EMIoT Lab 2 Report:
Energy Efficient Displays

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Contents

1 Introduction

1.1 background

OLED is a self-luminous display technology. Its core feature is that each pixel generates light independently. This structure makes the power consumption of OLED show significant content dependence. The size of its power consumption directly depends on the color and brightness of the pixel display.

LCD is a non-self-luminous technology, which relies on the backlight module to provide a global light source, and the liquid crystal layer only acts as an optical valve to control the transmittance of light. Its power consumption is mainly dominated by the backlight module. Whether the screen displays an all-white image or an all-black image, as long as the backlight brightness setting remains unchanged, the overall power consumption is basically the same. The impact of pixel color changes on total power consumption is negligible, and significant energy saving cannot be achieved by adjusting the color distribution of image content like OLED.

1.2 objective

Through image processing technology, reduce the energy consumption of OLED display under the premise of ensuring a certain visual quality.

2 Methodology

2.1 power consumption model

To estimate the power saving potential, we utilize mathematical models that approximate the power consumed by the OLED panel based on pixel values.

Standard RGB Model (Part 1)

In the first phase, a fixed power model is employed where power consumption is strictly dependent on the R, G, and B components of each pixel. The power contribution of a single pixel is calculated using experimentally determined weights (w_R, w_G, w_B) and a gamma coefficient (γ), as shown in Equation 1:

$$P_{pixel} = w_R \cdot R^\gamma + w_G \cdot G^\gamma + w_B \cdot B^\gamma \tag{1}$$

The total power of the image is the summation of all individual pixel contributions plus a static power constant (w_0).

$$P_{\text{image}} = w_0 + \sum P_{\text{pixel}} \tag{2}$$

Voltage-Dependent Model (Part 2)

In the second phase, the supply voltage (V_{dd}) is introduced as a dynamic variable. The total panel power is derived by determining the current flowing through each cell (I_{cell}), which is a function of both the pixel value and the applied voltage:

$$P_{panel} = V_{dd} \times \sum_{i=1}^{W} \sum_{j=1}^{H} \sum_{c \in \{R,G,B\}} I_{cell}(i,j) \tag{3}$$

This model facilitates the simulation of **Dynamic Voltage Scaling (DVS)**, where reducing V_{dd} lowers the overall power consumption but imposes a limit on the maximum achievable luminance.

3 Experimental setup

3.1 image dataset selection

- 50 Images are natural from the BSDS500 training set.
- 5 Images from computer screenshots.

3.2 Part 1

3.2.1 Test logic

Dataset strategy

- Natural Images: Rich colors, complex textures
- Screenshots: User interface, large areas of color, text and high-contrast edges

Objective: To verify whether the same power-saving strategy works consistently when viewing photos and browsing web pages/apps.

Algorithm Comparison Strategies

- Strategy 1: Hungry Blue
- Strategy 2: Brightness Scaling
- Strategy 3: Histogram Equalization basic version
- Strategy 4: Histogram Equalization improve version
- Strategy 5: Gamma correction

For each strategy, parameters are varied and scanned stepwise. For each parameter, average, minimum, and maximum values are calculated for 55 images. This allows observation of the algorithm's stability across different images. It also automatically identifies the most power-efficient and least power-efficient images under specific parameters.

3.2.2 Strategy 1: Hungry Blue

This strategy directly subtracts a **constant k** from blue channel.

First, we compare two classes. The first one is natural pictures from BSDS500 training set. The other one is the screenshots from our computer.

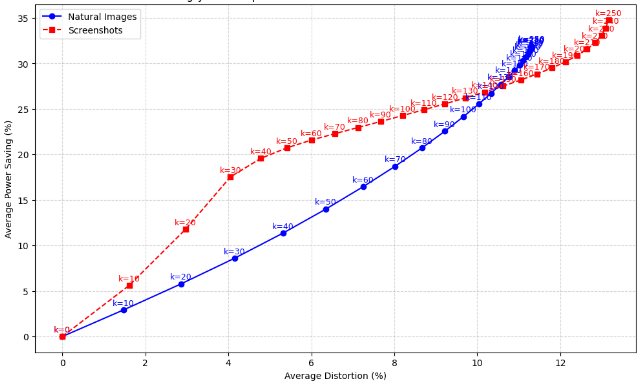


Figure 1: Hungry-blue: natural pictures and screenshots

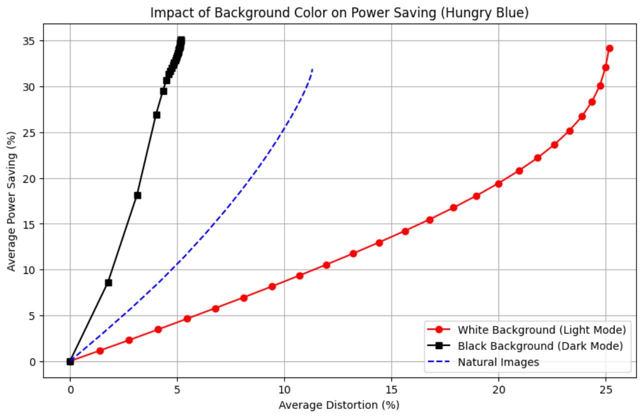


Figure 2: Hungry-blue: black and white screenshots

Analysis:

- Screenshots are usually more power-saving than natural images.
- Computer screenshots (such as Word documents and web pages) usually have a large white background. In RGB, white is (255, 255, 255), which contains the maximum blue value. When you apply Hungry Blue minus k, the power consumption of the white background drops drastically. The blue weight of natural images (such as forests and portraits) may already be low, so the effect of subtracting the same k is not so obvious.
- More than 90% of the Dark Mode screen is pure black pixels (RGB: 0,0,0) or almost all black. Because black does not contain blue (or the blue value is very low), the pixel value remains unchanged after algorithm processing. Only 10% of text/icons generate displacement. This 10% error is evenly distributed by the 90% zero error area, resulting in extremely low overall average distortion. Although the total power consumption of the black background is low, the power is all spent on the 10% bright elements. Cutting off the blue color in these elements is equivalent to cutting off the only main power consumption.

Second, the average/maximum/minimum statistics of the strategy.

Table 1: Summary Statistics for Hungry Blue Strategy

Parameter (k)	Avg Saving %	Min Saving %	Max Saving %	Avg Distortion	Min Distortion	Max Distortion
0	0.00	0.00	0.00	0.00	0.00	0.00
20	5.79	3.30	8.72	2.86	2.01	3.47
40	11.35	6.74	18.45	5.32	3.25	6.55
60	16.47	10.25	26.93	7.25	4.06	9.45
80	20.74	13.62	30.79	8.67	4.61	11.94
100	24.16	16.89	33.38	9.67	4.98	13.93
120	26.71	19.79	37.95	10.33	5.20	15.61
140	28.54	21.93	42.29	10.75	5.31	17.45
160	29.84	22.39	44.83	11.02	5.35	18.95
180	30.71	22.44	45.07	11.17	5.35	20.06
200	31.29	22.45	45.08	11.25	5.35	20.74
220	31.68	22.46	45.09	11.29	5.35	21.05
240	31.86	22.46	45.09	11.31	5.35	21.11

Analysis:

- As k increased from 0 to 240, the average power saving rate (Avg Saving) and the average distortion (Avg Distortion) both showed a monotonous upward trend. This means that the more the original color of the image is modified, the more energy will be saved, but the greater the cost of visual quality.

- **Saturation**: It is observed that after k=180, the growth of the power saving rate becomes very slow (from 30.71% to 31.86% at 240). This is because the value of the blue channel in most images has bottomed out (to 0) after subtracting 180. Continuing to increase the k value will no longer produce additional energy-saving effects on it.

Third, We chose the case of K=120 for analysis, and you can see the maximum and minimum distortion images and the maximum and minimum energy saving images below.

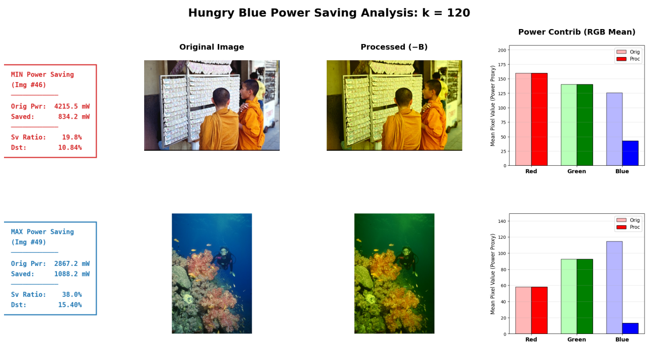


Figure 3: K=120 Min and Max power saving

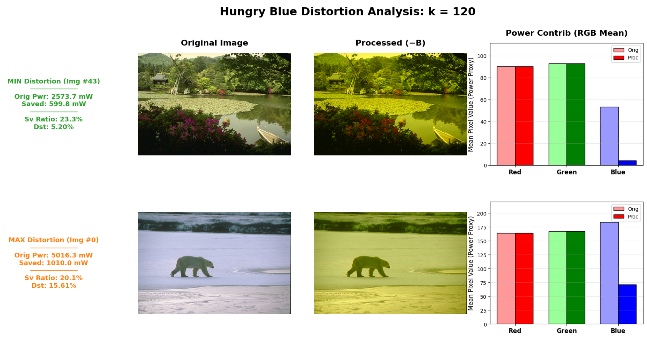


Figure 4: K=120 Min and Max distortion

Analysis:

- Derivative Analysis: Our model is $P_{pixel} = w_R \cdot R^\gamma + w_G \cdot G^\gamma + w_B \cdot B^\gamma$, and $\gamma = 0.7755 < 1$. From the perspective of calculus, the derivative (change rate) of power consumption to pixel value is $\frac{dP}{dB} = w_B \cdot \gamma \cdot B^{\gamma-1}$(for blue channel). Since $\gamma - 1$ is negative(-0.2245). This means that the smaller the blue pixel value B, the steeper the slope. In the low-brightness range, the power consumption change caused by the change in the unit pixel value is much greater than in the high-brightness range. Give priority to weaken dark and medium-brightness blue pixels, which can get higher savings while maintaining small distortion, which is the most cost-effective.

