UNIVERSITÄT LIECHTENSTEIN

Evaluating State of the Art Upscaling Technologies: Performance, Image Quality and Gaming Scenario Suitability

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220076

Master's thesis

to obtain the degree of

Master of Science in Information Systems (MSc)

University of Liechtenstein

Programme: Information Systems

Assessor: Assoz. Prof. Dr. Johannes Schneider

Working period: 01/02/2024 to 20/06/2024

Date of submission: 20/06/2024

Abstract

Table of contents

1 Introduction

Nowadays video game graphics are improving constantly. Complex particle physics as well as racy-traced light effects where lighting is rendered in real time as individual rays, have become the standard within the video gaming industry. These effects require lots of processing power. For consumers of video games to run these video games they rely on dedicated hardware known as Graphics Processing Units (GPUs) from one of the three major companies such as Nvidia, Intel, and AMD (Watson, 2020, p. 1).

However, the pursuit of increasing GPU processing power to cope with ever-new great-looking video games is faced with challenges such as the issue that transistors approach atomic sizes. Furthermore, the pursuit of engineering new and more powerful GPUs comes with a huge problem which is an increase in energy consumption. This increased energy demand is not only a challenge for efficient hardware usage but also raises concerns regarding sustainability and the contribution to environmental issues such as the climate change. Another issue is that consumer cannot choose the most energy efficient hardware now, which leads to a waste of energy. At this time, it is not clear which methods or algorithms work best in practice which is needed for further development.

Therefore, major companies in the industry are exploring innovative solutions, particularly in the area of upscaling technologies. One such technology is Nvidia's Deep Learning Super Sampling (DLSS) technology which uses the power of Artificial Intelligence (AI) in the upscaling process.

The goal of these technologies is to allow the majority of the graphics rendering to run at a lower resolution for increased performance, and then create a higher resolution image from that approximates the same level of detail as if the image had been rendered at this higher resolution. Astonishingly, Nvidia's DLSS can even increase the level of detail and image quality in video games (NVIDIA Corporation, 2023b).

A recent performance test of Cyberpunk 2077, the action RPG developed by CD Projekt RED, showcased impressive results with the utilization of the latest DLSS version, DLSS 3.0. When DLSS is enabled, the frames per second (FPS) skyrocket from a mere 20 to a remarkable 100 (Burnes, 2023). It's noteworthy that anything exceeding 30 FPS is generally considered to be smoothly without stuttering.

Moreover, upscaling technologies can also help to decrease power consumption since they optimize the rendering process of video games. For instance, DLSS 3.0, the latest version of DLSS, can help to reduce power consumption by up to 40 percent (White, 2022).

In addition to DLSS, there are other noteworthy technologies in the gaming world. One of these is XeSS by Intel which uses machine learning for image upscaling. Another technology is AMD FSR which takes a different approach without relying on artificial intelligence.

1.1 Research Objective

The research objective centers around the evaluation and assessment of the three upscaling technologies in form of a benchmark. That problem that comes up when looking at various benchmarks of large video game magazine such as Gamestar is that the focus is often on sole technology such as DLSS without testing the other technologies. As an example, in the technic report of Cyberpunk 2077 the author Nils Raettig solely focused on DLSS as a performance evaluation criterion and did not mention FSR. Furthermore, only the upscaling settings Performance and Quality were considered but not the setting Balanced. Furthermore, there were no tests regarding the GPU efficiency in terms of power consumption when using upscaling technologies (Raettig, 2020).

Another example hereby is Gamer Nexus, a large hardware review channel on YouTube. The review on the Nvidia Geforce RTX 4060 does include the power consumption of the RTX 4060 but does not emphasize whether the usage of upscaling technologies affect the power consumption. What is more, the benchmarks on Cyberpunk 2077 are extensive but does not include a variety of different upscaling technologies nor different graphical settings (Gamers Nexus, 2023).

By recognizing the limitations in current benchmarks and evaluations conducted by entities such as Gamestar or Gamer Nexus, this research aims to resolve these shortcomings by conducting a comprehensive and comparative assessment of the three upscaling technologies – Nvidia DLSS, AMD FSR and Intel XeSS. Unlike previous evaluations, the research objective is focus on all different graphical settings, upscaling settings and also to consider differences in GPU power consumption since energy efficiency is becoming more and more crucial to consumers.

1.2 Research Questions

Research Question:

How do various state-of-the-art upscaling technologies compare in terms of performance, image quality and suitability in the context of modern video games?

The aim of the research is to conduct a comparative analysis of state-of-the-art upscaling technologies. The focus lies on the performance measurement, energy consumption and image quality. Furthermore, a very important aspect is to the assess the suitability for optimal gaming experiences.

Sub Research Questions:

Sub-question 1: What are the key technological differences and underlying mechanisms between Nvidia DLSS, Intel XeSS, and AMD FSR in the context of image upscaling and enhancement for gaming?

This sub question is intended to go deeper into the technological differences and mechanisms among Nvidia DLSS, Intel XeSS, and AMD FSR. It aims to investigate the different approaches for image upscaling.

Sub question 2: How do Nvidia DLSS, Intel XeSS, and AMD FSR impact performance measured in frames per second (FPS) and frametimes across a diverse range of modern video games and different graphics card generations, specifically assessing their combined effect on overall performance and gameplay smoothness?

This sub question seeks to analyze the influence of Nvidia DLSS, Intel XeSS, and AMD FSR on the performance in terms of frames per second and frametimes in different video games and across graphics card generations.

Sub question 3: In what ways do Nvidia DLSS, Intel XeSS and AMD FSR influence the gaming scenario suitability in terms of a smooth gaming experience, image quality and energy consumption?

The third sub question aims to further highlight the gaming separability which can interpreted as the balance between a smooth gaming experience in terms of a high framerate in combination with a solid frametimes and a sharp and flawless image quality. In addition, since high energy consumption is becoming more and more a problem, this sub question also aims to investigate the influence that upscaling technologies have in terms of energy efficiency.

2 Research Background

In this chapter, a systemic literature review was conducted to better understand the image upscaling process as well as the current landscape of state-of-the-art upscaling technologies. The chapter focuses on their functionalities and operational methodologies. Each of these technologies represents up to date approaches in video game graphics enhancement whether it is by using neural networks, machine learning or advanced algorithms as in the case of AMD FSR.

2.1 The Theory behind Image Upscaling Technologies

GPUs were invented in order to meet the demands of parallel computation tasks from computer graphics. In the recent years display devices have developed a lot and displays which offer a 4K or 8K high resolution are not uncommon anymore. In addition, state-of-the-art video games and virtual reality headsets also demand higher resolutions, levels of detail and refresh rates than before. This results in the problem that the hardware power of GPUs has to increase exponentially but GPU can only grow in a linear fashion. That is why it is important to keep rendering at low resolution and obtain high resolution by applying image upscaling technologies (Zhihua et al., 2023, p. 2).

Image upscaling which is also known as super resolution is the process of increasing the resolution of an image to a higher resolution than the original resolution. There are several techniques which are used for image upscaling. Traditional methods such as interpolation for example and more advanced approaches such as machine learning based image upscaling (Zhihua et al., 2023, p. 2).

Traditional methods such as bilinear and bicubic interpolation work by estimating the values of new pixels based on the values of neighboring pixels in the original image. The bilinear approach uses the weighted average of the four nearest pixels. The bicubic interpolation uses a more complex approach. A complex algorithm which involves a large number of neighboring pixels to estimate the new pixel values. These methods are very effective but might result in blurred or low-quality images (Zhihua et al., 2023, p. 4).

In the recent years, machine learning-based approaches such as neural networks have gained attention because of the ability to generate high-quality images. One example for such a machine learning based approach would be Nvidia’s DLSS. These methods involve training a neural network on a massive dataset of low-resolution and high-resolution image pairs. These image pairs allow the network to learn complex patterns and features which enables it to generate realistic high-resolution images from low-resolution inputs. These techniques often produce superior results compared to traditional interpolation methods and are especially effective when it comes to preserving fine details and textures in the upscaled images. This is an important advantage when it comes to video games because this preservation of fine details and textures significantly enhance the immerse experience for gamers and also ensures a high level of visual fidelity and realism in gameplay (Zhihua et al., 2023, p. 4).

2.2 Definition of the State-of-the-Art Upscaling Technologies

In this paragraph the upscaling technologies Nvidia DLSS, AMD FSR and Intel XeSS are explained in detail in order to better understand how these technologies work and operate. These three technologies are the state-of-the-art upscaling technologies and leverage neural networks, machine learning or in the case of AMD FSR advanced algorithms.

2.2.1 Nvidia Deep Learning Super-Sampling (DLSS)

In modern video games the rendered frames are not display directly but rather the frames first endure a post processing image enhancement step which connects the input from multiple rendered frames. This process tries to remove visual artifacts such as aliasing. One of these techniques is called Temporal Anti-Aliasing (TAA) where a shader-based algorithm connects two frames by introducing motion vectors to determine where to sample the previous frame. The problem with such an image enhancement process is that the process is very hard to get in order to create a perfect image (NVIDIA Corporation, 2018, p. 34).

That is why Nvidia came up with an AI based solution called Nvidia DLSS. This solution to the image analysis and optimization problem uses a deep learning approach. Nvidia's deep neural network is called Deep Learning Super-Sampling. In contrast to the previously mentioned TAA approach, DLSS creates a much higher quality output from a given set of input samples and also has the capability to improve the overall performance of the video game in terms of frames per second (FPS). Another very important aspect is that Nvidia's solution allows for a faster rendering process since the algorithm uses lower input samples and then upscales the input to the target resolution (NVIDIA Corporation, 2018, p. 34).

DLSS features various quality presets that users can choose from. These modes provide different balances between image quality and performance. These modes differ by their pixel upsampling rates, with Performance linked to 4x, Balanced to 3x, and Quality to 2x upsampling (Liu, 2020, p. 20).

Another important component of Nvidia's architecture is the Tensor Cores. These Tensor Cores are used for tensor and matrix operations, which are essential computations for the deep learning model. DLSS uses the power these Tensor Cores to efficiently process and combine information from multiple frames, which allows DLSS to reconstruct high-quality images (NVIDIA Corporation, 2018, p. 4).

The convolutional neural network of Nvidia is trained by supercomputers ahead of time and is then delivered to the consumer's GPU through driver updates. In video game applications the pre-trained model which is part of the driver package works together with the GPU during gameplay. The GPU uses the pre-trained model in combination with the Tensor Cores to perform the neural network's computations in real-time (Watson, 2020, p. 4). Additionally, DLSS is an exclusive feature for Nvidia graphics card. DLSS debuted with the RTX 20 and the version 1.0 in the year 2018. (NVIDIA Corporation, 2022, pp. 9–11).

The latest version of DLSS is version 3.0. This version which is only available for Nvidia RTX 4000 graphics cards which use an all-new Optical Flow Accelerator and AI frame generation that boosts the frame rates up to 2 times over the previous DLSS 2.0 version while also maintaining or exceeding native image quality. In addition, compared to traditional graphics rendering, DLSS 3 is up to 4 times faster while also offering low system latency (NVIDIA Corporation, 2022, p. 5).

2.2.2 AMD FidelityFX Super Resolution (FSR)

FSR is a high-quality solution which is designed to produce high resolution frames from lower resolution inputs similar to Nvidia's DLSS. In addition, FSR is an open-source solution, and the source code can be accessed on GitHub (Riley & Arcila, 2022):

FSR does not use artificial intelligence, but the technology uses a spatial upscaler. This upscaler works by taking the current anti-aliased frame at render resolution and upscales it to the display resolution without relying on other data such as frame history or motion vectors (AMD, 2021b).

FSR is an algorithm that detects and recreates high-resolution edges from the source image. According to AMD those high-resolution edges are an utterly critical element which is indeed required for turning the current frame into a super resolution image (AMD, 2021b).

According to AMD, FSR is composed of two main passes:

- EASU (Edge-Adaptive Spatial Upsampling) an upscaling pass which also performs edge reconstruction. In this pass the input frame is analyzed and the main part of the algorithm detects gradient reversal from a set of input pixels (AMD, 2021b).
- RCAS (Robust Contrast-Adaptive Sharpening) is a sharpening pass which extracts details in the upscaled image (AMD, 2021b).

FSR features a variety of different quality modes including ultra quality, quality, balanced and performance. These modes offer different balances between image quality and performance. The difference between the modes is due to the increase of the scale factor between input resolution and output resolution. For example, an output resolution of 1920 by 1080 pixels means that in performance mode an input resolution of 960 by 540 pixels is used while in ultra quality mode an input resolution of 1477 by 831 pixels is used (AMD, 2021a, p. 10).

FSR is not bound to a specific graphics card vendor like Nvidia or AMD but can run on a variety of different GPUs. The technology also supports older GPU architectures (AMD, 2021a, p. 28).

2.2.3 Intel Xe Super Sampling (XeSS)

Intel XeSS is another upscaling technology which boots performance and allows upscaling from 1080p up to 4K. The technology tries to preserve the original image quality. This is even true when the upscaling factor is 2 (Kawiak et al., 2022, p. 3). Similar to DLSS and FSR, XeSS offers different quality modes which differ in performance and image quality, including ultra performance, performance, balanced, quality and ultra quality. The scale factors range hereby from 1.3 when using ultra quality to 2.3 when using ultra performance (Kawiak et al., 2022, p. 24).

XeSS is a deep learning based super sampling technique and replaces the TAA stage in the render stage. Furthermore, XeSS is a cross-platform solution and does not require a per-title training. The super sampling technique uses data the current and the previous frames and also increases the amount of information for the upscales. The technology also treats anti-aliasing and upscaling as a single problem in the process. In addition, XeSS preserver the quality at higher scaling factors when compared to spatial upscaling. FSR uses spatial upscaling for instance (Kawiak et al., 2022, p. 6).

It is worth noting that state-of-the-art super sampling techniques also come with their own issues. For example, ghosting, blurring and even flickering are problems that can occur (Kawiak et al., 2022, p. 6).

The software development kit (SDK) is also open source to developers. The Unreal Engine, which is used by many video games, includes a XeSS plugin for developers (Kawiak et al., 2022, p. 11).

The key difference between DLSS and XeSS is that XeSS supports graphics cards from multiple vendors, while DLSS relies on the usage of Nvidia graphics cards.

According to Sydney Butler (Butler, 2023b) DLSS also provides a better image quality compared to XeSS or even FSR and is present in more games and also offers a unique frame generation option which was introduced in version 3.0 of DLSS.

3 Research Design

The following sections describes the research design employed in the master thesis. The sections thoroughly explain the benchmark process in order to comprehensively evaluate Nvidia DLSS, AMD FSR, and Intel XeSS against native (standard) rendering. This approach aims to assess performance, image quality and gaming scenario suitability across diverse gaming environments.

