both equalization should be wisely applied to preserve original color quality. On the other hand, for equivalent color and luminance reduction, the color detail quality appears to be worse in case of luminance equalization. In fact, the image starts to look in grayscale starting from a reduction of 40 %.

Personal image observations

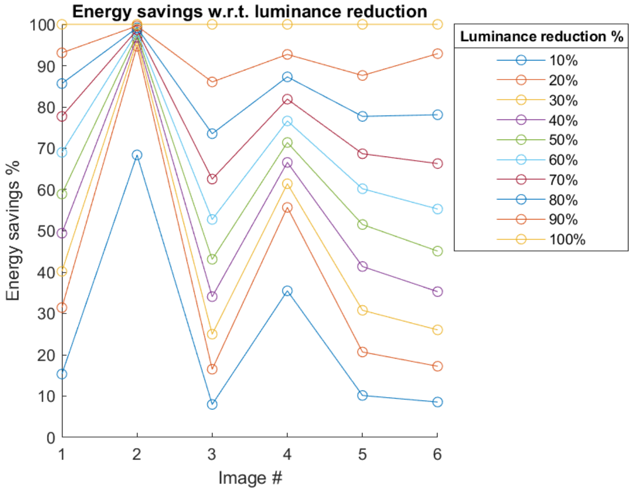


Figure 13 - Luminance reduction statistics for the additional images

Figure 13 shows the energy savings we have obtained after applying luminance reduction on the set of personal images. The results are very similar with respect to color reduction. However, as happened for the average energy statistics, we can notice a slight decrement in energy savings.

Dynamic Voltage Scaling

Power Consumption Estimation

The image power consumption is now computed by using a model that emphasizes a voltage scaling dependency. In particular, the model defines the power as the sum of the current flowing in each pixel multiplied by the voltage supply. The formulas for computing the current and the power are shown below.

$$Icell = \frac{p_1 V_{dd} D_{RGB}}{255} + \frac{p_2 D_{RGB}}{255} + p_3 \qquad P_{panel} = V_{dd} \sum_{i=1}^{W} \sum_{j=1}^{H} I_{cell(i,j)}$$

Experimental results

Voltage scaling is simulated on the entire set of images by using the provided *display_image()* MATLAB function. The function receives the desired voltage supply in the range [15-11.5] V with a 0.5 V for each sweep. The reason in such a limited range is to reduce, possibly sacrificing occasion for higher energy savings, the amount of distortion we would have for lower voltage supply. Two different equalization techniques, brightness compensation and contrast enhancement, are applied prior to DVS to compensate the distortion and to preserve, as much as possible, the original image characteristics. A further third version as a mix of the two manipulations is generated. Two versions of brightness and contrast compensation are developed. The first, referred as *version 1*, is based on the luminance loss caused by the applied voltage scaling and further corrections based on empirical point of view. The second, referred as *version 2*, is based on a factor *b* obtained as a function of the standard *Vdd* and its scaled version. For each version of the images, the correspondent power consumption and distortion are computed. Given the high number of images, for each type of equalization, the average results regarding power savings and distortion are shown to have a global view of the quality of the equalization. Moreover, only the results of a single image is shown in detail.

Dynamic Voltage Scaling without compensations

No compensation is applied prior to DVS. The reason is to evaluate the impact on power consumptions and similarities without compensating the distortion caused by DVS.