- For power saving: from Figure 3, we can see that the blue pixels in image 46 contribute less power than those in image 49, meaning their proportion is smaller. However, image 46 initially has a higher power, so the combined effect is that image 46 represents the minimum power saving, while image 49 represents the opposite. The figure shows that pixels with a higher proportion of blue pixels (contributing more power) save more power after applying the hungry blue strategy.

- For distortion: Figure 4 shows that image 0, with maximum distortion, completely distorts the image, turning the white background into a yellow one. However, image 43, with the smallest distortion, was originally yellowish; reducing the blue only deepened the yellow-green, so the distortion appears minimal to the human eye. Looking at the RGB distribution, blue contributes relatively little power to image 43. Considering blue is the most power-consuming color, we can infer that its proportion is quite small. For images with low blue proportions, the hungry blue strategy can achieve excellent results: low distortion while reducing the most power-consuming blue.

3.2.3 Strategy 2: Brightness Scaling

This strategy converts to HSV space and scaling the V(value) component by a factor c.
First, we implemented different c to see the result of saving and distortion in total group(natural images and screenshots).

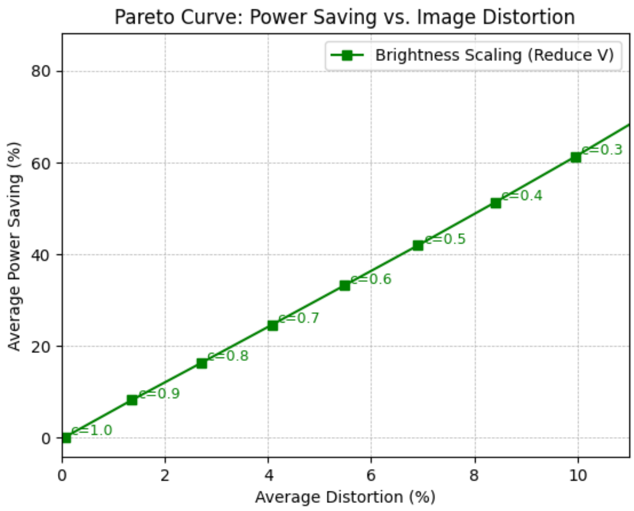


Figure 5: Brightness-Scaling

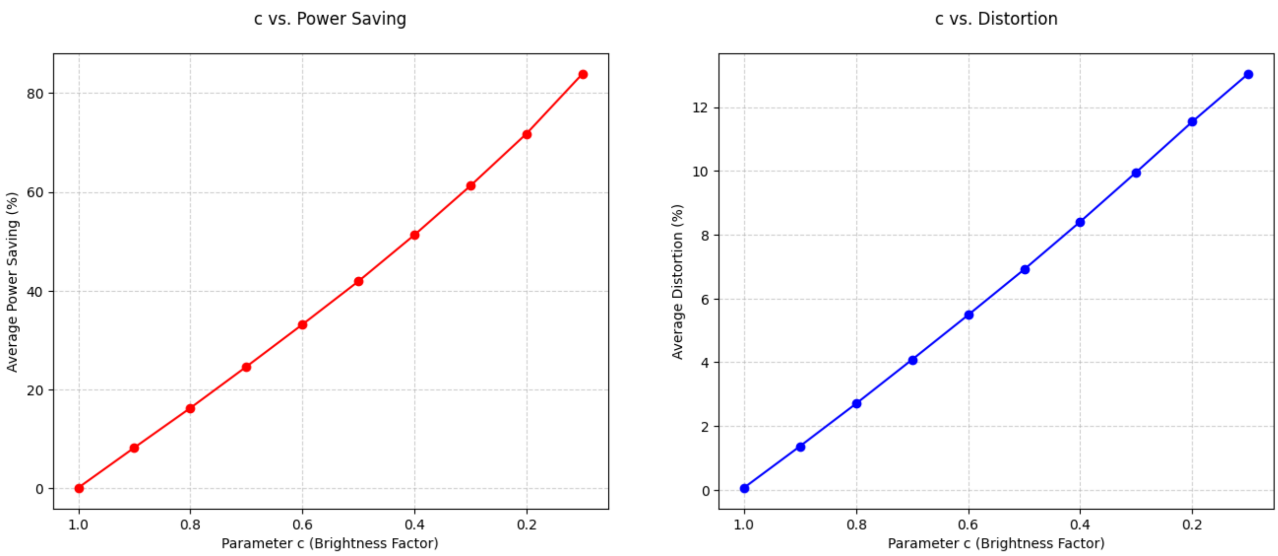


Figure 6: C-changes

Table 2: Performance metrics for different Parameter (c) values(only natural images)

Parameter (c)	**Avg Saving %**	**Min Saving %**	**Max Saving %**	**Avg Distortion**	**Min Distortion**	**Max Distortion**
1.0	0.15	0.05	0.38	0.07	0.03	0.10
0.9	8.22	8.06	8.47	1.37	0.97	1.75
0.8	16.23	16.09	16.46	2.72	1.90	3.47
0.7	24.60	24.42	24.82	4.11	2.87	5.26
0.6	33.13	32.96	33.36	5.53	3.84	7.07
0.5	41.91	41.76	42.15	6.98	4.83	8.93
0.4	51.27	51.10	51.52	8.49	5.87	10.88
0.3	61.20	60.99	61.48	10.07	6.93	12.91
0.2	71.77	71.57	72.07	11.67	7.96	15.00
0.1	83.84	83.59	84.16	13.18	8.78	17.16

Table 3: Performance metrics for different Parameter (c) values(total images)

Parameter (c)	**Avg Saving %**	**Min Saving %**	**Max Saving %**	**Avg Distortion**	**Min Distortion**	**Max Distortion**
1.0	0.14	0.00	0.38	0.06	0.00	0.10
0.9	8.25	8.00	8.99	1.36	0.43	2.35
0.8	16.27	15.92	17.94	2.70	0.83	4.67
0.7	24.63	24.33	25.59	4.08	1.12	7.12
0.6	33.17	32.75	34.56	5.48	1.46	9.55
0.5	41.91	41.63	42.55	6.91	1.71	12.14
0.4	51.29	50.90	52.22	8.40	2.01	14.74
0.3	61.24	60.91	63.27	9.96	2.28	17.55
0.2	71.78	71.34	72.45	11.54	2.49	20.42
0.1	83.90	83.47	86.08	13.05	2.75	23.64

Analysis:

- Based on Figure 5, Figure 6, and table 2 and 3, it's clear that the c decreases the power saving and distortion increases.
- The difference between min saving and max saving is small. In the HSV color model, the Value (V) is defined as $V = \max(R, G, B)$. When we keep the Hue (H) and Saturation (S) constant and only scale V by a factor of c (meaning $V' = c \cdot V$), it is mathematically equivalent to scaling the R, G, and B channels by the same factor c simultaneously.

  That is:
  $$R' = cR, \quad G' = cG, \quad B' = cB \tag{4}$$

  By substituting these new RGB values into the dynamic power formula, we can factor out c^γ:
  $$P'_{pixel} = w_R(cR)^\gamma + w_G(cG)^\gamma + w_B(cB)^\gamma = c^\gamma \cdot P_{pixel} \tag{5}$$

  The saving formula is:
  $$\text{Saving } \% = \frac{(\sum P_{pixel} + W_0) - (\sum c^\gamma P_{pixel} + W_0)}{\sum P_{pixel} + W_0} = \frac{(1 - c^\gamma)\sum P_{pixel}}{\sum P_{pixel} + W_0} \tag{6}$$

  The W_0 is very small (like 1.48×10^{-6} W), and the $\sum P_{pixel}$ is around 2 to 5 W. So we assume $W_0 \approx 0$, and then $\sum P_{pixel}$ can be canceled. The Saving % $\approx 1 - c^\gamma$ shows that the saving mainly depends on c (brightness factor). Therefore, the power saving is independent of the image content.
- For the distortion, the difference between the maximum distortion and the minimum distortion is huge.

Secondly, in order to find the reasons of distortion gap, we implemented a script to determine the distribution of Lab values in the natural images group.