3.1 Methodology

In order to answer the research questions an extensive benchmark test will be conducted. A benchmark is generally defined as the measure of the quality of something by comparing it with something else.

In this master thesis the benchmark process is serving as a methodical approach in order to test the performance, image quality and gaming scenario suitability of Nvidia DLSS, AMD FSR and Intel XeSS in comparison to native rendering.

The benchmark test will also be conducted by using two different graphics cards of two different generations. In particular, the Nvidia RTX 3060 from the Ampera microarchitecture which supports DLSS 2.0 and the Nvidia RTX 4060 from the Ada Lovelace microarchitecture which supports DLSS 3.0 (NVIDIA Corporation, 2023a, p. 9).The benchmark test is conducted on Nvidia graphics cards since Nvidia supports all three upscaling technologies.

Moreover, the selection of the Nvidia RTX 3060 and the newly introduced Nvidia RTX 4060 for this study finds its validation in the November 2023 Steam Hardware Survey. The RTX 3060 is used by 4.89 percent of all steam users. The RTX 4060 is already used by over 2 percent and growing (Valve, 2023). This justifies the selection of these two graphics cards. The complete experimental setup is mentioned in section 3.5.

The benchmark metrics include the average frames per second (FPS), the 1 % low fps, 0.1 % low fps, frametimes, GPU utilization and GPU energy consumption. These terms are defined in section 3.2.

The game selection spans across various different genres which offers a diverse set of gaming environments for the benchmark tests. The selection includes games such as Cyberpunk 2077, an award-winning action role playing video game developed by CD Project or Call of Duty Modern Warfare III, a first-person shooter game developed by Sledgehammer Games which offers intense and fast-paced combat scenarios. These games, alongside others in the selection support all three upscaling technologies. The complete selection can be found in section 3.3.

The data collection and data processing methodology are explained in section 3.6 and 3.7 respectively. This also involves the usage of various Python to facilitate the large-scale data collection, required for the comprehensive evaluation.

The sections 3.8 to 3.10 explain the process behind the evolution regarding performance, image quality and gaming scenario suitability.

3.2 Benchmark Metrics

Average FPS:

Frames per second is a highly important metric for PC gamers. In the gaming world, FPS and Hertz are often interchanged and misused. Hz is defined as cycles per second and is associated with the monitor. In contrast, FPS is the rate at which the system completes frames. FPS is typically rolling average since frame times are not consistent from frame to frame. In addition, the higher the FPS the smoother animations are. Furthermore, the author mentions an example that shows 240 FPS delivers a way smoother animation compared to 60 FPS (Tamsai, 2019).

Minimum FPS:

Minimum FPS refers to the lowest frame rate recorded during gameplay or a benchmark test. This metric is crucial as it highlights performance dips and can be a strong indicator of the game's stability under load. A low minimum FPS can result in noticeable stuttering and interruptions, which can significantly impact the player's experience, especially in scenarios that demand high processing power from the system. For example, in complex scenes with many elements or high-resolution textures, a low Minimum FPS can lead to a sluggish response, which is critical in fast-paced games where timing and quick reactions are essential.

Maximum FPS:

Maximum FPS represents the highest frame rate achieved during a gaming or benchmarking session. While this metric might suggest the peak performance capability of the gaming setup, it is less indicative of the overall smoothness of gameplay compared to average or 1% low FPS metrics. High maximum FPS rates are often reached during less demanding scenes within a game, such as looking at the sky or being in a less detailed environment. As such, while a high maximum FPS can be impressive, it does not always translate to a consistent or reliably smooth gaming experience.

1% Low FPS and 0.1% Low FPS:

The term "1 % low FPS" is the lowest frame rates one can experience 1 % of the time during gameplay. Similarly, the term "0.1% low FPS" refers to the lowest FPS one can experience 0.1 % of the time (Butler, 2023a).

These metrics give a more accurate understanding of the gaming experience than just using the average FPS since these metrics give insight into the worst-case scenarios. In addition, they help to identify instances of stuttering or lagging which can significantly impact gameplay even though the average FPS are fine (Butler, 2023a).

Frametimes:

Frametime is defined by the time which passes between a frame that is rendered and the next frame. It also be defined in more simpler terms as how long a frame is on a screen. For example, if a frametime of a given time duration is 16 milliseconds that means that the last frame has been on the screen the exact period of time (Digital Masta, 2022).

Consistent frametimes have a significant impact on gameplay. The more consistent the frametimes are the less lags and stuttering occurs (Digital Masta, 2022).

In addition, the optimal frametime for 30 FPS is about 33.3 milliseconds and for 60 FPS it is about 16.7 milliseconds (Digital Masta, 2022).

GPU Utilization:

"GPU utilization refers to the percentage of time that a GPU is actively performing computations or processing data" (Ferro et al., 2017, p. 5). Therefore, GPU utilization measures how much of the GPU's processing capacity is used at a given time. High utilization indicates that the GPU is being fully utilized and is operating at its maximum capacity (Ferro et al., 2017, p. 5). This case can often be seen in AAA video games where the utilization is often sitting at 99 percent.

GPU Energy Consumption:

The GPU power consumption is the amount of electrical power consumed by the GPU while performing a specific task such as running a video game or an application. The energy consumption is typically measured in watts (W) and can be affected by various factors such as the workload, temperature and also the utilization of the GPU (Ferro et al., 2017, pp. 2–11).

Energy consumption can be measured through various means. For example, direct measurements such as internal sensor which collect samples to estimate the power consumption during a time interval. There are various third-party tools available to measure power consumption (Ferro et al., 2017, pp. 2–11).

Performance per Watt (PPW)

Performance per Watt is a crucial metric in computing, representing the efficiency of a system or component by measuring its performance relative to the power it consumes. It signifies how effectively a device utilizes energy resources to achieve desired outcomes. Determined by dividing achieved performance by power consumption, a higher Performance per Watt indicates greater energy efficiency, while a lower value suggests less efficient energy utilization (Supermicro, 2024).

This metric is essential for assessing the balance between performance and power consumption, helping users make informed decisions when selecting hardware or optimizing system configurations.

Performance per Watt is calculated by the taking the Average Frames per Second and divide it by the Energy Consumption which is measured in Watts. A value of 1 means that, on average, the system can render 1 frame per second for each watt of energy consumed. Higher values indicate greater efficiency, as more frames are rendered per watt. Conversely, lower values suggest less efficient performance, meaning the system requires more energy to produce each frame.

3.3 Benchmark Setup

The experimental setup looks as following:

Benchmark PC Configuration:

- Central Processing Unit (CPU): Intel Core I5-10600K (Intel, 2020):
  - Total Cores: 6, Total Threads: 12
  - Processor Base Frequency: 4.10 GHz (No overlocking applied)
  - Max. Turbo Frequency: 4.80 GHz
  - All-Core Turbo Frequency: 4.50 GHz
  - TDP: 125 W (indicates the maximum heat output the CPU cooling system needs to handle)
  - Lithography: 14 nm
- CPU Cooler: be quiet! Dark Rock Slim (180W TDP)
- Mainboard: Asus Prime Z490-A
- Random Access Memory (RAM): Corsair Vengeance LPX 32GB (2x16GB) DDR4 3200MHz
- Graphics Card 1: ZOTAC GAMING GeForce RTX 3060 Twin Edge OC (Architecture: Ampere)
- Graphics Card 2: Gigabyte NVIDIA GeForce RTX 4060 AERO OC (Architecture: Ada Lovelace)
- Storage: SanDisk Ultra 3D 1 TB SSD (Internal SATA SSD)
- Power Supply: be quiet! Pure Power 11 600 watts

Monitor (Baker, 2020)**:**

- Model: Samsung Odyssey Gaming Monitor C27G73TQSR
- Resolution: 2,560 x 1,440 pixels (supports lower resolutions)
- Panel Type: VA-Panel
- Supported Technologies: AMD FreeSync Premium Pro, G-Sync, HDR
- Reaction time: 1 millisecond

Input Device:

To conduct the benchmark tests the Xbox Elite Wireless Controller Series 2 is used for input and control during gaming sessions. The controller is connected via a USB-C cable.

Detailed Specifications of GeForce RTX 3060 and RTX 4060 Graphics Cards

Specification	**ZOTAC GAMING GeForce RTX 3060 Twin Edge OC** (ZOTAC, 2022)	**Nvidia GeForce RTX4060 AERO OC 8G** (Gigabyte, 2023)
Graphics Processing	GeForce RTX 3060	GeForce RTX 4060
Architecture	Ada Lovelace	Ampere
Core Clock	1807 MHz	2550 MHz
CUDA Cores	3584	3072
Memory Clock	15 Gbps	17 Gbps
Memory Size	12 GB	8 GB
Memory Type	GDDR6	GDDR6
Memory Bus	192-bit	128-bit
Card Bus	PCI-E 4.0	PCI-E 4.0
Digital Max Resolution	7680x4320	7680x4320
Multi-Display Support	4	4
PCB Form	ATX	ATX
DirectX	12 Ultimate	12 Ultimate
OpenGL	4.6	4.6
Recommended PSU	600W	450W
TDP	170W	115W

Table 1: Specifications of the Graphics Cards (GPUs)

Graphics Drivers:

The same NVIDIA graphics drivers are installed for both the Nvidia Geforce RTX 4060 and Nvidia Geforce RTX 3060 in order to ensure consistent and comparable performance across the two graphics cards during the benchmarking process.

Resizable BAR Support:

Resizable BAR support has been enabled for both graphics cards in the motherboard UEFI settings. This feature allows the GPU to access the system's entire memory which can potentially improve performance in certain scenarios (Archer, 2021).

Hyperthreading Configuration:

To maintain consistency and maximize the potential performance of both graphics cards, Hyperthreading has been enabled on the Intel i5 10600K processor within the system's BIOS/UEFI settings. This technology allows each physical core to function as two logical cores, potentially boosting performance in multi-threaded workloads and reducing CPU bottlenecks that could limit GPU performance (Intel, 2020).

Operating System:

- Edition: Microsoft Windows 11 Home, 64-bit
- Version: 23H2
- OS Build: 22631
- Experience: Windows Feature Experience Pack 1000.22688.1000.

3.4 Video Game Selection

In order to perform the benchmark tests the following video games have been selected:

- Call of Duty Modern Warfare III (2023)
- Diablo IV
- Assassin's Creed Mirage
- Cyberpunk 2077 Ultimate Edition
- The Witcher 3: Wild Hunt

All of these games support Nvidia DLSS, AMD FSR and Intel XeSS. The game selection covers a broad field of different genres including a first-person shooter, adventure games, an action role-playing dungeon crawling game as well as adventure games (PCGamingWiki, 2023). These games are also new, relevant and are played by millions worldwide.

The selection of video games for the benchmark tests is based on a comprehensive evaluation beyond factors just as popularity. Each game was chosen deliberately to include diverse genres, ensuring a comprehensive representation of different gaming experiences and demands.

Game Title	Genre	Justification
Call of Duty Modern Warfare III (2023)	First-Person Shooter	Chosen for its fast-paced gaming that requires high framerate and steady frametimes to avoid stuttering, which can affect a responsive gaming experience. High frame rates are crucial for Esports players to maintain accuracy and competitiveness.
Diablo IV	Action Role-Playing	Selected for its action role-playing and dungeon crawling aspects, which involve complex scenes with numerous characters and effects. This genre tests the system's ability to handle intensive graphical loads and complex animations while maintaining smooth gameplay.
Assassin's Creed Mirage	Action-Adventure	Included for its expansive open-world environment and detailed graphics. This game demands robust GPU performance to render large, detailed environments and character models smoothly, providing a comprehensive test of the system's capabilities in handling

		high-quality textures and complex lighting effects.
Cyberpunk 2077 Ultimate Edition	Action Role-Playing	Chosen for its demanding graphics and complex world, which push the limits of modern hardware. The game's detailed cityscapes, dynamic lighting, and high-quality textures make it an excellent test case for benchmarking both graphical fidelity and performance under heavy load.
The Witcher 3: Wild Hunt	Action Role-Playing / Open World	Selected for its richly detailed open world and complex character interactions. The game's high demand for rendering extensive environments and intricate character details makes it ideal for assessing the performance of different graphical settings and upscaling technologies, ensuring smooth gameplay in expansive, visually rich worlds.

3.5 Resolution, Graphics Quality Settings, and Upscaling Settings

Resolution Testing:

- **1,920 x 1,080 pixels (1080p):** Testing at the standard Full HD provides insights into the performance on mainstream display configurations. This standard is used by over 60 percent of all Steam users. Steam is a very popular online video game platform (Valve, 2023).
- **2,560 x 1,440 pixels (1440p):** Since higher resolutions than Full HD are getting more common in the gaming world and the required monitors are also getting more affordable, this resolution is perfect for additional testing. According to the Steam Hardware Survey, 15 percent of all Steam users already use this resolution for their gaming experience (Valve, 2023).

Graphics Quality Settings:

Each game is tested across a spectrum of quality settings.

The following settings are tested: High Settings, Medium Settings, and Low Settings.

This range of settings aims to evaluate how the upscaling technologies adapt to different graphical settings and optimize performance across different levels of detail and graphical complexity.

Settings for the Upscaling Technologies:

The upscaling technologies, namely Nvidia DLSS, AMD FSR and Intel XeSS, are tested across multiple preset modes. These preset modes are Performance, Balanced and Quality.

Additionally, investigating how GPU energy consumption varies across different resolutions, graphics quality settings and upscaling settings can yield valuable insight into the efficiency and resource utilization of these technologies.

3.6 Data Collection

During the benchmarking process the following data is collected:

- Average Frames per Second (FPS)
- Minimum FPS
- Maximum FPS
- 1 % Low FPS
- 0.1 % Low FPS
- Frametimes
- GPU Energy Consumption
- GPU Utilization
- Screenshots

The data is collected using various kinds of different third-party software:

- **MSI Afterburner:** This tool is used to collect the average FPS, Minium FPS, Maximum FPS, the 1% low FPS and the 0.1% low FPS. In addition, the screenshots saved as bmp files are also collected with this tool
- **HWInfo**: This tool is used to collect sensory data. This includes GPU utilization, temperatures, core clocks, memory clock speed and GPU power consumption.
- **RTSS (River Tuner Statistics Server):** This tool is to display the data from MSI Afterburner and HW Info as an in-game overlay in order to see the data at first glance.
- **CapFrameX**: This tool is used to capture the frametimes.
- **Nvidia Frameview.** This tool is used in order to validate the data collected by MSI Afterburner.

3.7 Data Processing

The collected data from MSI Afterburner, HW Info, and CapFrameX is processed and cleaned using Python scripts. Python is used as the main programming language here since Python supports a vast number of different libraries. For example, CapFrameX outputs the logs as a JSON file, which is perfect for Python's inbuilt JSON library in order to further process the data.