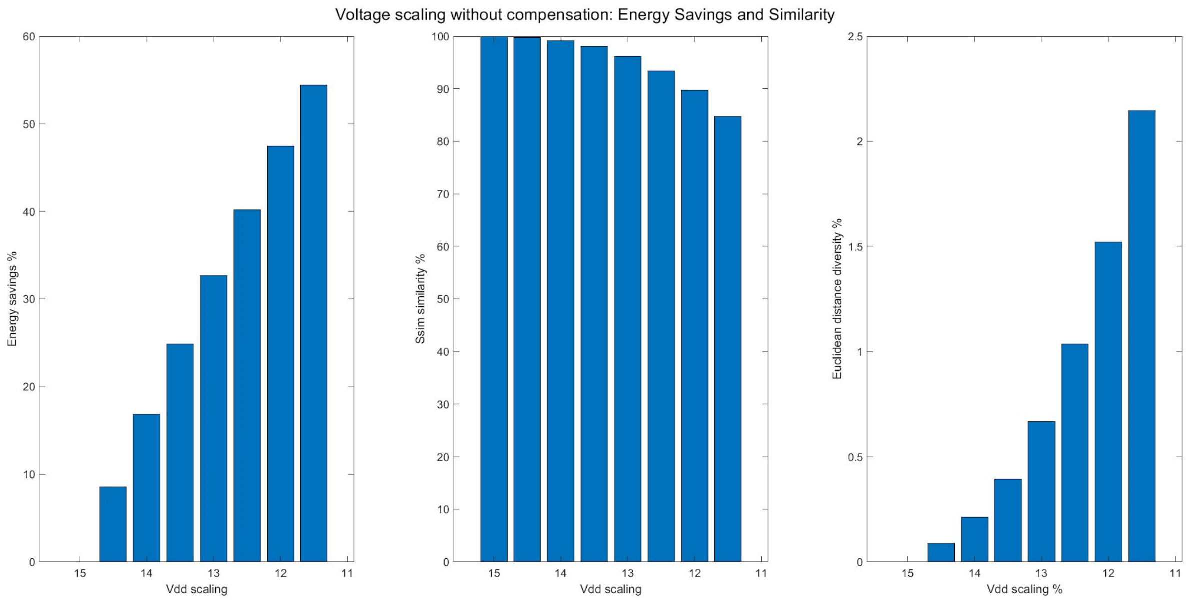


Figure 14 - Average voltage scaling without compensation statistics

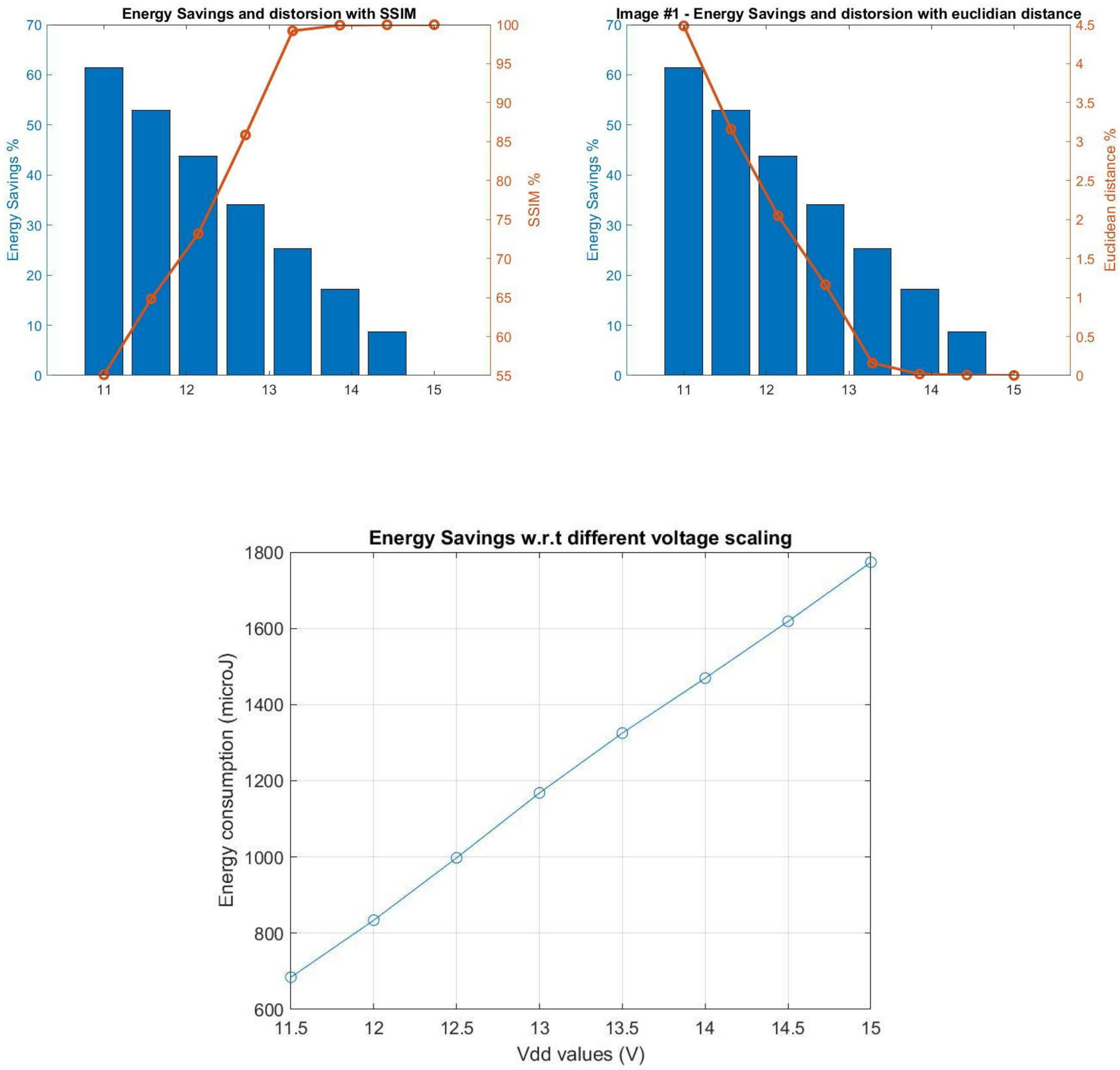


Figure 15 - Voltage scaling without compensation for image (1)

Observations

In *figure 14*, the average results after applying DVS without compensation is shown. There is a clear dependency between the increment in power savings as voltage scaling decreases. Even if the visual quality of the image is very compromised for some images, the distortion is limited overall. As an example, in *figure 15*, the detailed results for *image (1)* are shown. The image remains very similar to the original one for supply voltage in the range [14.5 - 13.5] V. For lower values, both mathematicals models and visual perception show a quite different image. In particular, in case of a *Vdd* set to 11.5 V, the details about the mountains and the background are completely lost.

Dynamic Voltage Scaling with brightness compensation

The compensation is applied in two versions: in the first solution (referred as *version 1*) as an increment in brightness obtained by summing the luminance loss caused by DVS to the V space of the HSV original image domain. In the second solution (referred as *version 2*) the new pixel values are obtained as $x' = min(1, x + b)$.

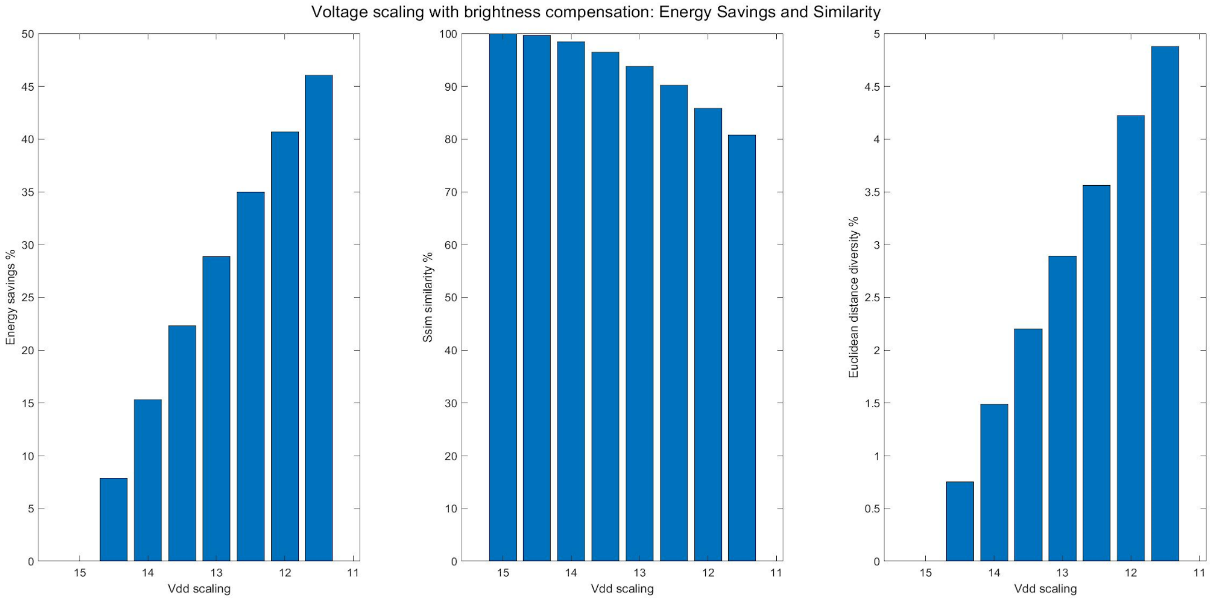


Figure 16 - Average voltage scaling with version 1 brightness compensation statistics