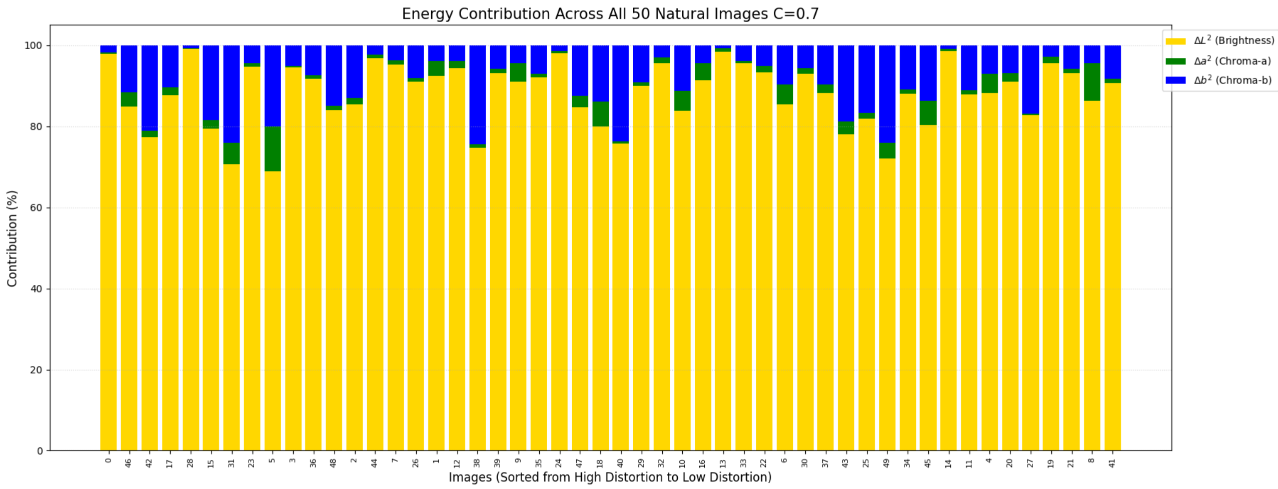


Figure 7: Lab-distribution-distortion

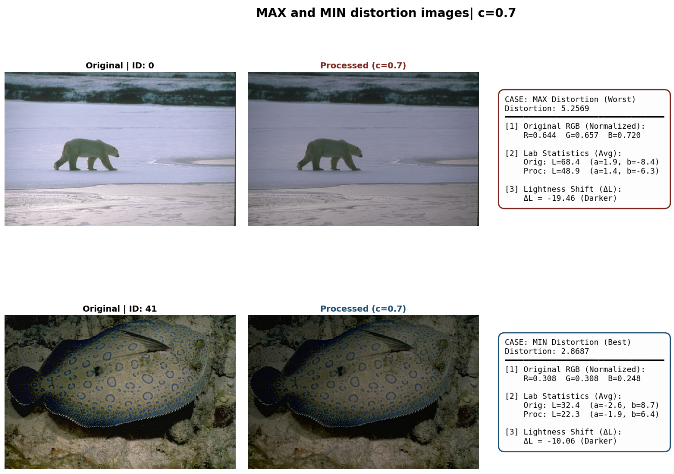


Figure 8: Max and Min distortion natural images

$$Y \approx 0.2126 \cdot R + 0.7152 \cdot G + 0.0722 \cdot B \tag{7}$$

Analysis

- That's because the calculation of distortion is based on Euclidean Distance. For Figure 7, we can see the Lab contribution for distortion. The L(brightness) is the domain factor of the image set. Let us analyze Figure 8. The minimum distortion image has the smallest L value. In contrast, the max distortion image has the largest L value. It's obvious that the ID 0 image has more light pixels, so the RGB values are higher than the ID 41 image.

Third, we compare screenshots and natural images.

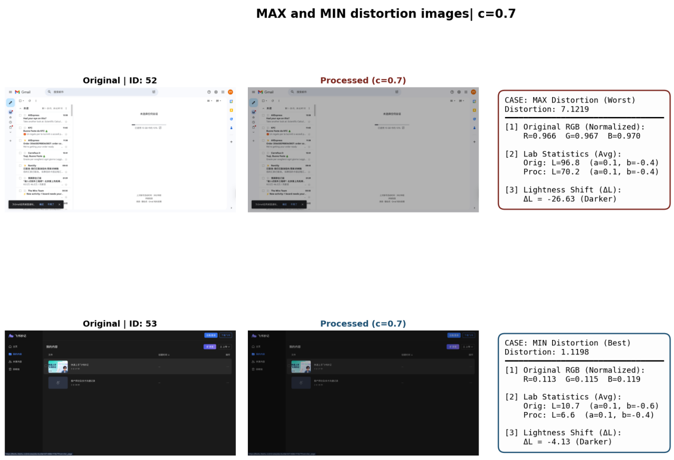


Figure 9: Max and Min distortion total images

Analysis:

- We found the maximum and minimum distortions in the screenshots. That's because those screenshots are almost entirely black or white. So they have the extreme values of RGB, and the normalized values are around 0.9 and 0.1. And the L values are extreme too, like 96.8 and 10.7. So the ID 52 has the bigger ΔL, and then has the bigger distortion.

3.2.4 Strategy 3: Histogram Equalization basic version

We transfer the RGB to HSV, and apply the histogram equalization on V, then transfer HSV to RGB.

Table 4: Histogram Equalization Result

Metric	Value
Power Saving	
Average	1.48%
Minimum	−38.87%
Maximum	26.69%
Distortion	
Average	3.05%
Minimum	1.19%
Maximum	5.83%

* Negative value indicates increased power consumption.