The data cleaning process involves the following steps:

1. **Data Aggregation:** The scripts are designed to read and aggregate the data from the benchmark output files. This includes extracting essential benchmark information such as game name, date, and specific frame rate metrics (average, minimum, maximum, 1% low, and 0.1% low). This data is then structured into a Pandas Data Frame to maintain a unified format for further analysis.

2. **Quality Check and Cleansing:**
   After aggregating the data, the scripts structure it into an Excel file, which serves as a repository for further analysis and graphical visualization. These Excel files are created dynamically with detailed naming conventions that include the game name, timestamp, and specific benchmark settings (technology, upscaling setting, graphics setting, resolution, and graphics card). This ensures each benchmark's data is easily identifiable and accessible for comparative analysis.

   For instance, a performance benchmark file generated by MSI Afterburner might be named benchmark_Cyberpunk2077_03_20_17_04_Native_None_High_1080p_4060.xlsx, clearly indicating the game, date, time, rendering technology, upscaling setting, graphics quality, resolution, and GPU used. An energy consumption file generated by HW-Info on the other hand would start with Merged_Energy_Consumption and then follow the same naming convention to clearly indicate that it contains consolidated data from the two benchmark runs specifically focused on power usage and GPU utilization.

In addition to generating Excel files, the scripts also include functionalities to manage data integrity, such as verifying the presence of necessary data points and removing the original benchmark file post-processing to prevent duplication in analyses. The script enhances the robustness of the data handling process by ensuring that all data is correctly formatted and saved in an organized manner.

The Python scripts and their detailed documentation are available at my GitHub repository for review and use: https://github.com/Chriz97/Master_Thesis_Uni_Li. This repository includes all scripts used in the thesis, facilitating transparency and reproducibility of the methods employed in data processing.

In addition to individual benchmark data files, the Master_Thesis_Cockpit_Excel file is used for this thesis, which contains a comprehensive compilation of performance data and energy consumption metrics across all tested games and graphics cards. This central repository ensures that results from every benchmark test are easily accessible and comparable. The Master_Thesis_Cockpit_Excel file is also available in the GitHub repository.

As shown in the screenshot below, results for Call of Duty: Modern Warfare III (2023) using the RTX 4060 provide detailed information such as Average FPS, Minimum FPS, Maximum FPS, Energy Consumption, and GPU utilization at both 1080p and 1440p resolutions under low settings. The file uses a structured format that includes essential validation and statistical information like "Perf. Validation OK?" and "T-Test Not Significant?" to maintain the accuracy and credibility of the benchmark results.

The procedure of the validation runs, and the methodology of the t-test is explained in section 3.8.

Call of Duty Modern Warfare III (2023) (RTX 4060)

RTX 4060

1080p

Low Settings

	Average FPS	Minimum FPS	Maximum FPS	1% low	0.1% low	Watt	Perf. per Watt	GPU Utilzation	Perf. Validation OK?	T-Test Not Significant?
Native	199.9	128.7	226.55	156.45	133.65	106.31	**1.88**	97.60	Yes	Yes
DLSS Performance	245.2	132.65	250.35	185.55	169.85	93.60	**2.62**	86.74	Yes	Yes
DLSS PF %	22.66%	3.07%	10.51%	18.60%	27.09%	-11.96%	39.32%	-11.12%		
DLSS Balanced	242.2	125.4	250.25	178.55	162.35	96.86	**2.50**	91.38	Yes	Yes
DLSS Balanced %	21.16%	-2.56%	10.46%	14.13%	21.47%	-8.89%	32.98%	-6.36%		
DLSS Quality	234.9	125.2	249.95	170.9	148.7	99.62	**2.36**	95.58	Yes	Yes
DLSS Quality %	17.51%	-2.72%	10.33%	9.24%	11.26%	-6.29%	25.40%	-2.07%		

Figure 1: Master_Thesis_Cockpit_Excel

3.8 Data Validation

To ensure the accuracy and reliability of the collected data, the validation process is carried out in several steps using multiple tools. The process begins with a second data collection run using MSI Afterburner. This run focuses primarily on verifying the performance metrics such as Average FPS, Minimum FPS, Maximum FPS, 1% Low FPS, and 0.1% Low FPS that were initially recorded. It is crucial to repeat this step to confirm consistency across multiple recordings.

After the repeat performance metrics are collected with MSI Afterburner, another validation run is conducted using Nvidia Frameview. This tool is particularly useful for its precision in validating GPU-related data, such as performance measurements like the average FPS or the 0.1 % Low FPS and offers a detailed comparison against the initial data captured through MSI Afterburner.

It is important to note that while MSI Afterburner provides real-time data display and can log performance data, it does not log energy consumption directly. Instead, the initial run with HWInfo is utilized to monitor energy consumption, leveraging its ability to log detailed sensory data.

Following the collection of validation data, both sets of performance data—the initial benchmarks and the validation runs of Nvidia Frameview and MSI Afterburner—are compiled into the same Excel file. This consolidation allows for a direct comparison of the initial and validation datasets. The differences in performance metrics are calculated as percentages, with an acceptable threshold established to ensure minor variations, indicating stability and reliability of the data.

Further statistical analysis is conducted to validate the significance of the differences observed. A t-test is performed to statistically assess whether the observed differences between the initial and validation runs are significant or merely due to random variations. The confidence interval is set at 95%, providing a valid criterion for assessing the reliability of the data.

This step is crucial for confirming the validity of the benchmarking process and ensuring that the conclusions drawn from the data are both robust and defendable.

3.9 Performance Evaluation

The performance evaluation metrics including average FPS, Minimum FPS, Maximum FPS, 1 % low FPS, 0.1% low FPS and frametimes serve as the starting point for the evaluation. The Frametimes represent the duration between frames and provide insight into the consistency of gameplay experiences.

This master thesis will also feature various graphs which showcase the performance differences between natively rendered graphics and those enhanced through upscaling technologies in video games. Plus, the thesis also includes graphs which show the consistency of frametimes.

ANOVA Test:

Moreover, to conduct a comprehensive analysis an ANOVA test will be conducted. The ANOVA test enables the comparison of means across multiple samples which allows for a statistical assessment of performance differences among the three upscaling technologies. The ANOVA tests helps to determine if there are statistically significant different among the technologies. It provides insight whether the observed differences in metrics like FPS or frametimes are due to the technology itself or are random occurrences (Newbold et al., 2023, p. 652).

In the ANOVA test the H0, the Null Hypothesis, is that there are no significant differences in performance among the various technologies tested. The H1, the Alternative Hypothesis, is that there is a significant difference in performance among the upscaling technologies (Newbold et al., 2023, p. 652).

The test will specifically focus on the differences within DLSS, FSR, and XeSS to provide a direct comparison between these upscaling methods. This approach will help identify if any of these technologies significantly outperform the others.

The test will be conducted using a 95 % (alpha = 0.05) confidence interval since it is the general rule for researchers (Fein et al., 2022). In addition, the test will be performed using Python libraries such as SciPy which offers functionalities for statistical analysis (Pypi, 2023).

3.10 Image Quality Evaluation

The image quality assessment involves comparing natively rendered screenshots captured from the gameplay with upscaled images.

This approach aims to evaluate sharpness, contrast, brightness, clarity, artifacts, and overall fidelity between the natively rendered image and the upscaled images using Nvidia DLSS, Intel XeSS and AMD FSR.

Screenshots are taken in the BMP format because it is a lossless image format that provides high fidelity and detail without any compression artifacts. This choice ensures that the images used for assessment are as close to the original quality as possible, allowing for a more accurate comparison of the native and upscaled images. Since BMP files are uncompressed, they retain all the original visual information, which is crucial when evaluating subtle differences in sharpness, contrast, and overall image quality that may be affected by upscaling algorithms. This is essential for a fair assessment of the upscaling technologies' performance (Adobe, 2024).

In this thesis, the comparison between natively rendered images and upscaled images is conducted using the Balanced mode at a resolution of 1440p with High settings, thereby ensuring a comprehensive evaluation under demanding conditions.

3.11 Gaming Scenario Suitability

The evaluation of upscaling technologies for gaming scenario suitability features various parameters. The first one is robustness which indicates a stable system without crashes or freezes during gameplay. This will be monitored throughout the benchmark tests and every crash or freeze will be logged and analyzed. Another important aspect is efficient hardware. Therefore, GPU power consumption and GPU

utilization are part of the benchmark test. The question hereby is to answer to which extent upscaling technologies influence the power consumption of GPUs when compared to native rendering.

What is more, performance metrics such as the average FPS and frametimes are also an important factor to consider when evaluation upscaling technologies. A high average framerate and consistent frametimes are key for a consistent and smooth gaming experience.

3.12 Recommendation

After conducting the benchmark tests where the performance, image quality and gaming scenario suitability is tested for all three upscaling technologies, the next step is to draw conclusion and give recommendations. One important aspect is of course to assess which technology performs decently, meaning increasing the frames per second significantly and keeping steady frametimes. Plus, the image quality should also remain at a high level.

The outcomes of the benchmarks are also mapped to sustainability, meaning that the upscaling technology which effectively lowers the energy consumption of the graphics card the best contributes significantly to sustainable gaming practices. Lower energy consumption not only reduces the carbon footprint but also aligns with global efforts to mitigate climate change.

By optimizing performance and reducing the power required to achieve high-quality graphics, these technologies offer a dual benefit: enhanced gaming experiences and a positive environmental impact. This is particularly important as the gaming industry grows, emphasizing the need for energy-efficient solutions that do not compromise on performance or visual fidelity.

3.13 3D Mark Results

In the evaluation of state-of-the-art upscaling technologies—specifically Nvidia DLSS, AMD FSR, and Intel XeSS—3DMark stands out as an essential benchmarking tool. Developed by UL Benchmarks, 3DMark is designed to test the graphical processing capabilities of computers through a series of graphically intensive tests that mimic demanding gaming scenarios. This benchmarking suite is crucial for the objectives of this thesis for several reasons:

Standardization of Performance Metrics: 3DMark provides a standardized approach to performance evaluation across different systems. It generates a 3DMark score, a composite metric that reflects the overall and graphical performance capabilities of a system. This standardization is vital for ensuring that the performance comparisons of upscaling technologies are objective and comparable across different hardware configurations.

Relevance to Real-World Gaming Scenarios: The suite's ability to simulate real-world gaming environments that are intensive on both GPUs and CPUs makes it particularly relevant for this study. These environments are the target scenarios for the upscaling technologies being evaluated, making 3DMark's tests directly applicable to the thesis's research questions.

Comprehensive Performance Insights: By pushing the hardware to its limits, 3DMark not only assesses basic performance metrics such as frame rates but also evaluates system latency, stability under load, and graphical output quality. This comprehensive testing is essential for analyzing how upscaling technologies perform under stress conditions that mimic high-end gaming.

Objective Comparative Analysis: 3DMark scores facilitate an unbiased comparison of Nvidia DLSS, AMD FSR, and Intel XeSS across various system configurations. This capability is crucial for this thesis, which aims to provide a comparative assessment of these technologies, highlighting their benefits and limitations in a controlled, standardized context.

Empirical Validation of Technology Claims: The benchmarking results from 3DMark are also used to validate the claims made by technology developers regarding performance enhancements and efficiency improvements. This empirical evidence supports the thesis's analysis, providing a solid foundation for recommending the most effective upscaling technology based on quantifiable data.

The ensuing figures illustrate the outcomes of the system performance evaluation conducted via the SPEED Way benchmark test, integral to the 3D-Mark suite. The system configurations utilized for this assessment are delineated in Chapter 3.3, "Benchmark Setup," ensuring consistency and replicability of the test conditions as detailed within the section of this dissertation.

The 3D-Mark suite was downloaded, installed, and executed using the Steam client to ensure standardized conditions for performance testing.