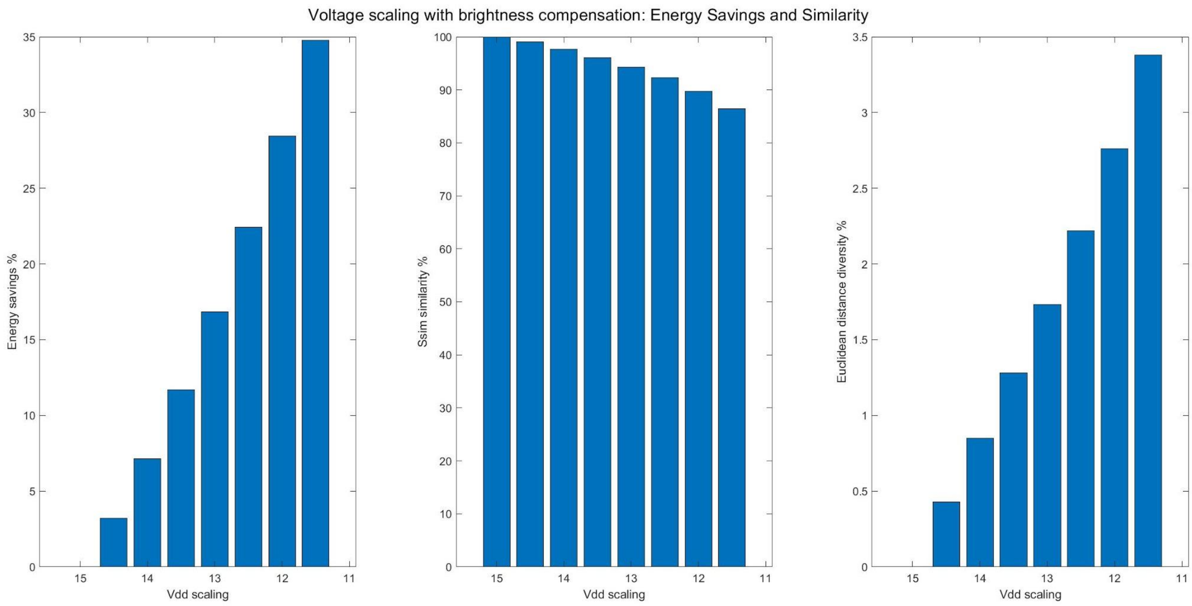


Figure 17 - Average voltage scaling with version 2 brightness compensation statistics

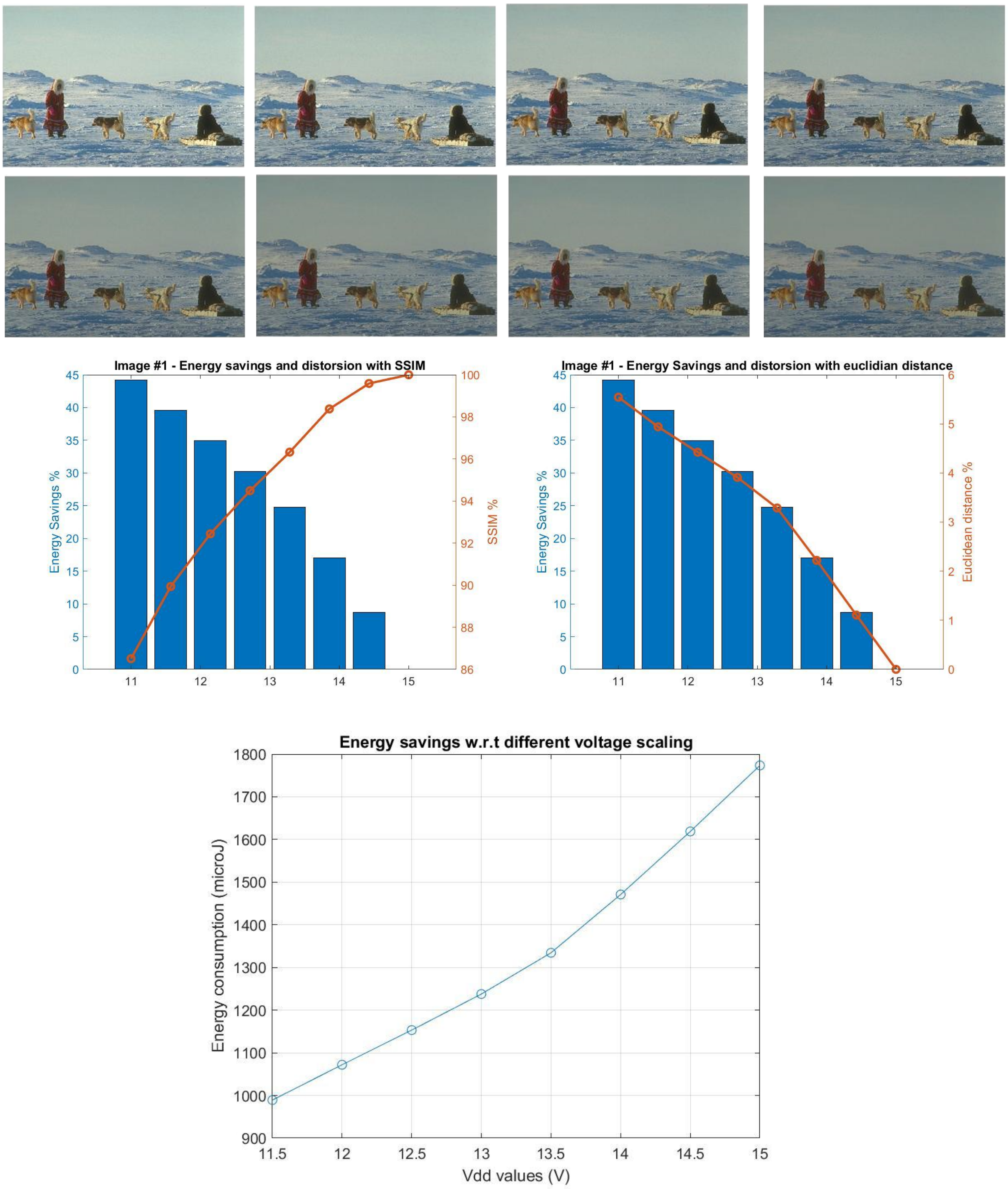


Figure 18 - Voltage scaling with version 1 brightness compensation for image (1)