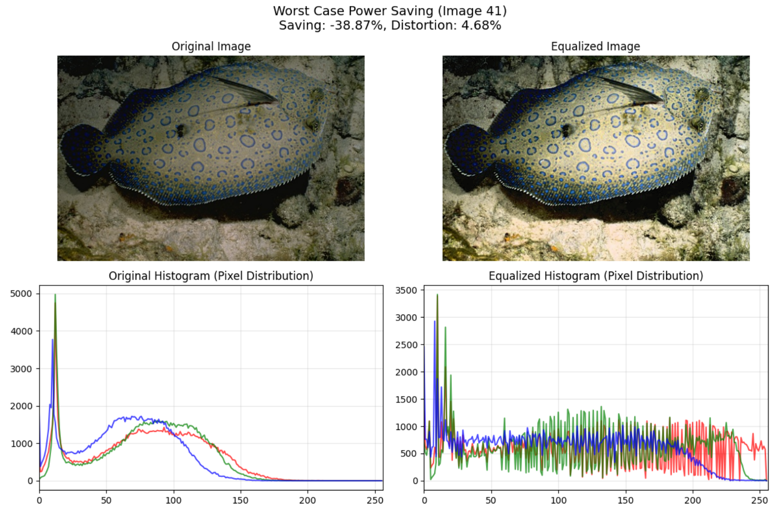


Figure 10: Min power saving natural images

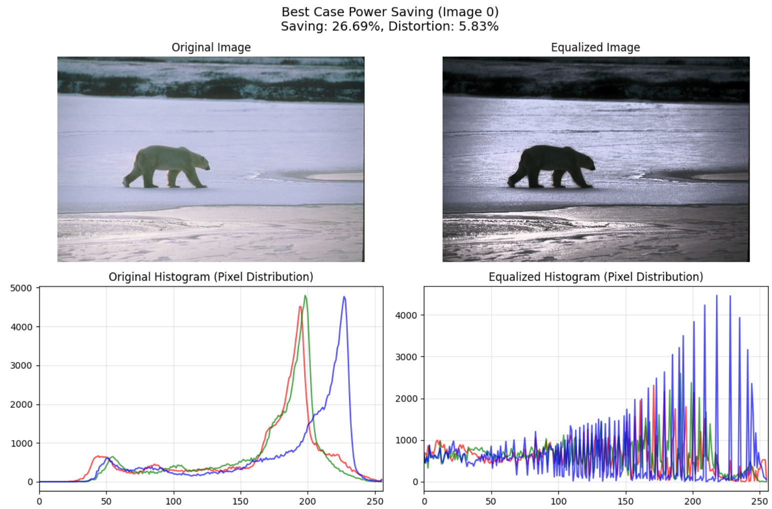


Figure 11: Max power saving natural images

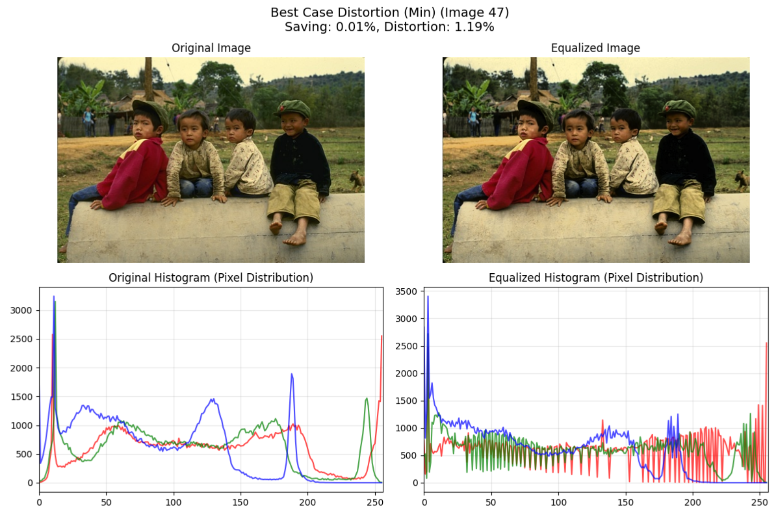


Figure 12: Min distortion natural images

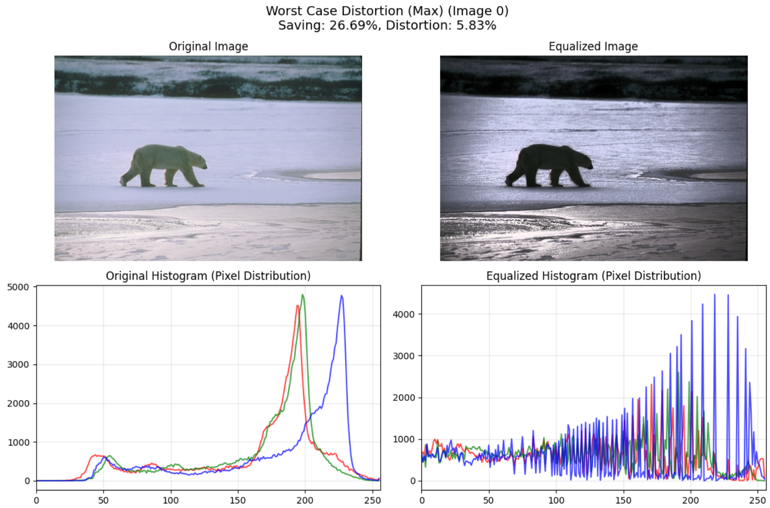


Figure 13: Max distortion natural images

Analysis:

- The gap between minimum and maximum power saving is huge. The minimum power saving is even a very large negative number.
- Image 41 contains a large number of low RGB values. After equalization, a large number of values between 0 and 20 that cost a little power are evenly distributed in the entire range of 0 to 250, so the power is significantly increased.
- Image 0 contains a large number of high RGB values. After equalization, a large number of pixel values between 200 and 250 cost a lot of power, and are evenly distributed in the entire range of 0 to 250, so the power is significantly reduced.
- The distortion analysis, we based on Figure 7, we know the major contribution of distortion is the L value. The bigger ΔL, and then has the bigger the distortion. A higher RGB value results in a higher L value (equation 4).
- From the pixel distribution map, the RGB distribution of image 47 is very balanced, and the number of pixels from 0 to 250 is relatively even. Therefore, the RGB pixel distribution is still very balanced after the histogram equalization strategy is adopted, resulting in low overall distortion. In contrast, the RGB distribution of image 0 is very unbalanced. The pixels are almost all distributed between 200 and 250. So, the RGB pixel distribution is much more balanced, resulting in significant distortion.

3.2.5 Strategy 4: Histogram Equalization improve version

This strategy blends the original image with a contrast-enhanced version using a weight α.

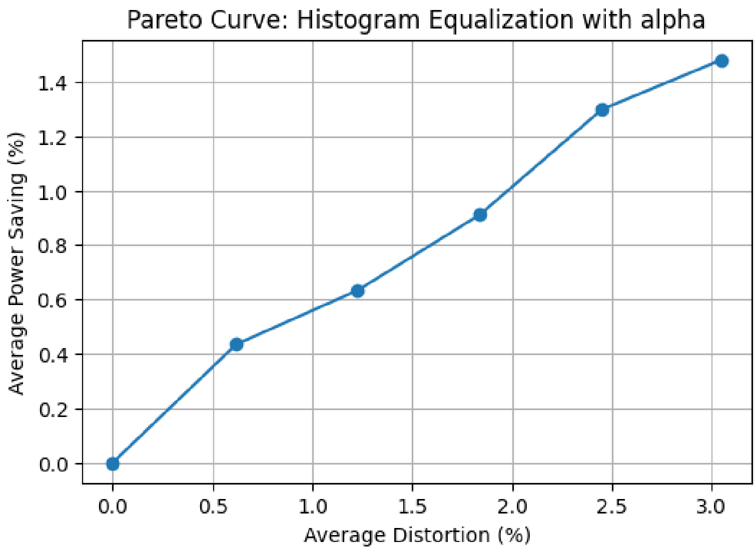


Figure 14: Histogram Equalization improve version pareto curve

Table 5: Saving and Distortion Metrics for Different Alpha Weights

Alpha (Weight)	**Avg Saving %**	**Min Saving %**	**Max Saving %**	**Avg Distortion %**	**Min Distortion %**	**Max Distortion %**
0.0	0.00	0.00	0.00	0.00	0.00	0.00
0.2	0.43	-7.65	5.19	0.62	0.25	1.16
0.4	0.63	-15.59	10.31	1.23	0.48	2.30
0.6	0.91	-23.34	15.62	1.84	0.72	3.47
0.8	1.30	-30.95	21.12	2.45	0.96	4.66
1.0	1.48	-38.87	26.69	3.05	1.19	5.83

Analysis:

- Clearly, an increase in the α value leads to a monotonic increase in both distortion and power saving.
- The result of alpha=1 is the result of strategy 3. By adding a parameter, we can control the effect of Histogram Equalization. We can find a suitable α to generate the image in order to meet the constraint of distortion.

3.2.6 Strategy 5: Gamma correction

The previous strategy 2: Brightness Scaling is a linear adjustment. Although this method can effectively reduce power consumption, we found a flaw in the experiment: it compresses all pixel values evenly. As a result, the pure white highlight will also be darkened to gray, which not only reduces the dynamic range but also makes the overall viewing dull.
According to the Weber-Fechner Law, the perception of brightness by the human eye is non-linear: we are extremely sensitive to small changes in the dark, but relatively slow to the fluctuations in the bright area. This theoretical basis guides us to try to deploy Gamma Correction. The strategy achieves intelligent adjustment of brightness by applying a nonlinear power transformation on the brightness (V) channel of the HSV color space:

$$V_{out} = V_{in}^{\gamma} \tag{8}$$

Where $V \in [0, 1]$. The absolute reduction in brightness for each pixel, which directly dictates both the power saved and the resulting mathematical distortion, is given by $\Delta V = V_{in} - V_{in}^{\gamma}$. Table 6 illustrates this absolute reduction across the $0.0 - 1.0$ spectrum for $\gamma = 1.4$.

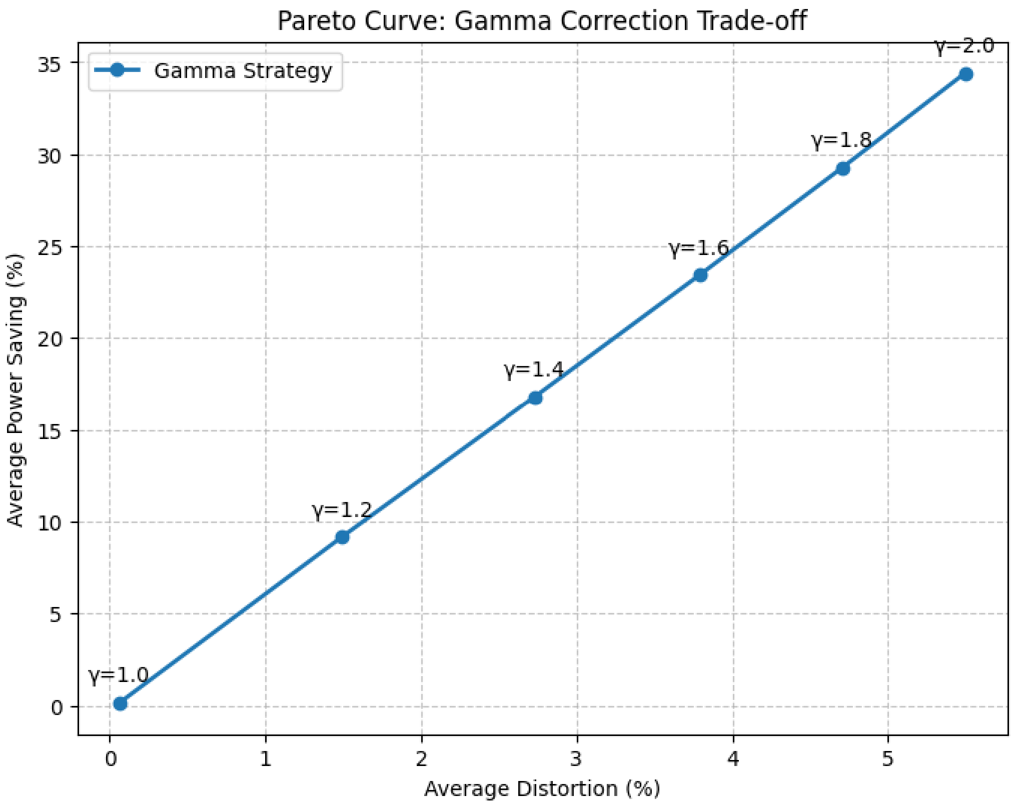


Figure 15: Gamma pareto

Table 6: Luminance Reduction Pattern for Gamma Correction ($\gamma = 1.4$)

Original Value (V_{in})	**Processed Value** (V_{out})	**Reduction** (ΔV)
0.00	0.0000	0.0000
0.10	0.0398	0.0602
0.20	0.1051	0.0949
0.30	0.1853	0.1147
0.40	0.2773	0.1227
0.50	0.3789	0.1211
0.60	0.4891	0.1109
0.70	0.6069	0.0931
0.80	0.7317	0.0683
0.90	0.8629	0.0371
1.00	1.0000	0.0000

Table 7: Saving and Distortion Metrics for Different Gamma

Gamma	Avg Saving (%)	Min Saving	Max Saving	Avg Dist (%)	Min Dist	Max Dist
1.0	0.15	0.05	0.38	0.07	0.03	0.10
1.2	9.17	4.53	15.35	1.49	0.98	1.87
1.4	16.79	8.45	27.62	2.73	1.83	3.35
1.6	23.43	12.08	37.86	3.79	2.59	4.64
1.8	29.27	15.44	46.43	4.71	3.23	5.81
2.0	34.40	18.54	53.61	5.50	3.80	6.82

Analysis:

- The gamma Pareto curve shows that the higher the savings, the higher the distortion.
- Unlike linear scaling, Gamma correction can selectively compress the brightness of Mid-tones while perfectly retaining the peak highlight.
- The higher reduction appears in the range of 0.3-0.6.