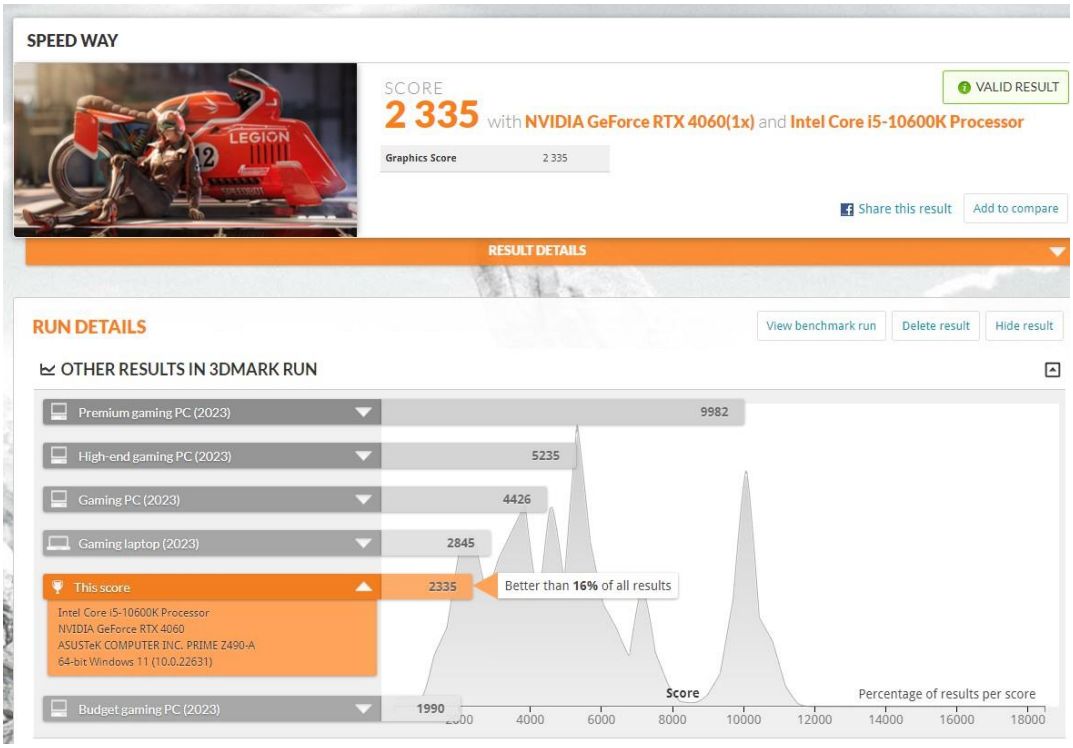


Figure 2: 3D-Mark Result RTX 4060

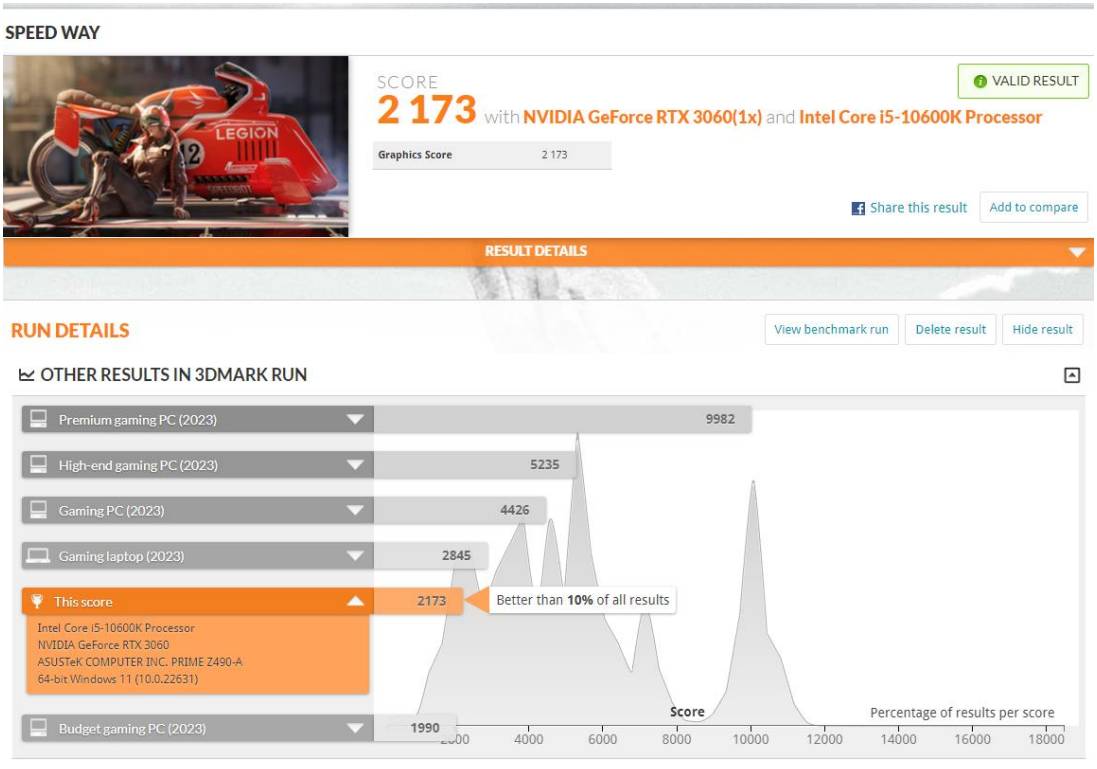


Figure 3: 3D-Mark Result RTX 3060

The results of the SPEED Way benchmark which is part of the 3D-Mark suite indicates that the system performance is on par with system which also use the Intel Core i5-10600K as the main processor and the Nvidia GeForce RTX 3060 or the Nvidia GeForce RTX 4060 respectively.

The test using the Nvidia GeForce RTX 4060 hereby is better than 16 percent of all results while the system using the Nvidia GeForce RTX 3060 is better than 10 percent of all results.

The system with the Nvidia GeForce RTX 4060 hereby achieves a score of 2335 points while the system with the Nvidia GeForce RTX 3060 achieves a score of 2173 points. This indicates a difference of 162 points or 7.46 percent.

To sum up, the benchmark results from the SPEED Way test in the 3D-Mark suite demonstrate that the system configurations using the Intel Core i5-10600K processor paired with Nvidia GeForce RTX 3060 and RTX 4060 graphics cards deliver competitive performance.

The RTX 4060 system outperforms 16% of all benchmarked results, while the RTX 3060 system surpasses 10%, confirming both setups are capable of reliable performance relative to a broad spectrum of systems assessed globally.

Specifically, the RTX 4060's score of 2335 points exceed the RTX 3060's score of 2173 by 162 points, or 7.46 percent. These results validate the suitability of both systems for evaluating upscaling technologies, in particular Nvidia DLSS, AMD FSR and Intel XeSS, under controlled conditions.

This balance of performance and accessibility makes the systems ideal candidates for detailed analysis in the context of gaming and graphics performance testing.

3.14 Benchmark Scenario Selection

The selection of benchmark scenarios aims to reflect the varying requirements and challenges posed by each game genre. Each scene has been chosen to push the graphics rendering capabilities, providing insights into the performance, image quality, and energy efficiency of the upscaling technologies.

Explicit descriptions of the benchmark scenes for all tested games can be found in Chapter 4.

Call of Duty: Modern Warfare III:

Scene Selection: The multiplayer map "Afghan," chosen for benchmarking due to its diverse terrain and high-intensity combat.

Requirement: For a fast-paced game like Call of Duty, achieving high FPS and reducing frame drops are crucial. Responsive controls and consistent frame rates are necessary to maintain accuracy in competitive multiplayer scenarios. Upscaling technologies are evaluated to see how they can maximize FPS while ensuring frame consistency.

Diablo IV:

Scene Selection: The city of Kyvoshad is a hub area filled with architectural detail and dynamic weather effects.

Requirement: In Diablo IV, a high and consistent frame rate is important due to the fast-paced dungeon-crawling combat. However, since it's an action RPG, maintaining a balance between image quality and FPS is crucial. Upscaling technologies need to ensure clear visuals amidst the effects-laden environments while enhancing frame consistency.

Assassin's Creed Mirage:

Scene Selection: The Round City is a bustling market with intricate alleyways and detailed architecture.

Requirement: In a game like Assassin's Creed Mirage, maintaining fluid motion through detailed environments is crucial, as players traverse the city using parkour. Upscaling technologies should ensure smooth transitions without compromising image quality, providing a seamless visual experience during exploration.

Cyberpunk 2077 Ultimate Edition:

Scene Selection: The Red Light Alley in Japantown provides a neon-lit, vibrant benchmark scenario.

Requirement: In Cyberpunk 2077, the futuristic urban environment requires both high FPS and detailed visuals. The game demands upscaling technologies that can maintain detailed neon lighting and complex architecture while increasing frame rates to support fast-paced vehicular or on-foot action.

The Witcher 3: Wild Hunt:

Scene Selection: The Duskwood area in the Toussaint region is rich in natural foliage and architecture.

Requirement: The Witcher 3 is a slow-paced RPG that prioritizes visuals over FPS. Here, upscaling technologies should emphasize image quality, maintaining high fidelity for natural landscapes while ensuring smooth gameplay in large, open environments.

4 Benchmark Tests

In this chapter, comprehensive benchmark tests are conducted to assess the performance, gaming scenario suitability, and energy consumption of contemporary upscaling technologies, specifically Nvidia DLSS, AMD FSR, and Intel XeSS, compared to Native rendering. The analysis encompasses a selection of popular and graphically demanding video games, including Call of Duty: Modern Warfare III (2023), Diablo IV, Assassin's Creed Mirage, Cyberpunk 2077 Ultimate Edition, and The Witcher 3: Wild Hunt. Each title is methodically tested under various system settings to evaluate the impact of different upscaling technologies on enhancing graphical performance while optimizing power efficiency. These benchmark tests are pivotal in understanding how each technology performs across diverse gaming environments, thereby providing insights into their practical applications in real-world gaming scenarios.

To provide a clear visual representation of the benchmarking process, videos of every benchmark scene for each tested game title have been uploaded to a Google Drive folder. The link to the public Google Drive folder can be found in the "Benchmark Scenes" section of the GitHub repository: https://github.com/Chriz97/Master_Thesis_Uni_Li. The videos clearly showcase how the testing was conducted.

Each section presents the results of the performance analysis for each upscaling technology, including a summary of the average performance achieved. Additionally, an analysis of frame times and image quality is included, both conducted at 1440p resolution using high graphics settings and the Balanced mode of the upscaling technology. Each section concludes with an analysis of energy efficiency and a game-specific conclusion, providing a comprehensive view of the technology's impact on gaming performance. All performance and frame time results can be found on the project's GitHub repository.

4.1 Call of Duty: Modern Warfare III (2023) Benchmark Results

The section is about the performance analysis of Call of Duty: Modern Warfare III (2023) which was developed by Sledgehammers in conjunction with Infinity Ward and Treyarch and published by Activision on November 10,2023. It is the latest entry of the highly acclaimed first-person shooter franchise Call of Duty (Activision, 2023).

4.1.1 Benchmark Scenario Description

The benchmark test takes place on the large-scale multiplayer map called "Afghan," known for its diverse terrain and extensive visual details that challenge graphic rendering capabilities. This map was selected due to its complexity and the variety of graphical elements it presents, ranging from vast open landscapes to densely packed urban structures, which provide a rigorous test environment for assessing GPU performance across different rendering technologies.

4.1.2 Nvidia DLSS Performance Analysis

In this section, the performance of Nvidia's DLSS technology in Call of Duty Modern Warfare III is analyzed on the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. The analysis begins with an evaluation of the technology across different graphics settings (Low, Medium, and High) and modes (Performance, Balanced and Quality). Following this evaluation, a summary of the average DLSS performance improvements is provided to give a comprehensive overview of how DLSS enhances the overall gaming experience.

4.1.2.1 Low Graphics Settings

Nvidia GeForce RTX 4060

At low graphics settings, the Nvidia GeForce RTX 4060 demonstrates significant performance gains when DLSS is enabled.

At 1080p resolution, DLSS increases the frame rate by up to 23 percent in DLSS Performance mode, raising the average frame rate from 199.9 frames per second in native rendering to 245.2 frames per second.

At 1440p resolution, the RTX 4060 shows even greater enhancements, with frame rates increasing from 124.00 frames per second in native rendering to 194.50 frames per second in DLSS Performance mode, an increase of around 56.85 percent. In DLSS Quality mode, the frame rate improves to 164.45 frames per second, and in DLSS Balanced mode, it reaches 178.90 frames per second.

Additionally, the critical 0.1% low FPS values are significantly improved at both resolutions, reducing frame drops and enhancing the overall smoothness of gameplay.

Nvidia GeForce RTX 3060

The previous generation model RTX 3060 also offers considerable performance improvements at low graphics settings when DLSS is enabled.

At the 1080 resolution, DLSS manages to increase the frame rate by up to 34 percent in DLSS performance mode. This result is quite interesting since the RTX 4060 only manages to increase the framerate up to 23 percent. The RTX 3060 hereby manages to output 154 frames per second in native rendering and up to 208 frames per second in DLSS performance. The results are hereby lower compared to the RTX 4060 which is to be expected due to generational improvements and the switch from DLSS 2 to DLSS 3.

At a 1440p resolution, the performance increase is even greater, like the RTX 4060. Framerates are increased from 25 percent in DLSS Quality mode to up to almost 50 percent in DLSS Performance mode. The framerate ranges from 115.75 frames per second in native rendering to 145 frames per second in DLSS Quality mode, 153.00 frames per second in DLSS Balanced mode, and 170 frames per second in DLSS Performance mode.

Additionally, it is remarkable that the very important 0.1% low FPS values are significantly improved at even the 1440p resolution by up to 60 percent in DLSS Performance mode, greatly reducing frame drops and enhancing the overall gameplay experience.

4.1.2.2 Medium Graphics Settings

Nvidia GeForce RTX 4060

Using the Nvidia GeForce RTX 4060 at medium graphics settings, DLSS continues to deliver considerable improvements in gaming performance.

At the 1080p resolution, the performance boost with DLSS ranges from a 24 percent increase in DLSS Quality mode to a 30 percent increase in DLSS Performance mode. The Balanced mode provides a 30.97 percent increase. The framerate improves from 179.55 frames per second in native rendering to 234.45 frames per second in DLSS Performance mode, 235.15 frames per second in Balanced mode, and 222.4 frames per second in Quality mode. Notably, the 1% low FPS and 0.1% low FPS also see substantial improvements. For instance, DLSS Performance mode boosts the crucial 0.1% low FPS by significant margins.

At 1440p, the performance increase is even higher, ranging from about 32.78 percent in DLSS Quality mode to 54.18 percent in DLSS Performance mode, with the Balanced mode showing an increase of 42.8 percent. The framerate improves from 124.30 frames per second in native rendering to 191.65 frames per second in DLSS Performance mode, 177.50 frames per second in Balanced mode, and 165.05 frames per second in Quality mode. The improvements in 1% low and 0.1% low FPS are also significant, ensuring a smoother visual experience even under graphically intensive scenarios.

Nvidia GeForce RTX 3060

The Nvidia GeForce RTX 3060 also shows notable performance improvements at medium settings when utilizing DLSS.

At 1080p, DLSS pushes the framerate from 151.45 frames per second up to 209.2 frames per second in Performance mode, marking an increase of up to 38.13 percent. The Balanced mode increases the framerate to 197.45 frames per second, a gain of 30.37 percent, and the Quality mode increases it to 184.35 frames per second, a gain of 21.72 percent.

At 1440p, DLSS enhances framerates from 116.65 frames per second to as much as 167.20 frames per second in Performance mode, an increase of 43.33 percent. The Balanced mode increases the framerate to 159.95 frames per second, a gain of 37.12 percent, and the Quality mode increases it to 144.70 frames per second, a gain of 24.05 percent. Additionally, the 0.1% low FPS are significantly enhanced, showcasing the robustness of DLSS in maintaining performance across varied graphical demands.

4.1.2.3 High Graphics Settings:

Nvidia GeForce RTX 4060

At high graphics settings, the RTX 4060 with DLSS enabled showcases significant improvements in Call of Duty Modern Warfare III.

At 1080p, DLSS boosts the average framerate from 177.85 to 238.8 frames per second in Performance mode, an increase of 34.27 percent. The Balanced mode increases the framerate to 233.05 frames per second, a gain of 31.04 percent, and the Quality mode increases it to 216.5 frames per second, a gain of 21.73 percent. The 1% low and 0.1% low FPS metrics also show notable gains across all modes, which are essential for a consistently smooth gaming experience during complex scenes.

At 1440p, the gains are even more substantial. DLSS Performance mode increases framerates from 111.95 to 176.15 frames per second, a remarkable 57.35 percent improvement. The Balanced mode

boosts the framerate to 164.95 frames per second, a gain of 47.34 percent, and the Quality mode increases it to 147.5 frames per second, a gain of 31.76 percent. These results underscore the capability of DLSS to optimize visual quality and performance seamlessly, with significant improvements in the 1% low and 0.1% low FPS metrics for smoother gameplay.

Nvidia GeForce RTX 3060

At the 1080p resolution, enabling DLSS results in a framerate increase from 151.45 to 205.4 frames per second in Performance mode, demonstrating a gain of 35.62 percent. The Balanced mode increases the framerate to 197.05 frames per second, a gain of 30.11 percent, and the Quality mode increases it to 186.3 frames per second, a gain of 23.01 percent. The improvements in 1% low and 0.1% low FPS across all modes are particularly notable, greatly reducing the frequency of frame drops and enhancing the overall gameplay experience.