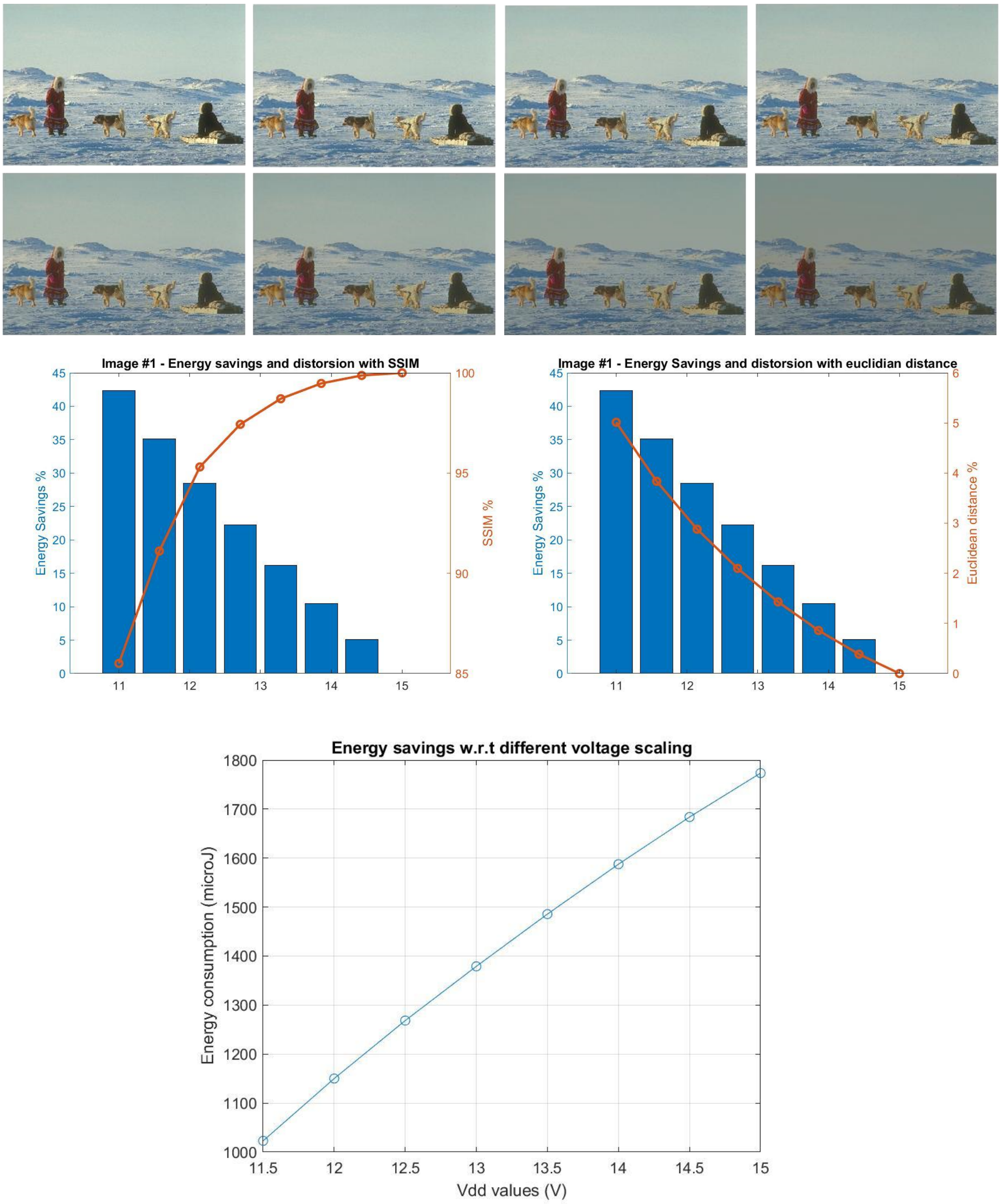


Figure 19 - Voltage scaling with version 2 brightness compensation for image (1)

Observations - version 1

Figure 16 provides the average results after applying DVS with brightness compensation for *version 1*. As expected, since the equalization is applied as an increment in the HSV space, the additional brightness produces a higher power consumption. There are unexpected results regarding average distortion. On average, the brightness equalization does not seem to limit the distortion for higher DVS with respect to the distortion without any compensations. One reason could be the fact that the majority of images does not benefit from a brightness compensation. However, the average behaviour is not shared by all the images. An example to show the goodness of the brightness compensation in limiting the distortion, is provided in *figure 18*. The figure shows the equalization applied to *image (1)*. In this case, besides the decrease in power savings, the measured distorsion is globally improved with respect to the solution without compensation. Specifically, the increase in distorsion changes less rapidly as the *Vdd* is reduced. From a visual point of view, the image has a better level of overall details, the shapes do not vanish in the background and the colors are more vivid, even for low voltage values.

Observations - version 2

Figure 17 provides the average results after applying DVS with brightness compensation for *version 2*. The results between the two versions are very similar. However, we obtain a less amount of energy savings as the voltage supply is scaled but with higher similarity. As a detailed example, *figure 19* shows the statistics for *image (1).* The graphical results for *version 2* are very similar to those obtained for *version 1.* Despite that, there are some differences regarding power savings and distorsions. In version 2, the energy savings are slightly lower, but the measured distortion is smoother and globally lower than the one for *version 1.*

Dynamic Voltage Scaling with contrast enhancement

The compensation is applied in two versions: in the first solution (referred as *version 1*) is obtained by increasing the V space of the HSV original image domain by an experimental factor. After multiple attempts on the entire set of images, the factor has been decided to be 1.75 - luminance loss. On average, this value shows good visual results for the majority of images. In the second solution, (referred as *version 2*) the new pixel values are obtained as $x' = min(1, x/b)$.