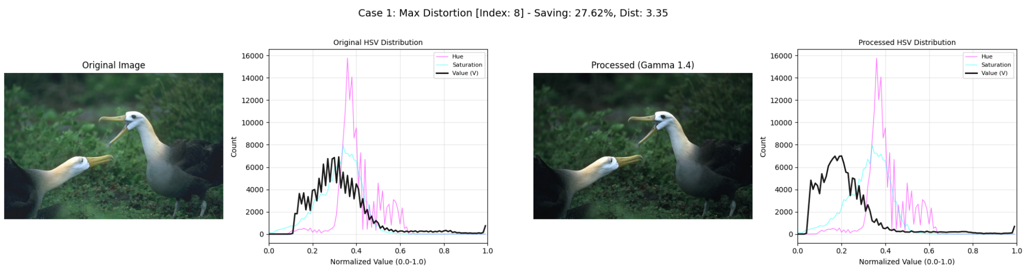


Figure 16: Max distortion natural images

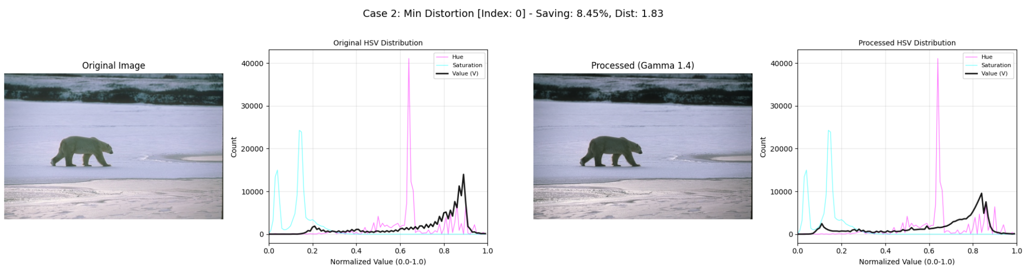


Figure 17: Min distortion natural images

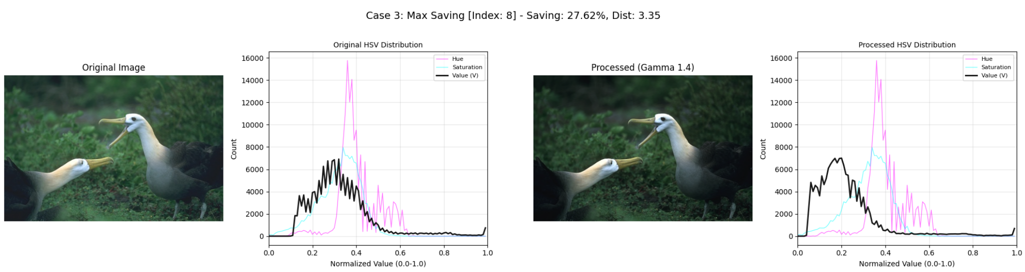


Figure 18: Max saving natural images

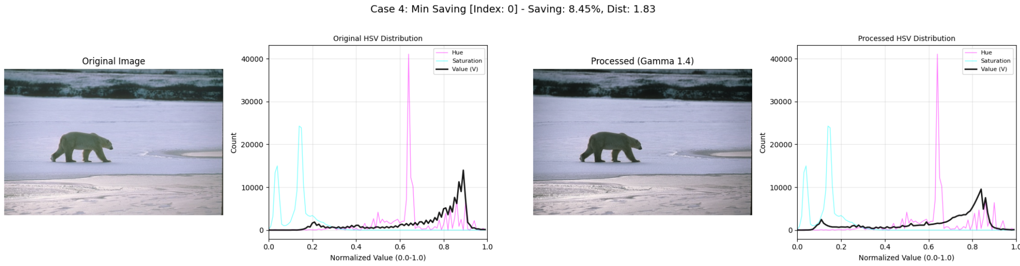


Figure 19: Min saving natural images

Analysis:

- Distortion: Table 6 illustrates the higher reduction appearing the middle range. We can see that most of the pixels in image 8 range from 0.2 to 0.4. And the processed image 8's V channel is clearly shifted left. So image 8 has the highest distortion. In contrast, image 0 has the minimum value of distortion because most of the pixels range from 0.8 to 0.9, which has the smallest reduction according to the table 6.
- Power Saving: The maximum power saving appears at image 8 because most of the pixel values are shifted left to reduce the power. But for image 0, which has the smallest power saving because of the smallest reduction. When the HSV turns back to RGB space, the RGB values change a little.

3.2.7 Comparison 5 Strategies

We limited the distortion to $< 2\%$ to find the best saving case.
It is clear that the brightness scaling and the gamma correction strategies have better power saving.

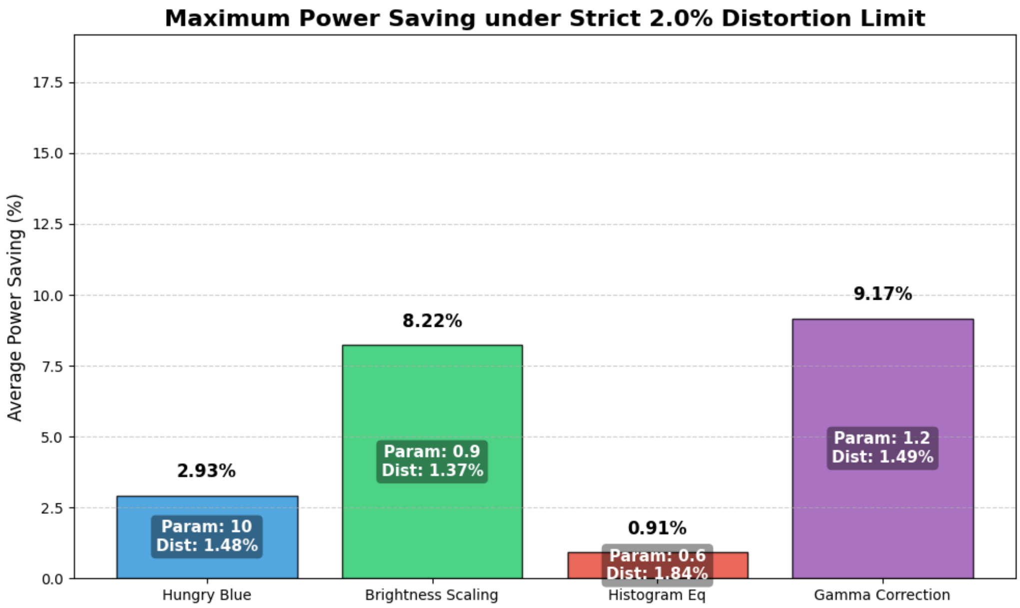


Figure 20: Limit 2% distortion

Analysis:

- We can see that the brightness scaling and gamma correction strategies achieve greater performance. We can remind the formula for OLED power consumption.

$$P \approx w_R R^\gamma + w_G G^\gamma + w_B B^\gamma \tag{9}$$

- For the hungry blue strategy, it only reduces the values of the B channel. Even if it reduces the value of the B channel to 0, the remaining R and G channels consume the power. It gives up the other two channels.
- For histogram equalization, it has the worst performance. The main purpose is to enhance contrast. If there is a very dark image, it will redistribute pixel values. This increases power consumption dramatically. The final power saving can be negative. So, in the set of natural images, the average saving is the lowest.
- For brightness scaling and gamma correction, adjusting the V channel means simultaneously reducing the values of R, G, and B channels. They can do more things to reduce power.