At 1440p, the improvement continues, with DLSS boosting framerates from 108.45 to 158.70 frames per second in Performance mode, an increase of 46.33 percent. The Balanced mode increases the framerate to 150.00 frames per second, a gain of 38.31 percent, and the Quality mode increases it to 136.20 frames per second, a gain of 25.59 percent. The improvement in the 0.1% low FPS is particularly notable, greatly reducing the frequency of frame drops and enhancing the overall gameplay experience across all DLSS modes.

4.1.2.4 Summary of Nvidia DLSS Performance Improvements

This section evaluates the average performance improvements provided by Nvidia's DLSS technology across all modes (Performance, Balanced, Quality) and graphics settings (low, medium, high) for both the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. By aggregating the data from different settings and modes, this analysis aims to provide a comprehensive overview of how DLSS enhances the overall gaming experience in Call of Duty Modern Warfare III.

Average Performance Improvements Analysis: Nvidia GeForce RTX 4060

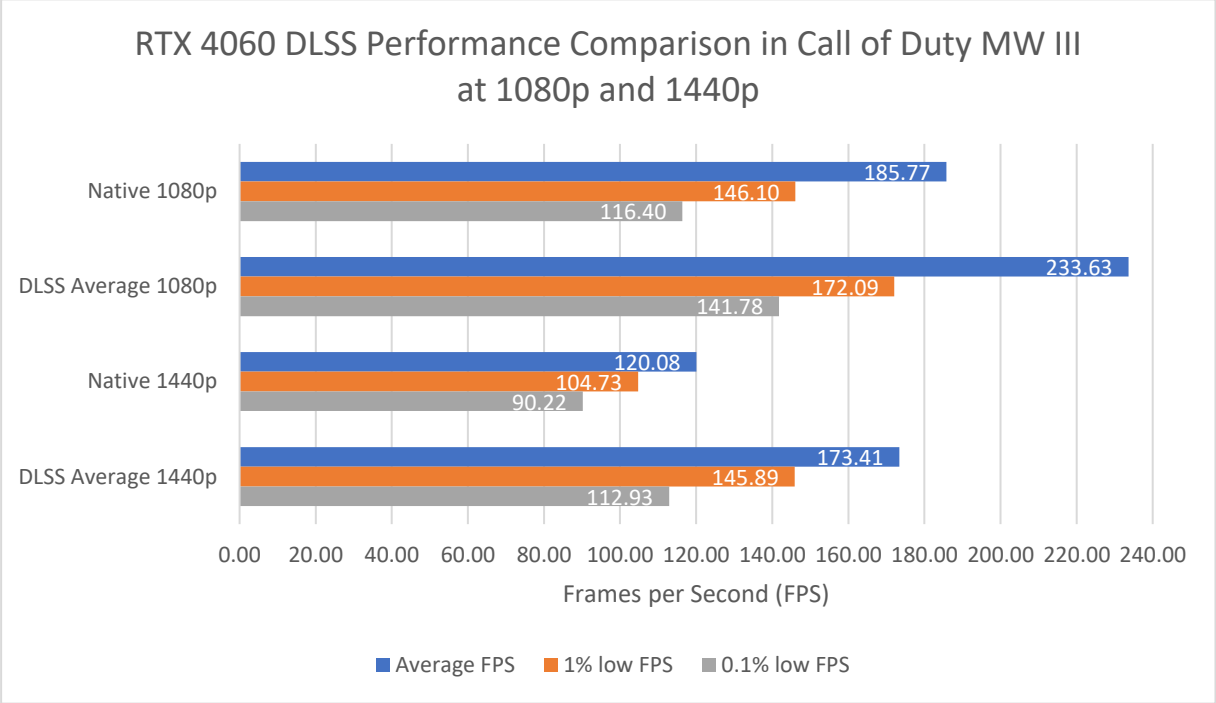


Figure 4: Nvidia DLSS Performance on RTX 4060 in Call of Duty MW III at 1080p and 1440p.

With the RTX 4060, DLSS provides a substantial increase in performance across both tested resolutions. At 1080p, the native rendering condition exhibits an average FPS of 185.77, with 1% low and 0.1% low FPS figures at 146.10 and 116.40, respectively.

When DLSS is applied, there is a remarkable jump to an average FPS of almost 234, accompanied by increases in 1% low FPS to 172.09 and 0.1% low FPS to 141.78. This represents an increase of approximately 25.74% in average FPS, which suggests a substantial enhancement in rendering efficiency and a smoother gameplay experience.

Moving to 1440p resolution, the benefits of DLSS are even more substantial. Native performance outputs an average FPS of 120.08, with the 1% and 0.1% lows at 104.73 and 90.22, respectively. Activation of DLSS technology raises the average FPS to 173.41, improving the 1% low to 145.89 and the 0.1% low to 112.93. This equates to a performance uplift of 44.42% in average FPS, underscoring DLSS's effectiveness at higher resolutions where rendering demands are more intensive.

Furthermore, the graph clearly demonstrates that the 1 % low FPS and 0.1 % FPS are improved significantly in both resolutions. This is very essential for a game like Call of Duty, where rapid response times and seamless gameplay are critical to the gaming experience. Consistently high frame rates are crucial for maintaining the fluidity of action, ensuring that players can react instantly to in-game events without the distraction of stuttering or lag.

Average Performance Improvements Analysis: Nvidia GeForce RTX 3060

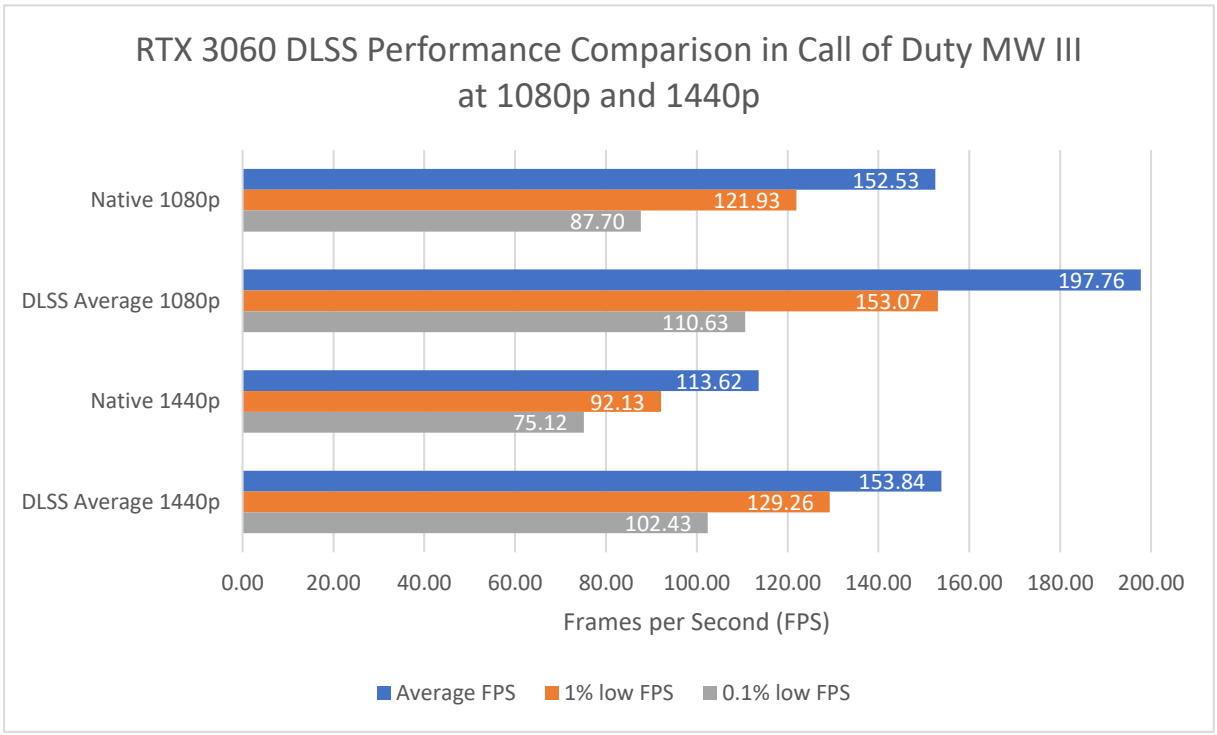


Figure 5: Nvidia DLSS Performance on RTX 3060 in Call of Duty MW III at 1080p and 1440p.

The performance uplift with DLSS on the RTX 3060 showcases similar trends, though the starting points differ due to the inherent differences in hardware capability between the two graphics cards.

At 1080p, the average FPS increases from 152.53 in native rendering to 197.76 with DLSS, marking a growth of 29.66%. In the 1440p scenario, where the demands on the GPU are greater, DLSS helps in lifting the average FPS from a native 92.13 to 129.26, a significant boost of 40.30%.

Similar to the results of the RTX 4060, the RTX 3060 in conjunction with DLSS also provides a significant uplift of the 1 % Low FPS and 0.1 % Low FPS values at both resolution which is highly important for a fast-paced ego-shooter like Call of Duty where every frame drop can decide between living and dying.

4.1.3 AMD FSR Comprehensive Performance Analysis

In this section, the performance of AMD's FSR technology in Call of Duty Modern Warfare III is analyzed on the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. The analysis begins with an evaluation of the technology across different graphics settings (low, medium, high) and modes (Performance, Balanced, Quality). Following this evaluation, a summary of the average FSR performance improvements is provided to give a comprehensive overview of how FSR enhances the overall gaming experience.

4.1.3.1 Low Graphics Settings:

Nvidia GeForce RTX 4060

Using the Nvidia GeForce RTX 4060 at low graphics settings, AMD's FSR technology provides significant performance enhancements.

At 1080p, FSR increases the framerate by 14.81 percent in Quality mode, 22.06 percent in Balanced mode, and 21.41 percent in Performance mode. The framerate improves from 199.9 frames per second in native rendering to 229.5 frames per second in FSR Quality mode, 244 frames per second in Balanced mode, and 242.7 frames per second in Performance mode. This quite unusual that the Performance does not output the most frames but could indicate some sort of bottleneck like a CPU bottleneck where the GPU is hindered by the CPU to performance at the maximum capacity. The 1% low FPS and 0.1% low FPS metrics also see substantial improvements, ensuring smoother gameplay during demanding scenes.

At 1440p, the performance gains are even more pronounced. FSR increases the framerate by 26.09 percent in Quality mode, 38.47 percent in Balanced mode, and 54.07 percent in Performance mode. The framerate thereby ranges from 124 frames per second in native rendering to 156.35 frames per second in FSR Quality mode, 171.70 frames per second in Balanced mode, and 191.05 frames per second in Performance mode. The enhancements in 1% low FPS and 0.1% low FPS further contribute to a smoother and more stable gaming experience.

Nvidia GeForce RTX 3060

The previous generation Nvidia GeForce RTX 3060 also benefits significantly from AMD's FSR technology at low graphics settings.

At 1080p, FSR boosts the framerate by 15.64 percent in Quality mode, 26.24 percent in Balanced mode, and 35.88 percent in Performance mode. The framerate increases from 154.7 frames per second in native rendering to 178.9 frames per second in FSR Quality mode, 195.3 frames per second in Balanced mode, and 210.2 frames per second in Performance mode. Unlike the results of the RTX 4060 here does not appear to be bottleneck neither by the GPU or CPU. The improvements in 1% low FPS and 0.1% low FPS are particularly notable, enhancing the overall gaming experience. The increases range up to more than 60 percent in Performance mode which further increases the gameplay experience.

At 1440p, the performance increase with FSR is even greater. FSR increases the framerate by 17.75 percent in Quality mode, 30.84 percent in Balanced mode, and 43.37 percent in Performance mode. The framerate thereby ranges from 115.75 frames per second in native rendering to 136.30 frames per second in FSR Quality mode, 151.45 frames per second in Balanced mode, and 165.95 frames per second in Performance mode. Additionally, the enhancements in 1% low FPS and 0.1% low FPS metrics ensure a more stable and fluid gaming experience.

4.1.3.2 Medium Graphics Settings

Nvidia GeForce RTX 4060

At medium graphics settings, the Nvidia GeForce RTX 4060 continues to show significant performance improvements with AMD's FSR technology. At 1080p, FSR increases the framerate by 20.38 percent in Quality mode, 28.01 percent in Balanced mode, and 33.39 percent in Performance mode. The framerate improves from 179.55 frames per second in native rendering to 216.15 frames per second in FSR Quality mode, 229.85 frames per second in Balanced mode, and 239.5 frames per second in Performance mode. The improvements in 1% low FPS and 0.1% low FPS are also substantial, contributing to smoother gameplay.

At 1440p, the performance gains are even more substantial. FSR increases the framerate by 25.34 percent in Quality mode, 34.55 percent in Balanced mode, and 51.77 percent in Performance mode. The framerate ranges from 124.30 frames per second in native rendering to 155.80 frames per second in FSR Quality mode, 167.25 frames per second in Balanced mode, and 188.65 frames per second in Performance mode. The enhancements in 1% low FPS and 0.1% low FPS metrics are significant, ensuring a smoother visual experience even during graphically intensive scenarios.

Nvidia GeForce RTX 3060

The Nvidia GeForce RTX 3060 also shows notable performance improvements at medium graphics settings with AMD's FSR technology.

At 1080p, FSR increases the framerate by 17.70 percent in Quality mode, 26.54 percent in Balanced mode, and 38.92 percent in Performance mode. The framerate improves from 151.45 frames per second in native rendering to 178.25 frames per second in FSR Quality mode, 191.65 frames per second in Balanced mode, and 210.4 frames per second in Performance mode. The improvements in 1% low FPS and 0.1% low FPS are significant, enhancing the overall gaming experience.

At 1440p, FSR increases the framerate by 16.80 percent in Quality mode, 26.36 percent in Balanced mode, and 38.62 percent in Performance mode. The framerate thereby ranges from 116.65 frames per second in native rendering to 136.25 frames per second in FSR Quality mode, 147.40 frames per second in Balanced mode, and 161.70 frames per second in Performance mode. The enhancements in 1% low FPS and 0.1% low FPS metrics further contribute to a smoother and more stable gaming experience.

4.1.3.3 High Graphics Settings

Nvidia GeForce RTX 4060

At high graphics settings, the Nvidia GeForce RTX 4060 continues to benefit significantly from AMD's FSR technology.

At 1080p, FSR increases the framerate by 18.41 percent in Quality mode, 25.67 percent in Balanced mode, and 32.86 percent in Performance mode. The framerate improves from 177.85 frames per second in native rendering to 210.6 frames per second in FSR Quality mode, 223.5 frames per second in Balanced mode, and 236.3 frames per second in Performance mode. The improvements in 1% low FPS and 0.1% low FPS are also significant, contributing to smoother gameplay during demanding scenes.