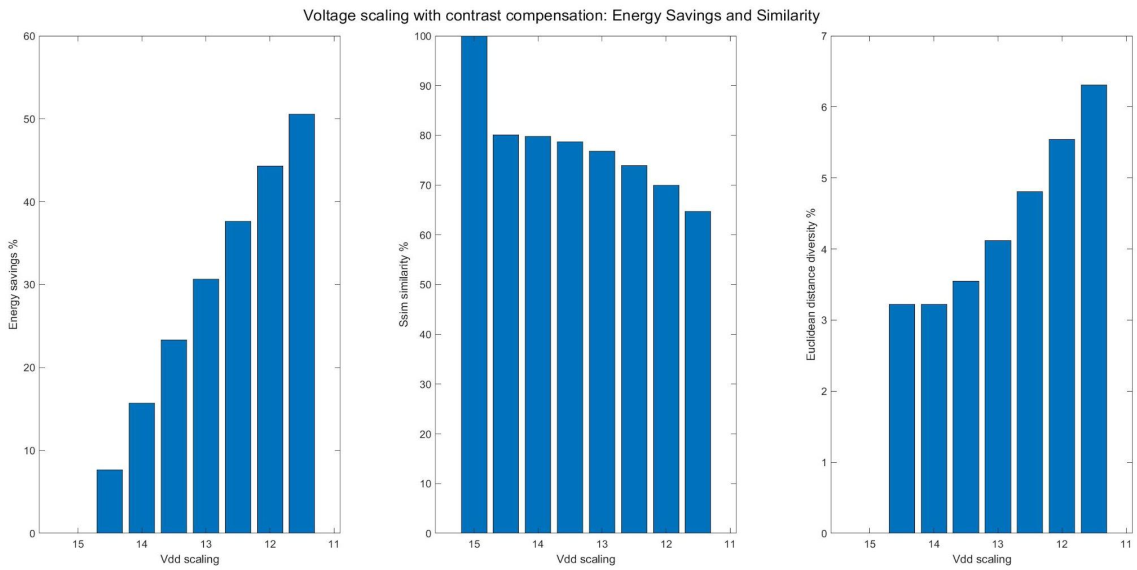


Figure 18 - Average voltage scaling with version 1 contrast enhancement statistics

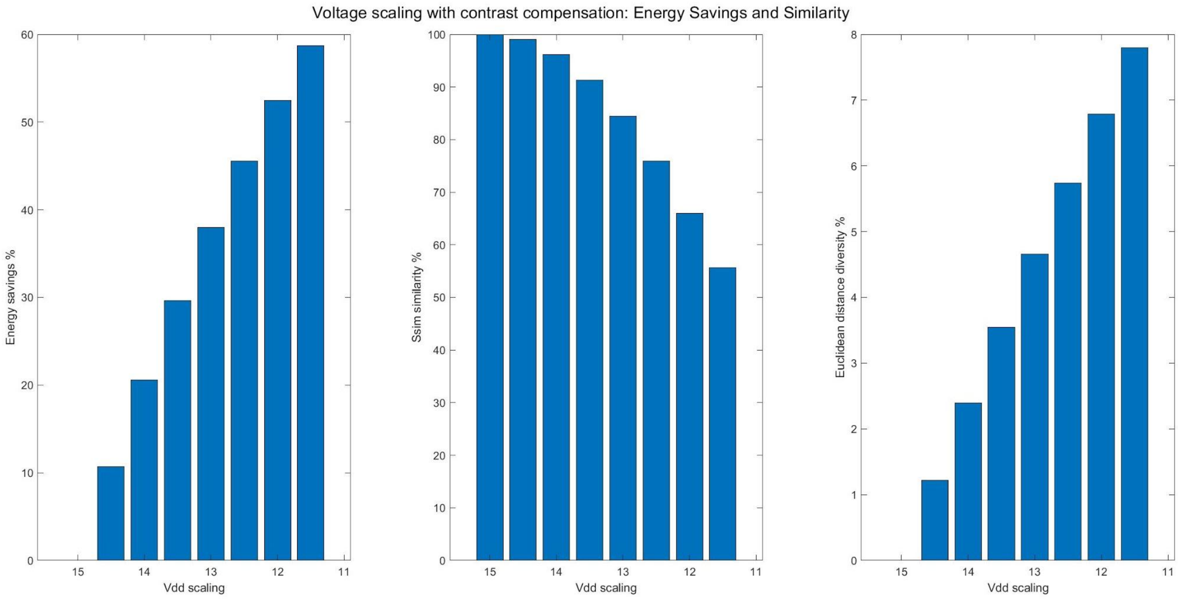
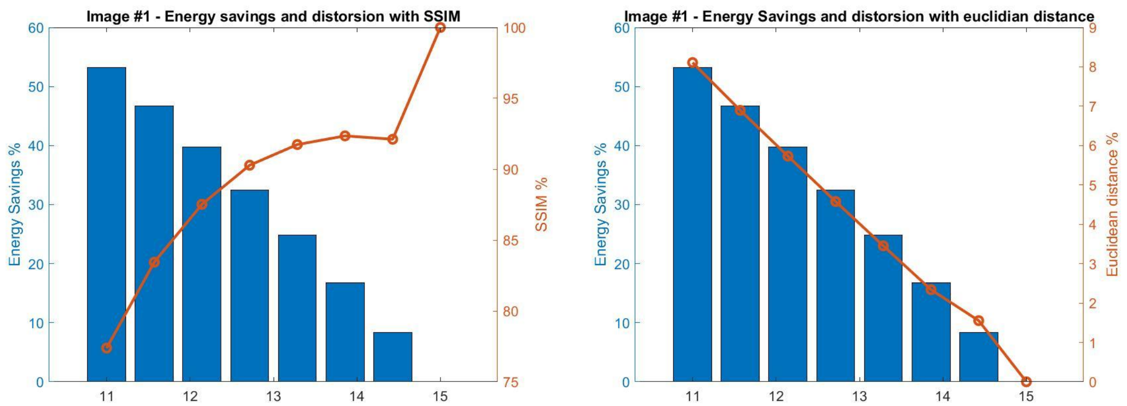


Figure 19 - Average voltage scaling with version 2 contrast enhancement statistics



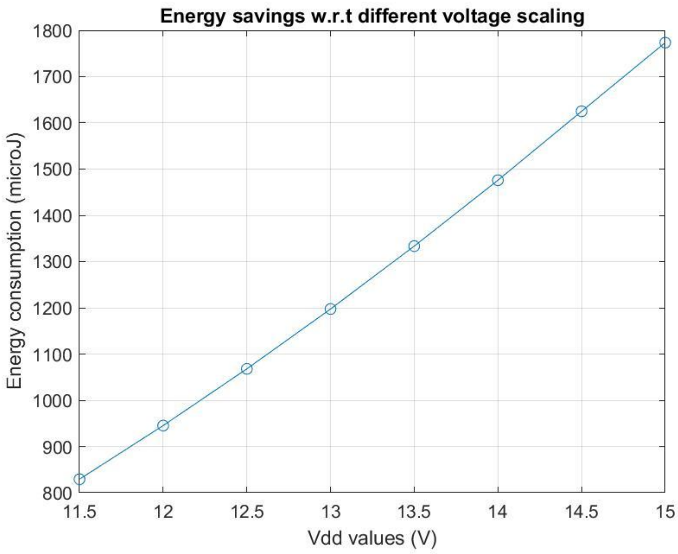
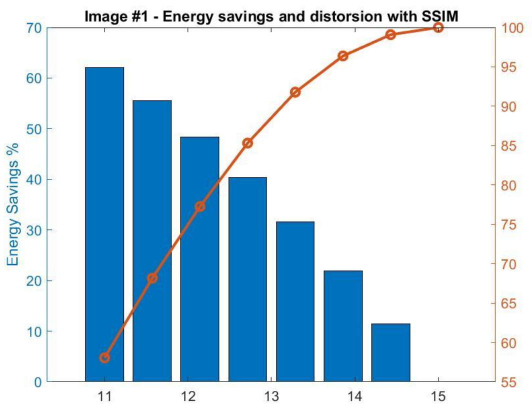
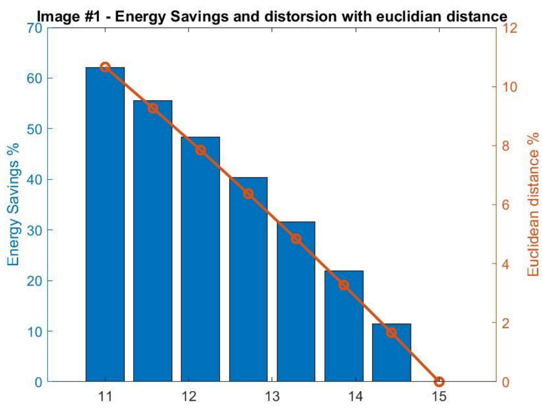