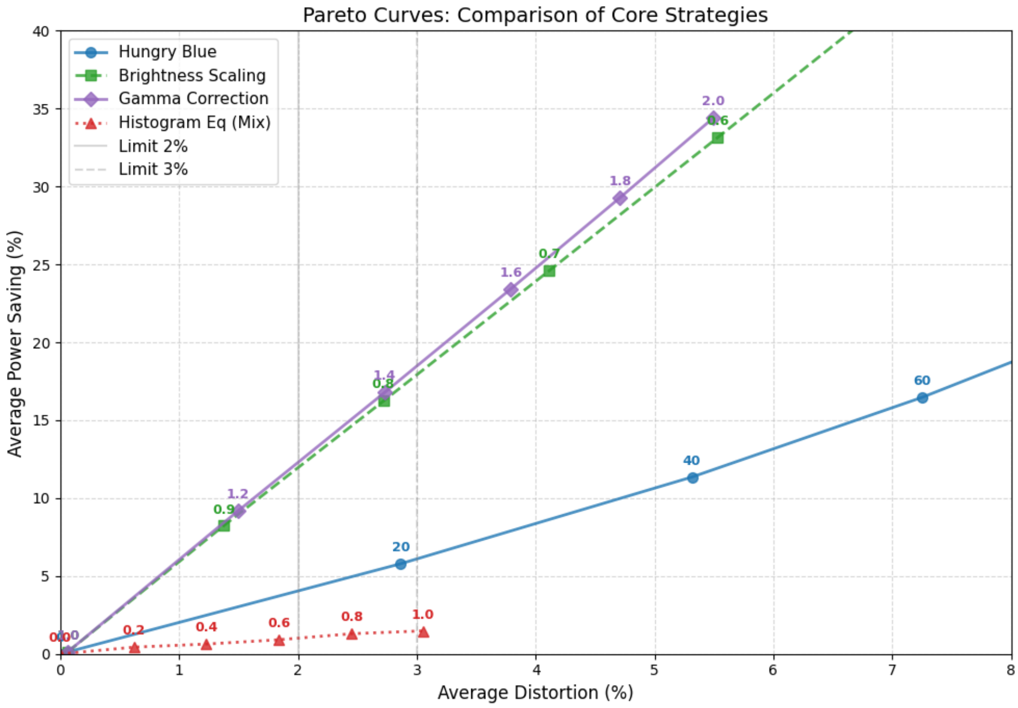


Figure 21: Pareto curves

Analysis:

- Gamma Correction and Brightness Scaling, located at the top of the chart, perform the best. Hungry Blue offers moderate performance because it only adjusts one channel. Gamma and Brightness Scaling adjust the V channel, allowing all three RGB channels to be adjusted simultaneously while maintaining contrast, resulting in an overwhelming advantage in energy saving and distortion tradeoff. Histogram equalization performs the worst because it primarily enhances contrast, even producing negative saving values in extremely dark images. Gamma is better than Brightness Scaling because it is more flexible than Brightness Scaling. The human eye is less sensitive to intermediate pixels, but more sensitive to brightening of extremely dark areas and darkening of extremely bright areas. Brightness Scaling, on the other hand, is a simple penalty, causing sensitive areas to darken proportionally, resulting in significant distortion.

3.2.8 Part 1: Discussion

Do different images behave differently? And what changes in terms of power consumption with different manipulation strategies?

For the two questions we answer together:

- **Power saving**: For general strategies, different images behave differently in power saving. But for brightness scaling, the content of the image doesn't impact the power saving(details check: brightness scaling analysis part).

  1. **Histogram Equalization:** Different images behave differently in power saving. For those extremely distributed pixel values images, like almost all pixels in 0-50 or 200-250, it appears the max power saving and min power saving. because the histogram equalization will re-align those pixels to 0-250. for those keep low power pixels will be distributed to high pixel values. for those keep high pixels will be distributed to low pixel values. (details check: Histogram Equalization analysis part)
  2. **Hungry Blue:** Different images behave differently in power saving. because this strategy highly rely on the blue pixels. for those have a lot of high B channel values images, the power saving will bigger than those have a lot of low B channel values images.
  3. **Brightness Scaling:** the difference is minimal among different content images. Whether the original picture is bright or dark, all pixels darken according to the same proportion C. The power saving ratio only depends on parameter C and has nothing to do with the content of the picture.
  4. **Gamma correction:** Different images behave differently in power saving. This strategy mainly reduces the v which is middle value. For those extremely dark or light images, the power saving is almost the same.

- **Distortion**: Yes. Different images behave differently in distortion in all strategies

  1. **Histogram Equalization:** For those images that concentrate the polar pixel values, there will be serious distortion, because the pixels will force the originally concentrated pixels to stretch, and for images that originally distributed pixels evenly, the distortion is very small, because for example, the pixels in the middle will run to both sides, but the pixels on both sides will also run to the middle, so they can compensate each other.
  2. **Hungry Blue:** For images rich in blue, the distortion is very serious, while the distortion of those images with little blue is extremely small, because there is not much blue that can be suppressed, so hungry blue hardly works.
  3. **Brightness Scaling:** In daily UI interfaces and most natural images, color saturation is usually not particularly extreme, so changes in brightness (L) play a leading role in evaluating visual differences. The initial L value of very dark pictures is low, while the initial L value of very bright pictures is high. When applying global brightness scaling, for those pictures that are already very dark, the absolute difference between the V (Value) channel before and after processing is very small due to the small base, so the distortion is smaller. For pictures that are already very bright, due to the large base, the absolute difference before and after V processing is very large. The size of the absolute difference of this V channel will spread with the error of the conversion of the color space: it directly determines the difference when converting back to RGB space, which in turn determines the ΔL (brightness difference) in the final Lab space, and finally determines the overall distortion.
  4. **Gamma correction:** The image distortion of pixels concentrated in the middle value is obvious, because gamma will reduce the middle value the most. And those polarized images have very little distortion.

How can I save more power with lower distortions?

In order to achieve the best balance between power consumption and quality, we must first analyze the characteristics of the image, and then choose the appropriate strategy accordingly. For example, if we encounter a very dark image, we can choose to zoom the brightness. In this case, the initial V value is very small, so the final change of the V value is also very small, and the final distortion is relatively low. At this time, the histogram equalization strategy cannot be selected, because it will force a large number of low RGB value areas to be highlighted, which is likely to lead to reduced power consumption and serious distortion. When we encounter extremely bright pictures, we can choose gamma correction. Gamma will retain pure white pixels and points close to pure white, while greatly reducing the V values in the middle, which looks relatively natural. In this scenario, brightness scaling should be used carefully, because a high initial V value will cause a huge L difference, resulting in massive distortion. For pictures with very little blue, since there is not much blue light but blue subpixels consume a lot of power, we can choose the hungry blue strategy. This can save electricity with almost no distortion. For pictures with many mid-tone values, it is better to use brightness scaling to maintain relative contrast. Use gamma correction carefully here, because it will lead to a serious loss of mid-tones and huge distortion.

Note: For other deep discussions, you can check the analysis part of different strategies in the previous contents.

3.3 Part 2

3.3.1 Test logic

Before apply the DVS, we apply the strategies below independently to do the pre-processing and to improve the final subjective visual quality.
The image test-set is use the BSDS50 training set.

3.3.2 Compensation Implementation and Voltage Relationship

The compensation parameters are derived from the voltage reduction ratio Ratio_V:

$$\text{Ratio\_}V = \frac{V_{dd\_origin} - V_{dd\_new}}{V_{dd\_origin}}$$

As the supply voltage V_{dd_new} decreases, the "voltage gap" increases, which in turn strengthens the following compensation factors:
Brightness Offset (b_{offset}): $b_{off} = \text{Ratio\_}V \times \text{coeff\_}off$
Contrast Factor (b_{factor}): $b_{fac} = 1 + (\text{Ratio\_}V \times \text{coeff\_}fac)$

3.3.3 Strategy 1: Brightness Scaling

We add a constant value b_{offset} to the V channel. This shifts the entire image to be brighter to offset the darkening effect of DVS.

3.3.4 Strategy 2: Contrast Enhancement

We multiply the V channel by a factor b_{factor} (where $b > 1$). This stretches the difference between light and dark areas, making details more visible even at lower voltages.

3.3.5 Strategy 3: Combined Brightness Scaling and Contrast Enhancement(Both)

We apply both techniques to find a balance between overall brightness and detail sharpness.

Test logic within script implementation

Before applying DVS, we calculate the per-pixel current and the total panel power. We use the `displayed_image` function to simulate the DVS effect. After applying DVS, we compute the panel power again to determine the power savings and the distortion between the original image and the one after DVS. For each image, we apply the three different strategies mentioned above and various V_{dd} values to find the best (V_{dd}, compensation strategy) pair under different distortion constraints. We designed a double-layered traversal loop. For the **Combined(Both)** strategy, the algorithm not only traverses the voltage gradient but also internally explores all combinations of brightness and contrast coefficients. This implementation expands the search space for the **Conbined(Both)** strategy from a one-dimensional linear search to a two-dimensional grid search, thereby increasing the probability of finding solutions that satisfy the distortion constraints.
We implemented the code to find the best power-saving strategy and related parameters (voltage, b_{offset}, and b_{factor}). This was done by testing different strategies with different voltages(0.5v per step, decreased to 9v) and scaling b_{offset} and b_{factor} through different coefficients to apply different compensation intensities for the decreased supply voltage.
Finally, we saved all combinations of these tests, along with their corresponding parameters and results (not just the best ones), into a CSV file for subsequent trade-off analysis. and we saved the best power saving configuration for each image in .txt file, meanwhile, saved the rated images to select the best quality one(but Subjective).

3.3.6 Test results

By analyzing the generated CSV data, we obtained the maximum power saving results for each image under various distortion constraints. Furthermore, for the entire test set, we evaluated the overall power saving performance. Table 2 below shows the aggregated trends for the test set (50 images).