At 1440p, the performance gains are even more substantial. FSR increases the framerate by 27.60 percent in Quality mode, 39.84 percent in Balanced mode, and 63.47 percent in Performance mode. The framerate ranges from 111.95 frames per second in native rendering to 142.85 frames per second in FSR

Quality mode, 156.55 frames per second in Balanced mode, and 183.00 frames per second in Performance mode. The enhancements in 1% low FPS and 0.1% low FPS metrics are significant, ensuring a smoother visual experience even during graphically intensive scenarios.

Nvidia GeForce RTX 3060

The Nvidia GeForce RTX 3060 also shows notable performance improvements at high graphics settings with AMD's FSR technology. At 1080p, FSR increases the framerate by 19.81 percent in Quality mode, 23.90 percent in Balanced mode, and 34.60 percent in Performance mode. The framerate improves from 151.45 frames per second in native rendering to 181.45 frames per second in FSR Quality mode, 187.65 frames per second in Balanced mode, and 203.85 frames per second in Performance mode. The improvements in 1% low FPS and 0.1% low FPS are significant, enhancing the overall gaming experience.

At 1440p, FSR increases the framerate by 18.76 percent in Quality mode, 29.97 percent in Balanced mode, and 45.32 percent in Performance mode. The framerate thereby ranges from 108.45 frames per second in native rendering to 128.80 frames per second in FSR Quality mode, 140.95 frames per second in Balanced mode, and 157.60 frames per second in Performance mode. The enhancements in 1% low FPS and 0.1% low FPS metrics further contribute to a smoother and more stable gaming experience.

4.1.3.4 Summary of AMD FSR Performance Improvements

This section evaluates the average performance improvements provided by AMD's FSR technology across all modes (Performance, Balanced, Quality) and graphics settings (low, medium, high) for both the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. By aggregating the data from different settings and modes, this analysis aims to provide a comprehensive overview of how FSR enhances the overall gaming experience in Call of Duty Modern Warfare III.

Average Performance Improvements Analysis: Nvidia GeForce RTX 4060

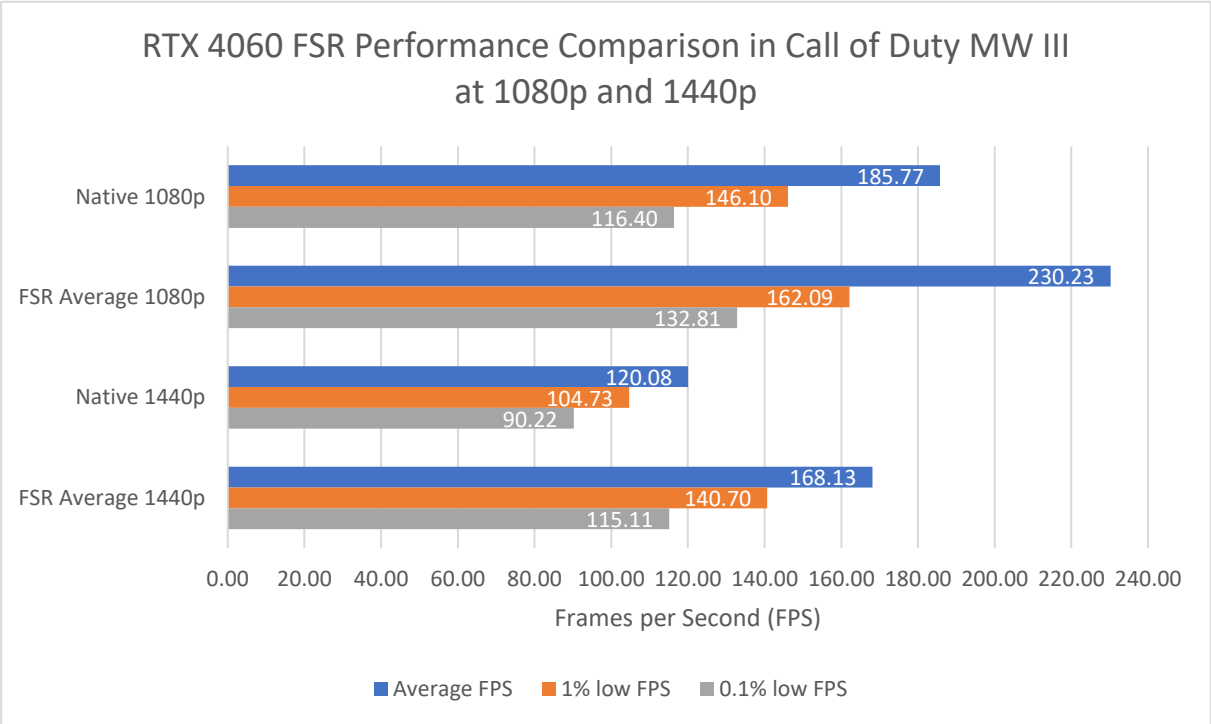


Figure 6: AMD FSR Performance on RTX 4060 in Call of Duty MW III at 1080p and 1440p.

The application of FSR on the RTX 4060 shows notable improvements across the board. At 1080p, native rendering achieves an average FPS of 185.77, with 1% low and 0.1% low FPS figures at 146.10

and 116.40, respectively. With FSR activated, the average FPS increases significantly to 230.23, with the 1% low and 0.1% low FPS improving to 162.09 and 132.81. This marks an average FPS increase of approximately 24%, demonstrating FSR's capability to enhance visual performance substantially without compromising gameplay smoothness.

At 1440p, the native performance offers an average FPS of 120.08, with 1% low and 0.1% low at 104.73 and 90.22. FSR enhances the average FPS to 168.13, with 1% low and 0.1% low FPS increasing to 140.70 and 115.11, respectively. This enhancement represents an increase of about 40% in average FPS, highlighting the effectiveness of FSR in maintaining higher frame rates even at higher resolutions, which is crucial for immersive gaming experiences.

Average Performance Improvements Analysis: Nvidia GeForce RTX 3060

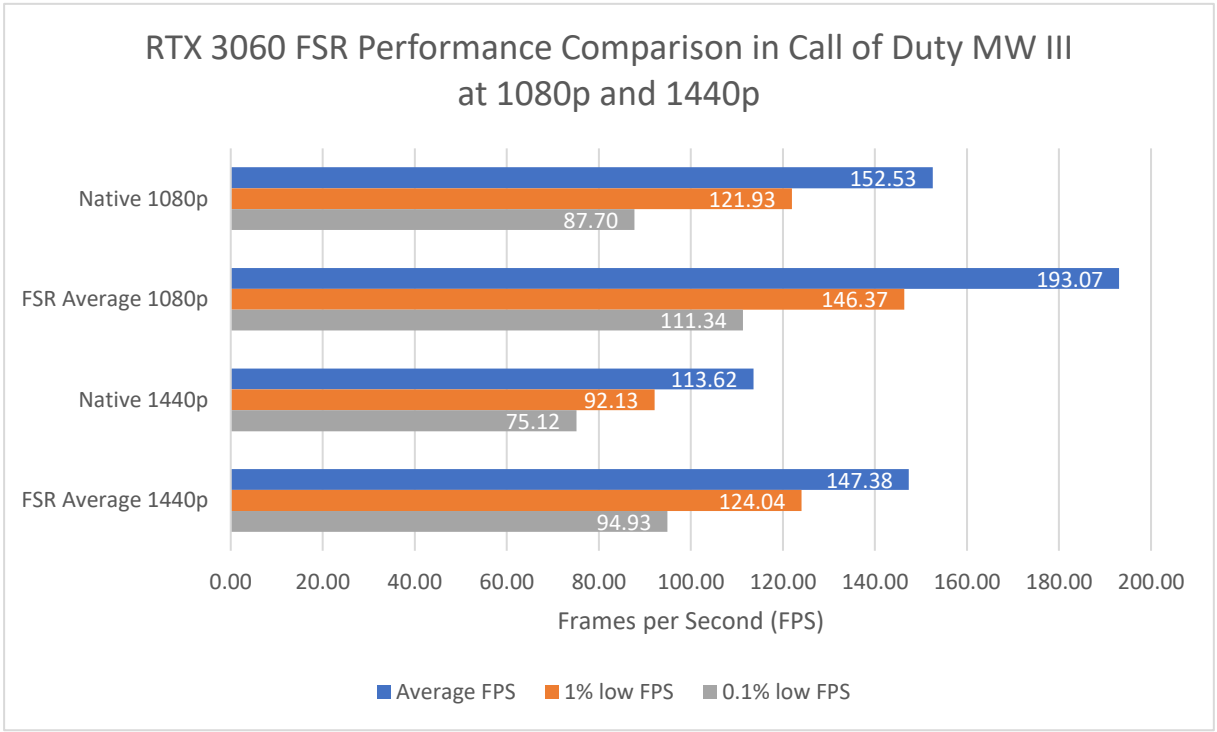


Figure 7: AMD FSR Performance on RTX 3060 in Call of Duty MW III at 1080p and 1440p.

For the RTX 3060, the improvements with FSR are similarly impressive.

At 1080p, the native rendering records an average FPS of 152.53, with 1% low at 121.93 and 0.1% low at 87.70. With FSR enabled, the average FPS jumps to 193.07, with 1% low and 0.1% low improving to 146.37 and 111.34, respectively. This reflects an increase of roughly 27% in average FPS, showcasing FSR's ability to boost performance effectively across different tiers of hardware.

In the 1440p scenario, native rendering shows an average FPS of 113.62, with 1% low and 0.1% low FPS at 92.13 and 75.12. FSR increases the average FPS to 147.38, with 1% low and 0.1% low FPS rising to 124.04 and 94.93. This translates to an increase of about 30% in average FPS, proving FSR's robustness in enhancing graphical output under more demanding resolution settings.

4.1.4 Intel XeSS Performance Analysis

In this section, the performance of Intel's XeSS technology in Call of Duty Modern Warfare III is analyzed on the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. The analysis begins with an evaluation of the technology across different graphics settings (low, medium, high) and modes (Performance, Balanced, Quality). Following this evaluation, a summary of the average XeSS performance improvements is provided to give a comprehensive overview of how XeSS enhances the overall gaming experience.

4.1.4.1 Low Graphics Settings:

Nvidia GeForce RTX 4060

At low graphics settings, the Nvidia GeForce RTX 4060 demonstrates significant performance improvements when XeSS is enabled.

At 1080p resolution, XeSS increases the frame rate by up to 14.21 percent in XeSS Performance mode, raising the average frame rate from 199.9 frames per second in native rendering to 228.3 frames per second. In XeSS Balanced mode, the frame rate reaches 222.85 frames per second, and in XeSS Quality mode, it achieves 214 frames per second. These improvements, while notable, are slightly lower compared to DLSS or FSR discussed in the prior sections.

At 1440p resolution, the RTX 4060 shows more substantial enhancements with XeSS enabled. The frame rate in native rendering is 124.00 frames per second, which increases to 177.70 frames per second in XeSS Performance mode, marking a performance boost of approximately 43.31 percent. In XeSS Balanced mode, the frame rate reaches 159.60 frames per second, and in XeSS Quality mode, it achieves 151.2 frames per second. The improvements in the critical 0.1% low FPS values are also significant, enhancing the overall smoothness of gameplay by reducing frame drops.

Nvidia GeForce RTX 3060

For the Nvidia GeForce RTX 3060, XeSS also provides considerable performance gains at low graphics settings.

At 1080p resolution, XeSS Performance mode increases the frame rate by up to 20.8 percent, with the frame rate rising from around 154 frames per second in native rendering to 186.9 frames per second. In XeSS Balanced mode, the frame rate reaches 175.25 frames per second, and in XeSS Quality mode, it achieves 164.35 frames per second.

At 1440p resolution, the performance increase is even more pronounced for the RTX 3060. XeSS Performance mode raises the frame rate from 115.75 frames per second in native rendering to 144.65 frames per second, an increase of approximately 24.97 percent. In XeSS Balanced mode, the frame rate reaches 133.90 frames per second, and in XeSS Quality mode, it achieves 119.6 frames per second. The 0.1% low FPS values also see a significant boost, reducing frame drops and providing a smoother gaming experience.

4.1.4.2 Medium Graphics Settings

Nvidia GeForce RTX 4060

At medium graphics settings, the Nvidia GeForce RTX 4060 continues to benefit from XeSS.

At 1080p resolution, XeSS Performance mode increases the frame rate from 179.55 frames per second in native rendering to 229.45 frames per second, an increase of approximately 27.79 percent. In XeSS

Balanced mode, the frame rate reaches 209.05 frames per second, and in XeSS Quality mode, it achieves 198.05 frames per second.

At 1440p resolution, the performance gains are significant. XeSS Performance mode increases the frame rate from 124.30 frames per second in native rendering to 165.70 frames per second, a boost of around 33.31 percent. In XeSS Balanced mode, the frame rate is 155 frames per second, and in XeSS Quality mode, it reaches 145 frames per second. The enhancements in the 0.1% low FPS values ensure smoother gameplay by reducing frame drops.

Nvidia GeForce RTX 3060

For the RTX 3060, medium graphics settings with XeSS enabled also show considerable improvements.

At 1080p resolution, XeSS Performance mode raises the frame rate from 151.45 frames per second in native rendering to 188.20 frames per second, an increase of about 24.27 percent. XeSS Balanced mode achieves 170.90 frames per second, and XeSS Quality mode reaches 166.10 frames per second.

At 1440p resolution, XeSS Performance mode increases the frame rate from 116.65 frames per second in native rendering to 144.25 frames per second, an improvement of approximately 23.66 percent. XeSS Balanced mode achieves 134.20 frames per second, and XeSS Quality mode reaches 122.50 frames per second. The 0.1% low FPS values also improve significantly, providing a more stable gaming experience with fewer frame drops.

4.1.4.3 High Graphics Settings

Nvidia GeForce RTX 4060

At high graphics settings, the Nvidia GeForce RTX 4060 benefits greatly from XeSS.

At 1080p resolution, XeSS Performance mode boosts the frame rate from 177.85 frames per second in native rendering to 217.75 frames per second, an increase of about 22.43 percent. XeSS Balanced mode reaches 209.05 frames per second, and XeSS Quality mode achieves 193.35 frames per second.

At 1440p resolution, XeSS Performance mode increases the frame rate from 111.95 frames per second in native rendering to 156.80 frames per second, an improvement of approximately 40.06 percent. XeSS Balanced mode achieves 142.85 frames per second, and XeSS Quality mode reaches 134.80 frames per second. These enhancements in the 0.1% low FPS values contribute to smoother gameplay by minimizing frame drops.

Nvidia GeForce RTX 3060

For the RTX 3060, high graphics settings with XeSS enabled also show notable improvements.

At 1080p resolution, XeSS Performance mode raises the frame rate from 151.45 frames per second in native rendering to 184.10 frames per second, an increase of about 21.56 percent. XeSS Balanced mode achieves 168.20 frames per second, and XeSS Quality mode reaches 161.50 frames per second.