Figure 20 - Voltage scaling with version 1 contrast enhancement for image (1)





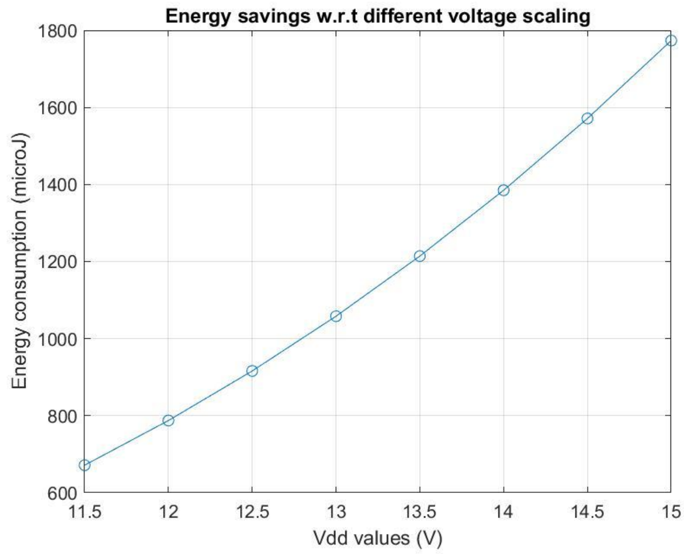


Figure 21 - Voltage scaling with version 2 contrast enhancement for image (1)

Observations - version 1

In *figure 18*, the average results of DVS with *version 1* contrast compensation is provided. The contrast modification has a lower impact on power consumption with respect to brightness equalization. However, a higher amount of distortion, as the *Vdd* decreases, is noticed. As a detailed example, *figure 20* shows the results for *image (1)*. In this case, the power savings values are found in between the ones for the DVS without compensation and the DVS with brightness compensation. As regards the MSSIM, as happens to the average results, a larger gap between the first two *Vdd* values is evident in *figure 20*. This behaviour does not have a direct confirmation from a visual point of view. The reason could be found in the fact that the applied technique seems to progressively transform the image in its greyscale version, sacrificing the colour vividness of the original image.

Observations - version 2

Figure 19 provides the average results after applying DVS with *version 2* contrast compensation. The results are better in the *version 2*. In fact, we can notice an overall higher energy savings and a better distributed distorsion. Moreover, the second version solves the *version 1* gap we obtained passing from the standard image to its first scaled version. As we can see, from *figure 21,* better results are shared by *image (1)* as well. Specifically, the image color vividness is preserved and the distortion is better distributed, even for higher voltage scaling.

Dynamic Voltage Scaling with brightness and contrast compensations

The compensation is applied in two versions: in the first solution (referred as *version 1*) is obtained as an increment in both contrast and brightness obtained by sequentially applying the two techniques to the V space of the HSV domain image. In addition, since multiple experiments show better visual results with a higher brightness, the brightness is further increased by a factor equal to 1.5. In the second solution (referred as *version 2*) the new pixel values are obtained using the formula below.

$$x' = \begin{cases} 0 & \text{when } 0 \le x \le g_l \\ \frac{1}{g_u - g_l}x + \frac{-g_l}{g_u - g_l} & \text{when } g_l \le x \le g_u \\ 1 & \text{when } g_u \le x \le 1 \end{cases}$$

$$g_u = \frac{(new\_Vdd)}{Vdd}$$

$$g_l = \frac{(Vdd - new\_Vdd)}{Vdd}$$

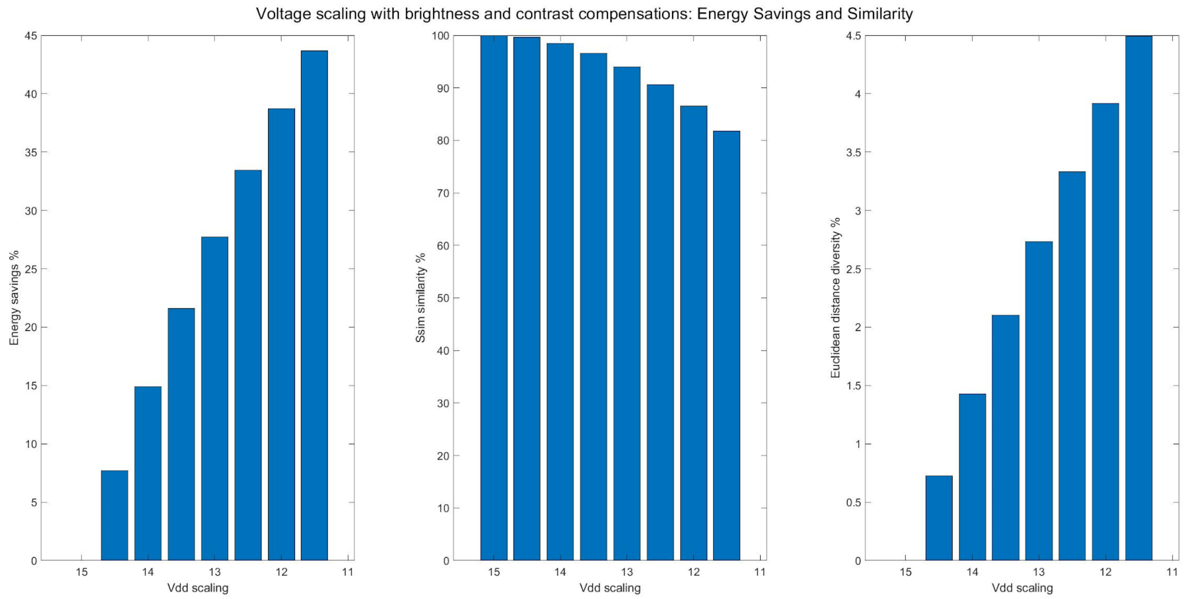


Figure 21 - Average voltage scaling with version 1 brightness and contrast compensations statistics