Table 8: Optimization Results: Power Saving under Different Distortion Constraints

Constraint (%)	Avg. Max Saving (%)	Min Saving (%)	Max Saving (%)
0.5	5.72	0.00	9.92
1.0	12.40	8.08	20.12
1.5	18.70	13.90	26.50
2.0	23.64	18.96	32.44
2.5	28.48	21.53	38.52
3.0	32.88	26.64	43.73

Notes: Here, the average Max Saving is calculated from selecting the ALL max power saving configurations of each figure and averaging them, the Min saving is the one selected from the Minimum power saving of all pictures, the Max saving is one selected from the maximum power saving of all pictures.
Considering the required distortion constraints, the figure below shows the number of different compensation strategies implemented to meet these constraints. We further broke down the results into specific distortion steps to visualize the frequency of each strategy at different error thresholds.

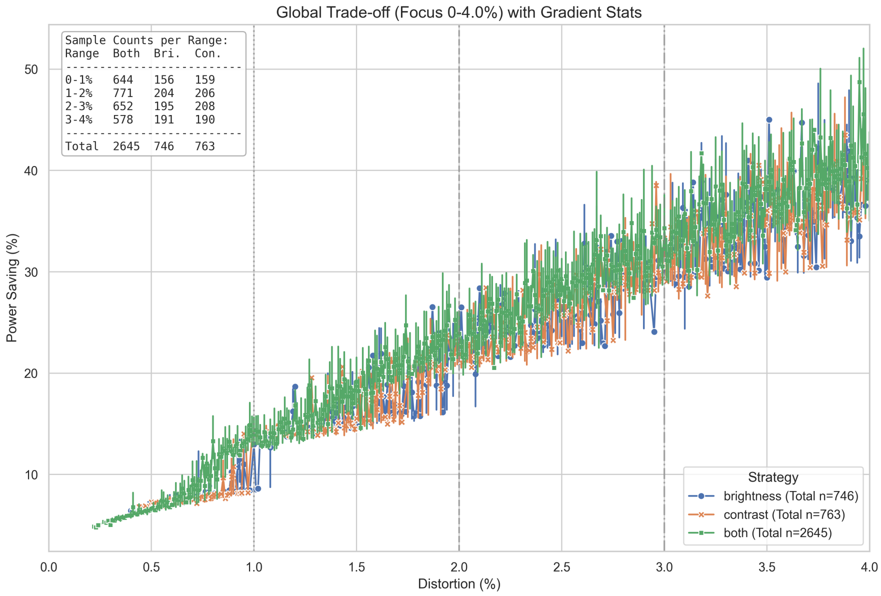


Figure 22: Global Trade -off

Analysis

1. **General Trend:** The graph demonstrates a clear trade-off: higher power savings come at the cost of increased distortion.

    - **Low Distortion (< 1%):** Power savings are limited (approx. 5%–15%), as high image fidelity restricts voltage scaling.
    - **Higher Distortion (2%–4%):** Savings increase significantly, reaching up to 50%, though with higher variance (indicated by larger error bars).

2. **Strategy Performance:** The **Combined (Both)** strategy (Green) outperforms the single strategies (Blue/Orange). It consistently occupies the *Pareto frontier* (the upper-left edge of the cluster), meaning it achieves the maximum possible power saving for any given distortion level.

3. **Statistical Insight:** The table in the top-left reveals the superior **robustness** of the Combined strategy:

    - It found **2,645** valid configurations within the 4% limit, more than **3.5 times** the count of Brightness (746) or Contrast (763) alone.
    - Even in the strictest **0–1% range**, the Combined strategy offers **644** valid options compared to ≈ 150 for the others.

4. **Conclusion:** The **Combined strategy** is optimal. It not only yields better efficiency but also provides a much larger search space (more valid samples), making it easier to find a configuration that meets strict quality constraints while lowering voltage.

Voltage effects on power saving

The scatter plot visualizes the fundamental trade-off between power reduction and image quality degradation. Each point represents a specific configuration (voltage, strategy, and image combination). However, in this specific view, we consider only the voltage effect on this trade-off, effectively separating the analysis from the strategy-specific trends observed in previous curves.

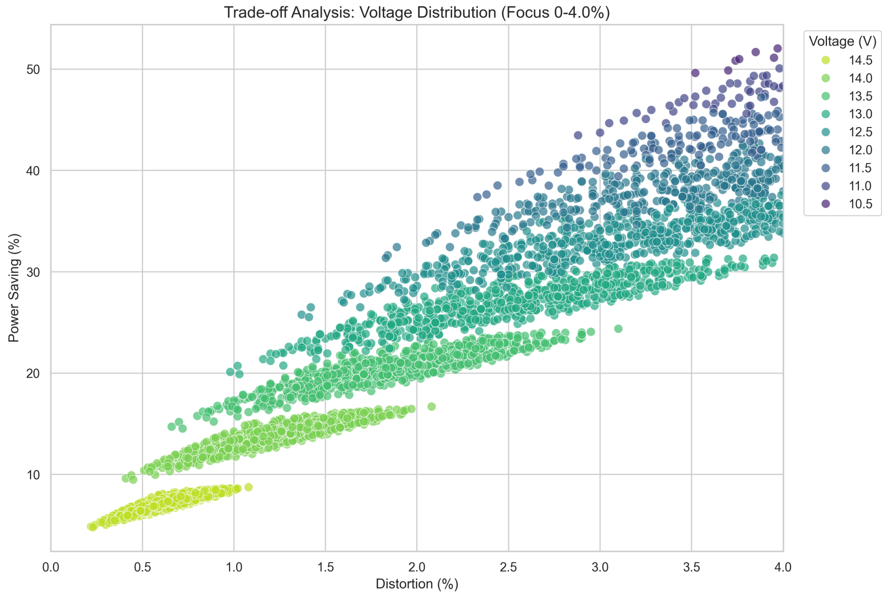


Figure 23: Trade off analysis for Voltage

Analysis:

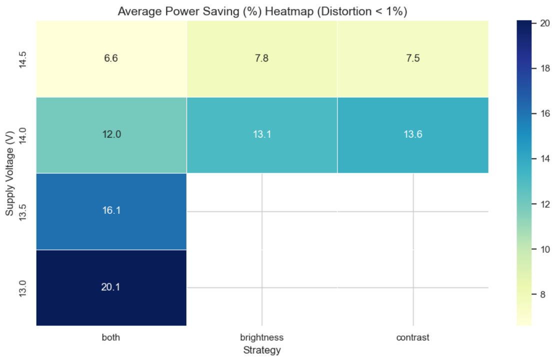
- In the previous curve (Figure 5), we observed the overall trade-off trends averaged across different strategies. While that view highlighted how mixed strategies perform, this scatter plot specifically isolates the voltage effect on the trade-off. By removing the strategy-specific lines, we reveal that the coarse position of any data point on the chart is fundamentally determined by the supply voltage.

- By decoupling the data from strategy lines, the distinct stratification by voltage becomes the dominant feature. The color gradient clearly maps the discrete voltage steps:
  High Voltage Cluster (14.5V - 13.5V): Located at the bottom-left, represented by lighter green hues. These points show that keeping voltage high results in minimal distortion but strictly limits power savings.
  Low Voltage Cluster (11.5V - 10.5V): Located at the top-right, represented by darker purple hues. This separates the high-efficiency region from the rest, showing that significant power savings are inherently tied to lower voltages, regardless of the strategy used.

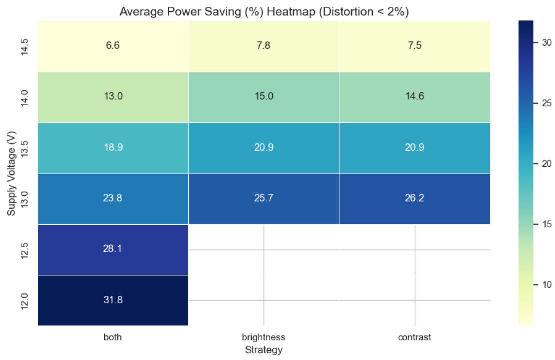
- Without the visual complexity of the strategy lines from the previous curve, the "Pareto Frontier" is clearly defined by voltage capabilities. The transition from teal to blue points (around 12.5V to 11.5V) marks the physical "sweet spot" where the hardware voltage limit balances efficiency and quality.

- Voltage acts as the dominant variable determining the macro-region of the operating point (e.g., the high-efficiency/high-distortion region). Compensation strategies only serve as secondary fine-tuning mechanisms, optimizing the result locally within the physical constraints imposed by the chosen voltage.