At 1440p resolution, XeSS Performance mode increases the frame rate from 108.45 frames per second in native rendering to 137.50 frames per second, an improvement of approximately 26.79 percent. XeSS Balanced mode achieves 127.25 frames per second, and XeSS Quality mode reaches 118.90 frames per second. The significant improvements in the 0.1% low FPS values help to reduce frame drops, enhancing the overall gaming experience.

4.1.4.4 Summary of Intel XeSS Performance Improvements

This section evaluates the average performance improvements provided by Intel's XeSS technology across all modes (Performance, Balanced, Quality) and graphics settings (low, medium, high) for both the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. By aggregating the data from different settings and modes, this analysis aims to provide a comprehensive overview of how DLSS enhances the overall gaming experience in Call of Duty Modern Warfare III.

Average Performance Improvements Analysis: Nvidia GeForce RTX 4060

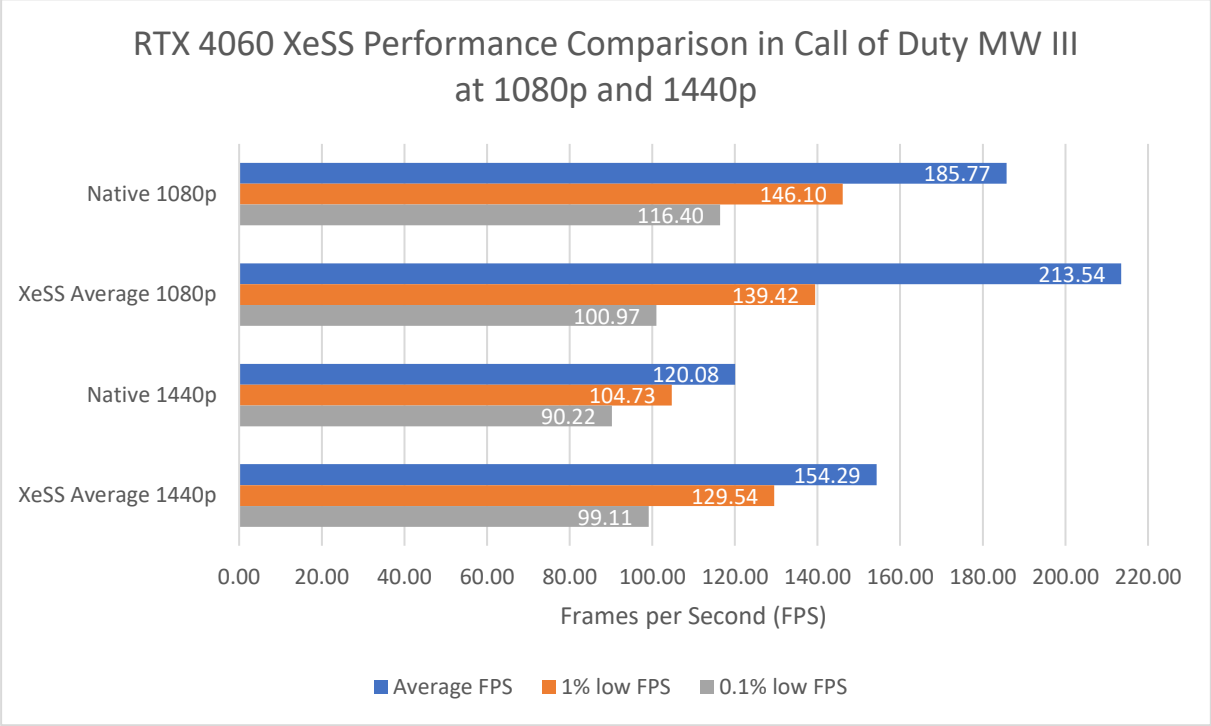


Figure 8: Intel XeSS Performance on RTX 4060 in Call of Duty MW III at 1080p and 1440p.

Using the RTX 4060, the impact of XeSS at 1080p resolution shows a substantial increase in average FPS from a native 185.77 to 213.54 with XeSS enabled, marking an improvement of approximately 15%. The 1% low FPS also rises from 146.10 to 139.42, while the 0.1% low FPS increases from 116.40 to 100.97. This indicates that while average frame rates see a notable boost, there is a nuanced dip in the consistency of frame delivery at the lowest percentiles,

At 1440p, XeSS elevates the average FPS from 120.08 in native rendering to 154.29, representing an increase of nearly 28%. The 1% low and 0.1% low FPS metrics, which stand at 104.73 and 90.22 natively, improve to 129.54 and 99.11 with XeSS, respectively, ensuring a more stable performance during intense gameplay scenarios.

Average Performance Improvements Analysis: Nvidia GeForce RTX 3060

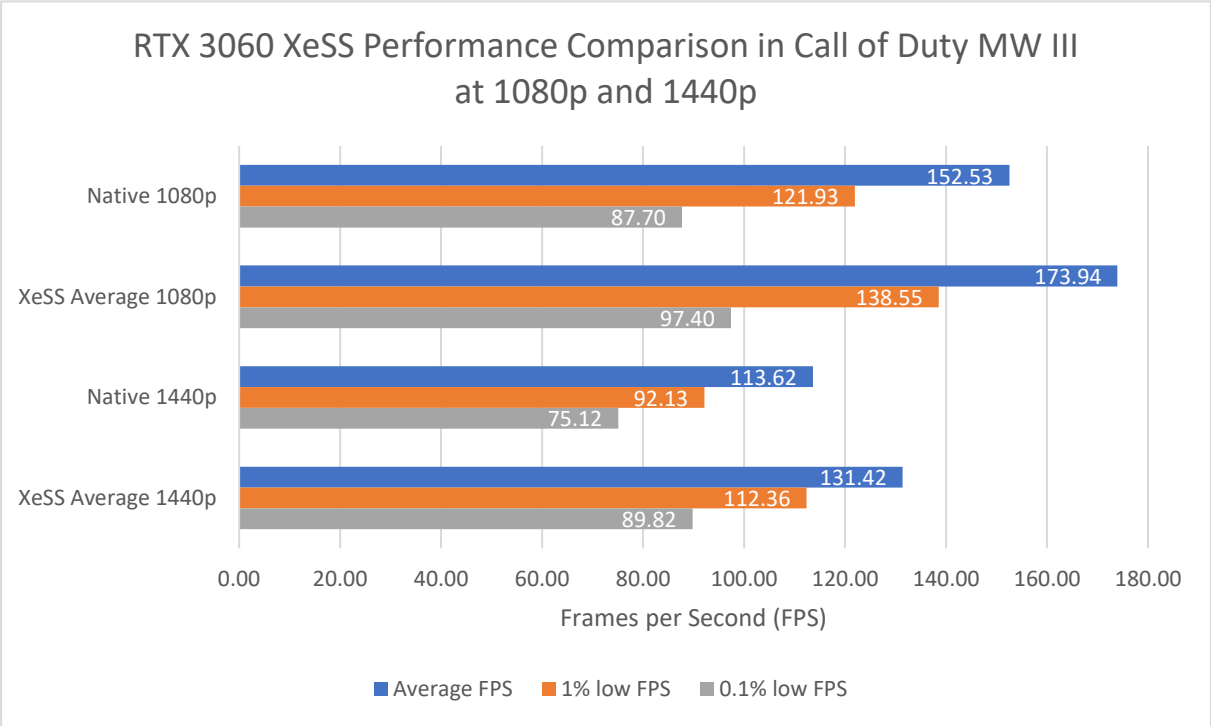


Figure 9: Intel XeSS Performance on RTX 3060 in Call of Duty MW III at 1080p and 1440p.

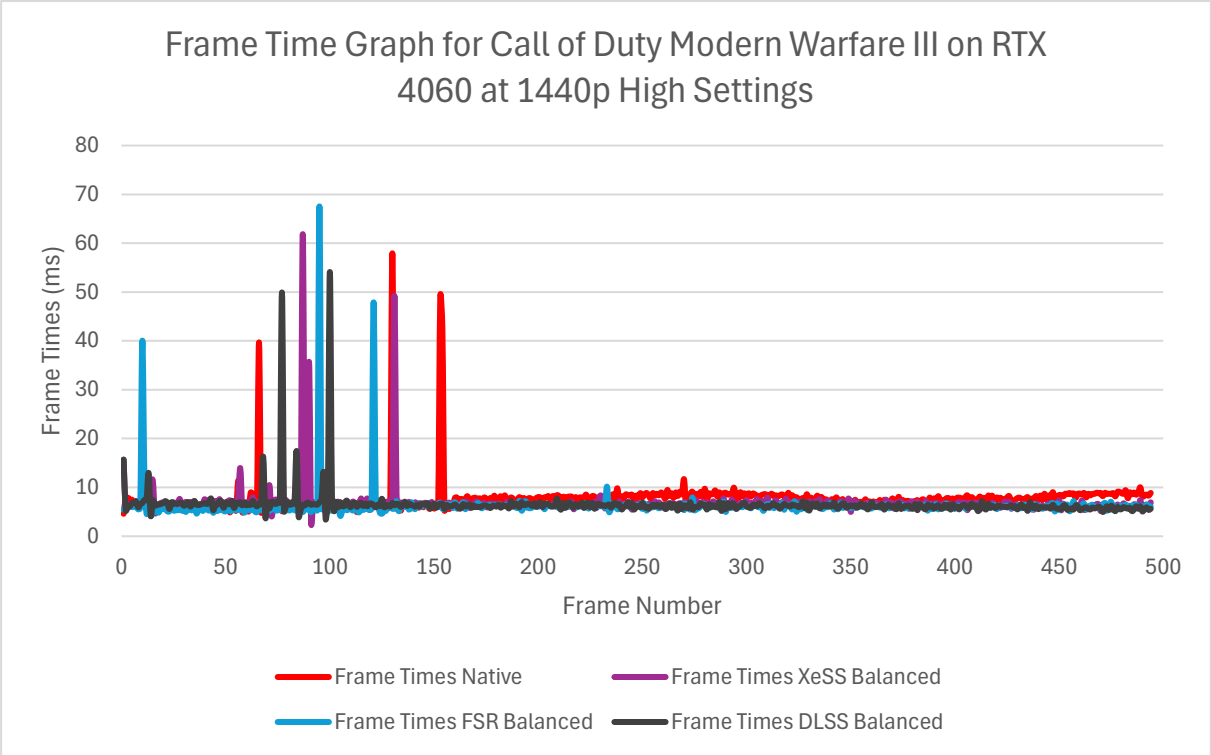
On the RTX 3060, the performance benefits of XeSS are similarly impressive.

At 1080p, XeSS boosts the average FPS from 152.53 to 173.94, an improvement of around 14%. The 1% low FPS increases from 121.93 to 138.55, and the 0.1% low FPS from 87.70 to 97.40, suggesting that XeSS not only enhances overall performance but also contributes to smoother gameplay by reducing frame rate dips.

In the 1440p setting, where the native rendering produces an average FPS of 113,62, XeSS raises this to 131.42, showing a remarkable improvement of approximately 16%. The 1% low and 0.1% low FPS metrics also show an increase.

4.1.5 Frametime Analysis

In this section the frametime consistency of the Nvidia GeForce RTX 4060 running Call of Duty Modern Warfare III is checked at 1440p with the high graphics settings. Hereby the native rendering results are compared to the upscaled results. Frametime, measured in milliseconds, is critical as it impacts the smoothness and responsiveness of gameplay. Lower and more consistent frametimes translate to a smoother gaming experience which especially important in a fast-paced action title like Call of Duty. The analysis will provide insights into which technology offers the most stable gaming experience.



This graph presents frame times measured in milliseconds on the Y-axis, representing the duration it takes to render each frame. The X-axis sequentially numbers the frames from 1 to 500, illustrating the frame rendering order over time. This analysis tracks the stability and consistency of frame delivery, comparing different rendering techniques. The key take aways are as follows:

- **Native Rendering (Red)**: Displays the highest variability in frame times, with several peaks reaching up to 60 ms. These spikes indicate significant stutters, which can disrupt gameplay, especially in fast-paced action sequences.
- **FSR Balanced (Blue)**: Shows a marked some improvement in stability compared to native rendering, with fewer and lower spikes, typically staying below 50 ms but also shows one peak of almost 70 ms. There is some improvement noticeable, but the technology does not really improve frame stability.
- **XeSS Balanced (Purple)**: Similar to FSR, XeSS demonstrates reduced frame time variability. However, there are a few spikes slightly higher than FSR, indicating occasional but noticeable stutters.
- **DLSS Balanced (Black)**: Achieves the best performance among the technologies tested, maintaining the most consistent frame times with minimal spikes. This consistency ensures a superior smooth gaming experience, free from distracting lags and jitters.

Overall, Nvidia's DLSS Balanced mode stands out by providing the most stable frame delivery, crucial for maintaining immersion and competitive performance in high-resolution, high-setting scenarios of "Call of Duty: Modern Warfare III".

4.1.6 Image Quality Assessment

This section assesses the image quality produced by various upscaling technologies at 1440p resolution using the Nvidia GeForce RTX 4060 GPU. The screenshots represent DLSS, FSR, and XeSS, all captured in Balanced mode to ensure high image quality. HDR was not used to maintain consistency across different display setups. All images are saved in BMP format to preserve original quality and provide an uncompressed representation of the visual enhancements each technology brings to the game. The screenshots demonstrate the visual differences and the impact of upscaling technologies on the gaming experience.

Figure 10: Call of Duty Modern Warfare III Native Rendering High Settings 1440p.

Figure 11: Call of Duty Modern Warfare III DLSS Balanced High Settings 1440p.

Figure 12: Call of Duty Modern Warfare III FSR Balanced High Settings 1440p.

Figure 13: Call of Duty Modern Warfare III XeSS Balanced High Settings 1440p.

The natively rendered image looks the best. The image is very sharp, with even distant details clearly visible. The smoke arising from the wrecked airplane is rendered with the highest quality. DLSS and XeSS are on par with each other in terms of quality; the image appears slightly less sharp due to upscaling but still maintains high quality. FSR, however, looks the softest and not as sharp as the others. In typical gameplay scenarios involving significant movement and action, such as sprinting and shooting, these differences in image quality are less perceptible.

4.1.7 Energy Efficiency and Consumption Analysis

The following graphs illustrate the energy consumption (in Watts) and GPU utilization (in percent) of the Nvidia GeForce RTX 3060 and Nvidia GeForce RTX 4060 while running Call of Duty Modern Warfare III (2023). The values for the upscaling technologies represent the average of their three modes: Quality, Balanced, and Performance. Additionally, the performance per watt for each configuration is shown in the accompanying table.