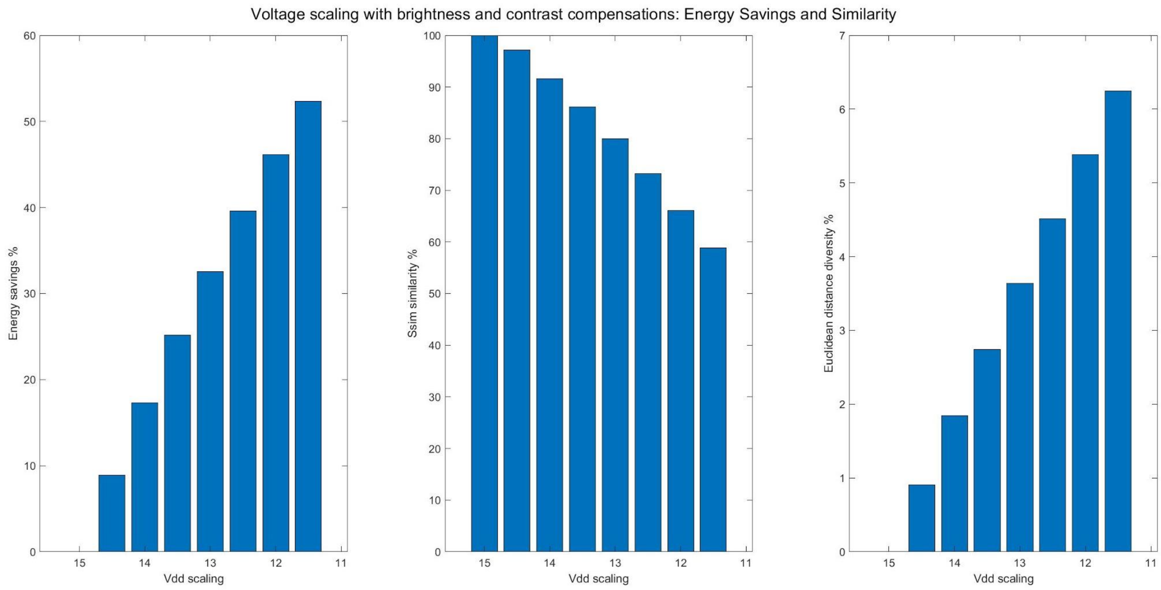


Figure 22 - Average voltage scaling with version 2 brightness and contrast compensations statistics

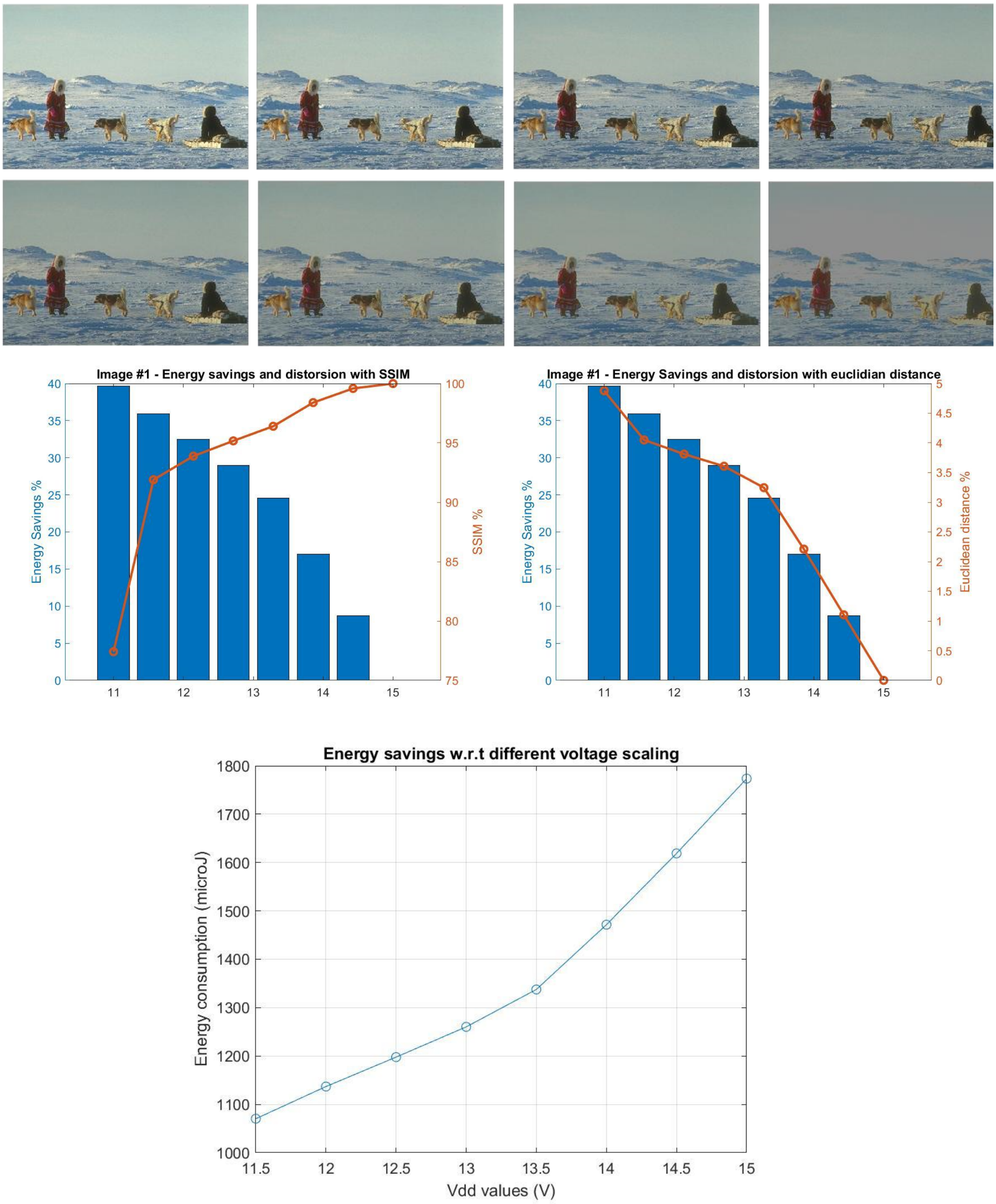


Figure 23 - Voltage scaling with version 1 brightness and contrast compensations for image (1)