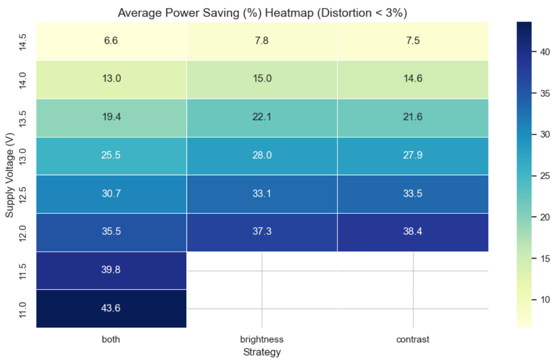
Voltage effects and Strategic Preferences



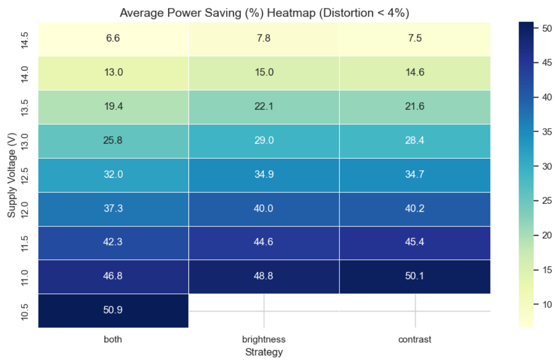
(a) Distortion constraint < 1.0%



(b) Distortion constraint < 2.0%



(c) Distortion constraint < 3.0%



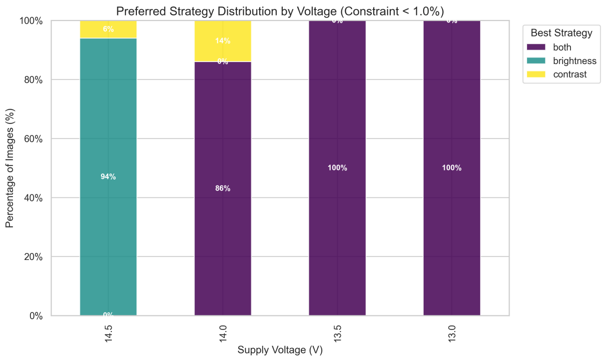
(d) Distortion constraint < 4.0%

Figure 24: Average Power Saving Heatmaps under Varying Distortion Constraints.

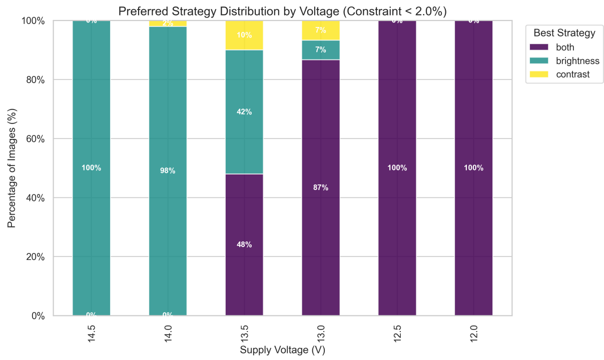
Analysis:

- As constraints are relaxed, the minimum available voltage decreases, enabling greater energy savings. When the distortion constraint is only 1 available, even though we use both strategies, the lowest voltage is only 13.0 V, and when the constraint is extended to 4, the lower voltage is available and more energy saving.
- In different distortion constraints, the Both strategy can always descend to the deepest in the figures, because the Both strategy have a larger parameter search space. When the voltage is too low, causing widespread pixel distortion, only by simultaneously fine-tuning both brightness and contrast can one find the solution that satisfies the constraints.
- Although the "Both" strategy demonstrates strong survivability under low voltage, within the medium-to-high voltage range, a single strategy often exhibits higher efficiency. For example, in Figure 7 (c), in row at 12.0 V, the power saving achieved by the brightness and contrast strategy is all higher than "Both strategy"

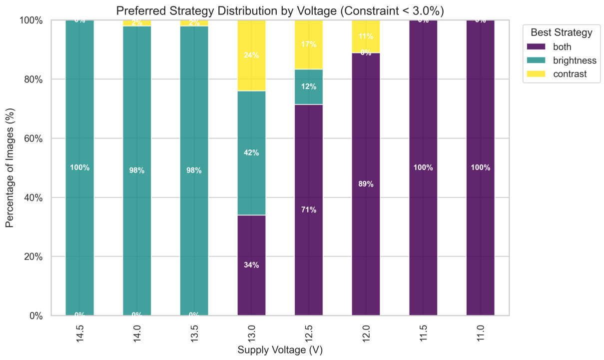
Distribution of strategy by Voltages for Best Power saving



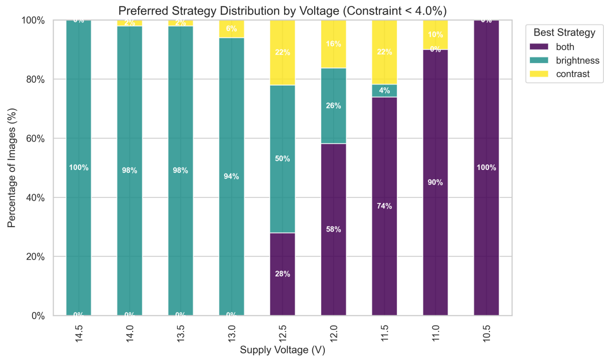
(a) Distortion constraint $< 1.0\%$



(b) Distortion constraint $< 2.0\%$



(c) Distortion constraint $< 3.0\%$



(d) Distortion constraint $< 4.0\%$

Figure 25: Distribution of strategy by Voltages under Varying Distortion Constraints.

Analysis:

- In different distortion constraints, the Brightness Strategy always holds an overwhelming dominance in the high-voltage range (14.5V – 14.0V), typically accounting for 94 percent to 100 percent of the optimal selection ratio. At high voltages, OLED panels exhibit minimal physical distortion. Within this “safe zone,” simple brightness compensation is sufficient to maintain image quality.
- As voltage decreases, the share of the ”both strategy” increases rapidly. Particularly at the minimum feasible voltage for each constraint, such as 13.0V at <1.0 or 10.5V at <4.0—the ”both strategy” achieves 100 dominance. This is not because ”both strategy” are inherently more efficient, but because they are the sole survivors. Under extreme voltage conditions, single-variable strategies (brightness/contrast) are often eliminated due to excessive distortion. ”Both strategy”, with their larger parameter search space (adjusting offset and scaling, as in previous analysis), become the only approach capable of finding viable solutions under such harsh conditions.
- In the intermediate voltage range (e.g., 12.5V–12.0V in Figures (c) and (d)), the contrast strategy accounts for a significant proportion, peaking at approximately 22–24. This represents a transitional zone where strategy selection is highly dependent on image content. For images with specific histogram characteristics, adjusting contrast alone proves more effective than adjusting brightness, eliminating the need for complex ”Both”(combined) strategies.

Discussions:

As observed in the experimental results, the "Both" (Combined) strategy demonstrates a significantly higher survivability at lower V_{DD} levels compared to single strategies. This superior performance is not accidental but stems from the synergy between its mathematical foundation and the algorithmic search implementation.
Mathematically, compensating for voltage drop requires modifying V (Value) channel in the HSV color space. Single strategies operate with only one Degree of Freedom. Brightness scaling acts as a simple translation

$$V_{new} = V_{old} + b_{offset}$$

which risks saturation and distortion. Contrast enhancement acts as pure scaling, which fails to recover the baseline luminance lost at low voltages.
In contrast, the combined strategy employs a dual-parameter adjustment:

$$V_{new} = (V_{old} \times b_{factor}) + b_{offset}$$

This allows the algorithm to simultaneously shift the baseline to offset darkening and adjust the dynamic range to prevent clipping.
As mentioned in previous. We use a nested-loop grid search to optimize these parameters. Unlike the 1D search used in single strategies, this method explores a full 2D space. This allows the algorithm to find a configuration that effectively balances the system: it minimizes voltage to save power while ensuring distortion remains below the constraint.

Notes:

The cross-verification between the trade-off analysis and the heatmaps reveals consistent patterns. For instance, under a strict distortion constraint of 1, the trade-off chart exhibits discrete data clusters at 13.0V and 13.5V, which directly corresponds to the valid blocks for the *both* (combined) strategy at these same voltages in the heatmap. This high density of the *both* strategy at lower voltages arises because its larger parameter search space allows it to satisfy the strict distortion requirements for various images where single strategies fail. Consequently, the significant volume of *both* data points is attributed to two factors: it inherently possesses more parameter combinations than single strategies, and it demonstrates stronger survivability under strict constraints, leading to a larger number of valid samples.

Furthermore, the apparent data discrepancy between the trade-off chart and the distribution chart—such as the *contrast* strategy appearing significantly less dominant in the distribution chart than in the trade-off chart—can be explained by their differing objectives. While the trade-off chart visualizes all valid possibilities, the distribution chart incorporates an additional filter for the **best power saving**. It calculates the percentage of strategies that achieve the maximum energy efficiency for each specific image at different voltages within the valid samples, subject to the distortion constraint. Therefore, the distribution chart reflects the most suitable compensation strategy for achieving better energy saving effects at each voltage level, rather than merely showing all feasible options.

Best image selection(among (Vdd, compensation)pairs)

By running the script under different Distortion Constraints, we produce the transformed images and the list of these images(in .txt file, with configuration desciption), each meet the distortion requirement and its configuration can achieve the best power saving among the whole list of possible configurations(described in .csv file), we choice to select the best quality among these images. And based on subjective judgment, we have selected the following images with the best quality after DVS adjustment.

(a) Original 107014.jpg

(b) Transformed 107014.jpg, With configuration of **Combined strategy**: b_offset: 0.0400, b_factor: 1.0400, Vdd: 13.0V, Power Saving: 26.70%, Distortion: 2.91%.

Figure 26: Selected best image