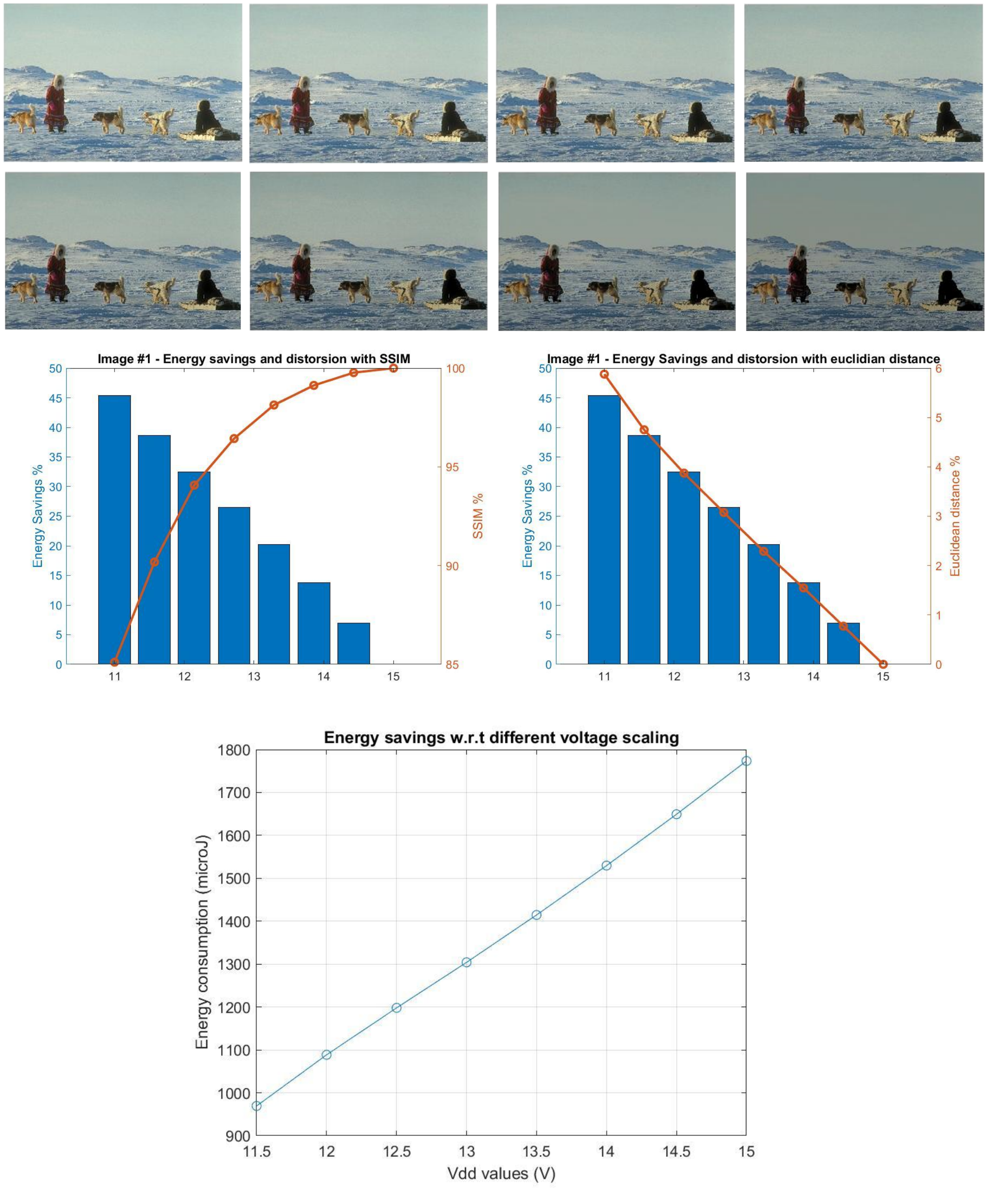


Figure 24 - Voltage scaling with version 2 brightness and contrast compensations for image (1)

Observations - version 1

In *figure 21*, the average results of DVS with *version 1* brightness and contrast compensation is provided. As expected, because of the use of multiple image equalization, we have lower power savings with respect to all the other cases. As regards average distortion, we notice the optimal solution with respect to the previous equalization techniques. Even for the lower *Vdd* value, the average MSSIM remains greater than 80%. Similar results are found in *figure 23* that shows in detail the results for *image (1)*. From a visual point of view, the use of multiple equalizations combine the positive aspects of the two techniques, limiting the negative ones. The image is not shaped and does not have a greyscale looking anymore as was happening for the brighter and the contrast enhanced version respectively. In fact, even for high DVS, a good amount of details in the background, as well as the shape, are preserved. However, the compensation starts to show its limit for the highest *Vdd* value. Visual distortion becomes more evident, especially for the background, whose colours appear to have a light gray-pink look.

Observations - version 2

In *figure 22*, the average results of DVS with *version 2* brightness and contrast compensation is provided. The comparison shows that the *version 2* is worse in both energy savings and average distorsions. As a detailed example, *figure 24* shows the equalization applied to *image (1).* From a graphical point of view, *version 2* seems to lose in color details especially for the human figures. Their colors gradually turn to black as voltage is scaled. On the other hand, *version 1* maintains the color details of the figures, but the image appears to be faded. Regarding the measured distorision, in *version 2* the loss in similarities are better distributed along voltage scaling.

Conclusions

In the first part of the experience, some techniques based on image manipulations for reducing power consumption have been tested. It is clear that each equalization, according to the intrinsic characteristics of the original image will differently affect the quality of the results. Color and luminance reduction show similar results regarding power savings and distorsions. Despite that, high levels of such equalizations cause the image to lose its color details, turning it into a totally black image. Histogram equalization shows good results on a limited number of images. For this reason, the choice of the equalizations should be always carefully made considering the trade off between the amount of distortions, the power savings and the visual look of the final result. In the second part, after applying DVS, the use of image manipulations become essential to limit the amount of distortion caused by the scaling itself. Two equalization techniques have been considered. Nonetheless, both of them, as well as their combination, show limited results in replenishing the original image quality whenever the scaling is particularly high. A solution could be using more complex compensation techniques that, depending on the color spectrum of the image, apply an optimal compensation. To conclude, an important factor never considered in energy saving discussions, but that should be definitely taken into account, is the additional computation power request to apply the pre-compensations. The power request becomes more and more relevant as the equalization technique complexity grows.