4.1.7.1 Energy Consumption Analysis Nvidia Geforce RTX 4060

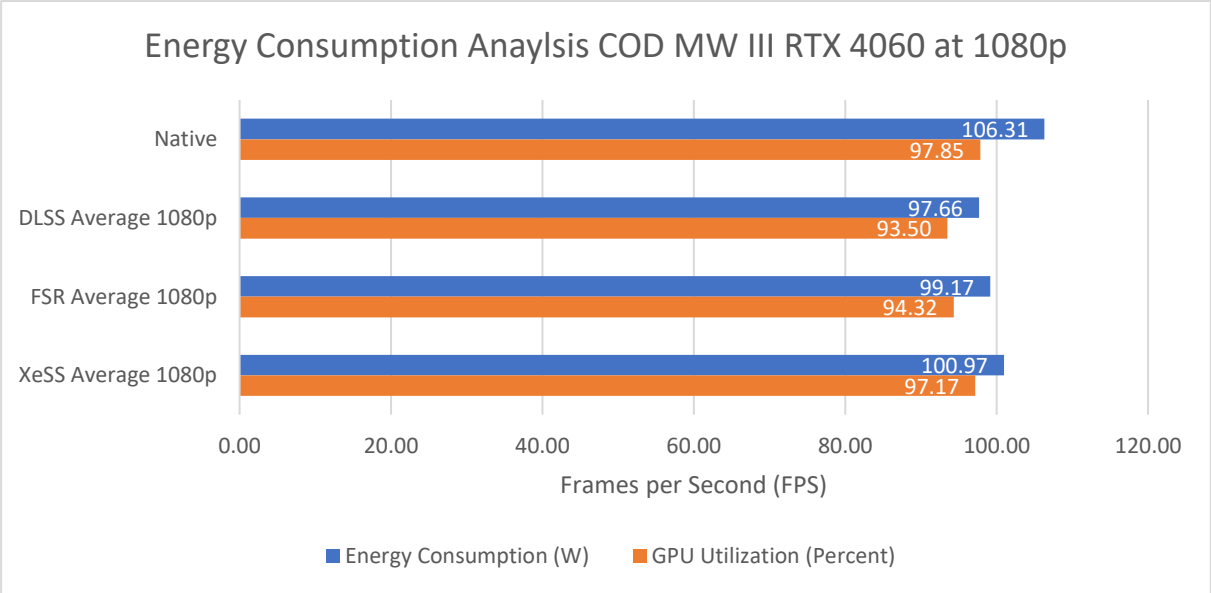


Figure 14: Energy Consumption Analysis COD RTX 4060 1080p.

This graph showcases the RTX 4060 at 1080p across the different upscaling techniques. Native rendering consumes the most power at 106.31 W with a GPU utilization of 97.85%.

DLSS on average at 1080p achieves the lowest energy consumption at 97.66 W, representing an 8% reduction compared to native rendering, with a slight decrease in GPU utilization to 93.50%. FSR on average at 1080p shows a marginal increase in energy consumption to 99.17 W and GPU utilization to 94.32%, which is 7% lower than native rendering. XeSS on average at 1080p maintains a balanced performance with energy consumption at 100.97 W and GPU utilization at 97.17%, representing a 5% reduction in energy consumption compared to native rendering.

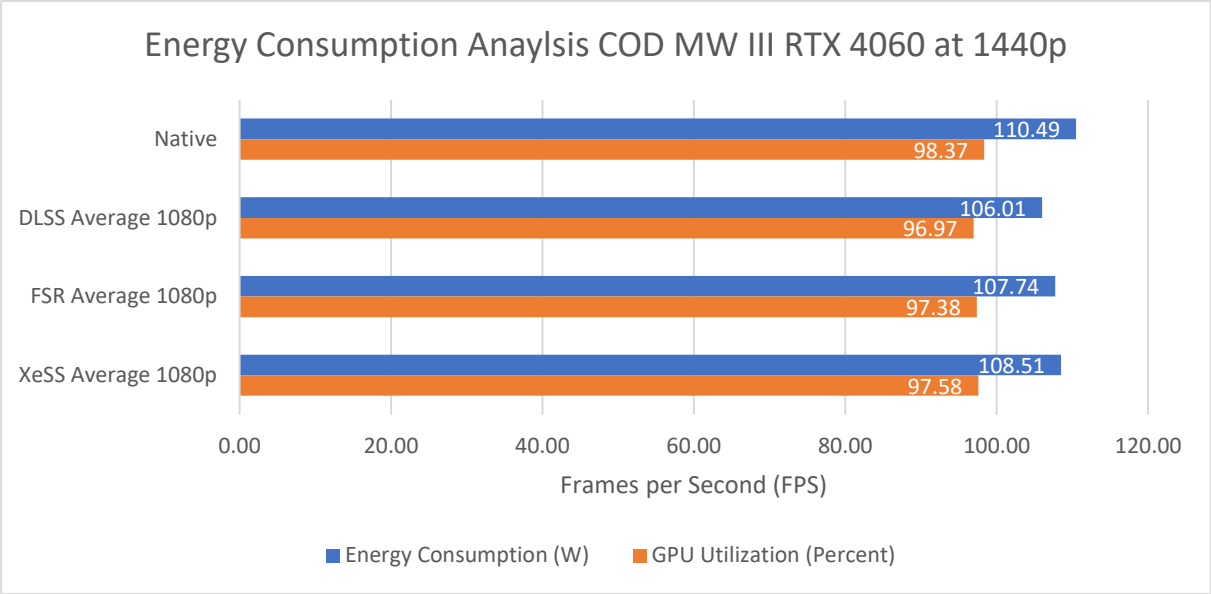


Figure 15: Energy Consumption Analysis COD RTX 4060 1440p.

This graph showcases the RTX 4060 at 1440p across the different upscaling techniques. Native rendering consumes the most power at 110.49 W with a GPU utilization of 98.37%.

Nvidia DLSS achieves the lowest energy consumption at 106.01 W, representing a 4% reduction compared to native rendering, with GPU utilization at 96.97%.

FSR shows a slight decrease in energy consumption to 107.74 W and maintains GPU utilization at 97.38%, which is a 2.49% reduction in energy consumption compared to native rendering

XeSS shows consistent performance with energy consumption at 108.51 W and GPU utilization at 97.58%, representing a 1.79% reduction in energy consumption compared to native rendering but lacks slighlty behind the other technologies.

4.1.7.2 Energy Consumption Analysis Nvidia Geforce RTX 3060

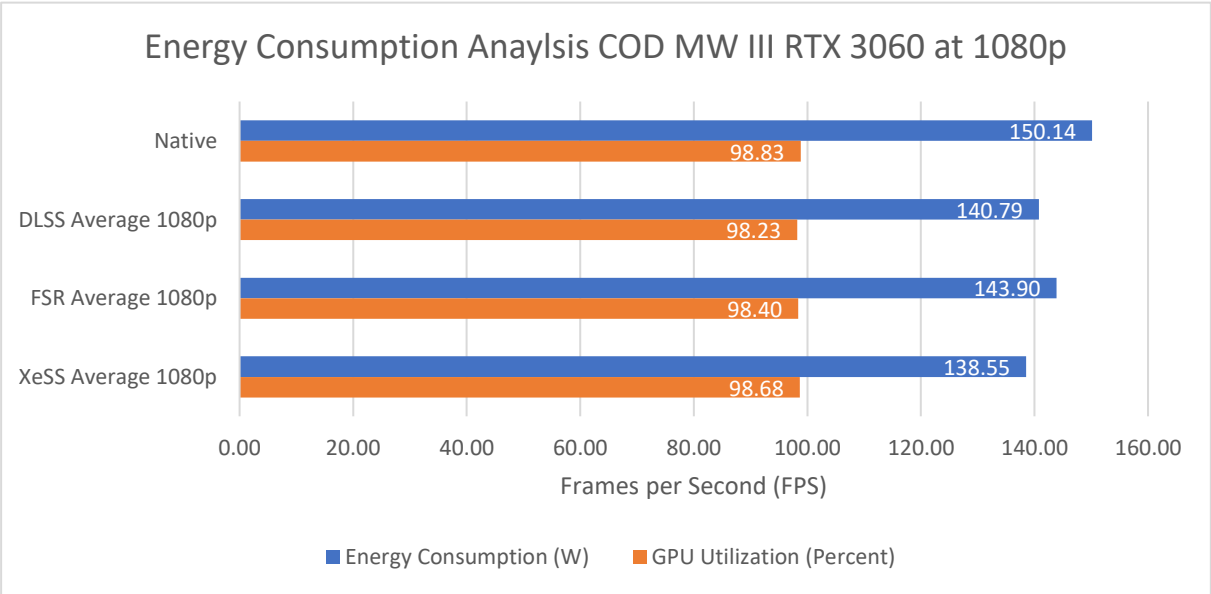


Figure 16: Energy Consumption Analysis COD RTX 3060 1080p.

This graph showcases the RTX 3060 at 1080p across the different upscaling techniques.

Native rendering consumes the most power at 150.14 W with a GPU utilization of 98.83%.

XeSS achieves the lowest energy consumption at 138.55 W, representing a 7% reduction compared to native rendering, with GPU utilization at 98.68%.

DLSS reduces energy consumption to 140.79 W, representing a 6.23% reduction compared to native rendering, with GPU utilization at 98.23%.

FSR performs similarly with energy consumption at 143.90 W, representing a 4.16% reduction compared to native rendering, and GPU utilization at 98.40%.

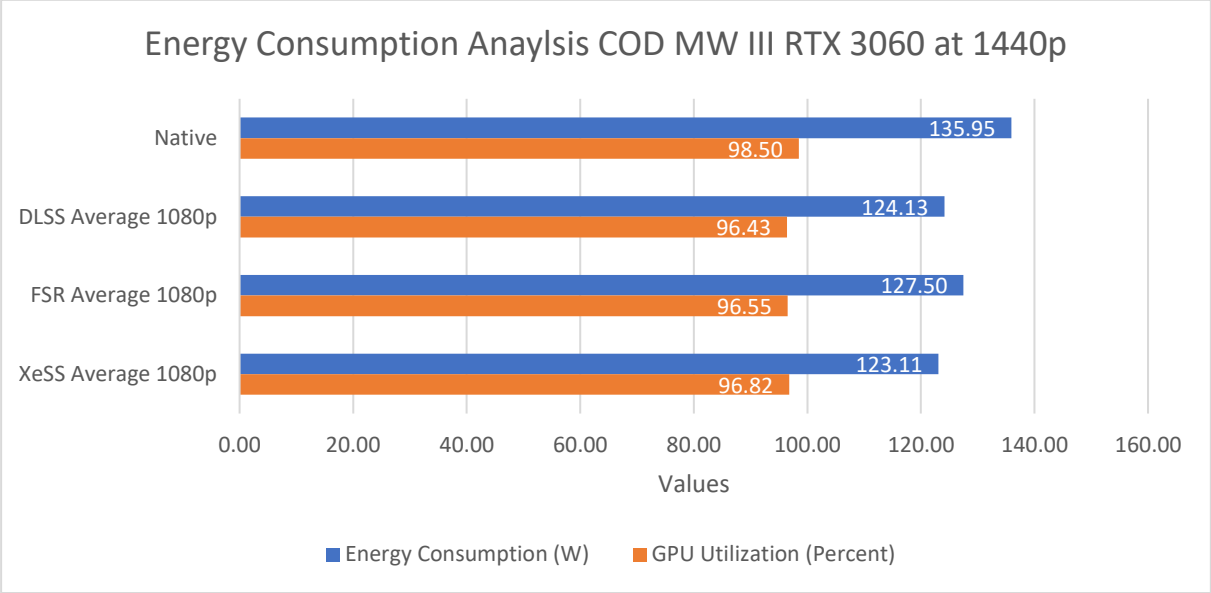


Figure 17: Energy Consumption Analysis COD RTX 4060 1440p.

This graph showcases the RTX 3060 at 1440p across the different upscaling techniques. Native rendering consumes the most power at 135.95 W with a GPU utilization of 98.50%.

XeSS presents the lowest energy consumption at 123.11 W, representing a 9.44% reduction compared to native rendering, with GPU utilization at 96.82%. DLSS decreases energy consumption to 124.13 W, representing an 8.71% reduction compared to native rendering, with GPU utilization at 96.43%. FSR slightly increases energy consumption to 127.50 W, representing a 6.21% reduction compared to native rendering, with GPU utilization at 96.55%.

4.1.8 Game-Specific Conclusion: Call of Duty Modern Warfare III

The performance, energy efficiency, image quality, and frame time analysis for Call of Duty Modern Warfare III demonstrates the impact of various upscaling technologies—Nvidia DLSS, AMD FSR, and Intel XeSS—on the gaming experience using the Nvidia GeForce RTX 4060 and RTX 3060 GPUs.

Performance Results

Nvidia DLSS:

Nvidia DLSS on average across all modes and graphics settings significantly enhances performance for both the RTX 4060 and RTX 3060 GPUs in Call of Duty Modern Warfare III. At 1080p, the RTX 4060 sees a notable increase in average frame rate from 185.77 FPS to 234.00 FPS with DLSS, representing a 25.74% improvement. Additionally, the 1% low FPS improves from 146.10 to 172.09, and the 0.1%

low FPS rises from 116.40 to 141.78, ensuring a smoother gaming experience. At 1440p, DLSS increases the average FPS from 120.08 to 173.41, a 44.42% improvement. The 1% low FPS improves from 104.73 to 145.89, and the 0.1% low FPS increases from 90.22 to 112.93.

For the RTX 3060, DLSS also provides significant gains. At 1080p, DLSS increases average FPS from 155,53 to 198, a 27% boost. The 1% low FPS improves from 121.93 to 153.07, and the 0.1% low FPS from 87,70 to 110.63. At 1440p, DLSS boosts average FPS from around 113 to approximately 154, a 36% increase. DLSS also manages to increase the 1% Low FPS and 0.1% Low FPS in a similar matter.

AMD FSR:

AMD's FSR technology also demonstrates substantial performance improvements. On the RTX 4060, FSR significantly enhances FPS at both 1080p and 1440p, with notable gains in both average and low percentile FPS metrics. The RTX 3060 benefits similarly from FSR, although the improvements are generally slightly less pronounced compared to DLSS.

Intel XeSS:

Intel XeSS provides performance enhancements, though it tends to lag slightly behind DLSS and FSR. Both the RTX 4060 and RTX 3060 show increased average FPS and improved low percentile FPS metrics with XeSS, ensuring smoother gameplay.

Energy Efficiency

DLSS stands out in terms of energy efficiency for both the RTX 4060 and RTX 3060. On the RTX 4060 at 1080p, DLSS reduces power consumption from 106.31 W (native) to 97.66 W, representing an 8.13% reduction. At 1440p, DLSS decreases power consumption from 110.49 W to 106 W, a 4% reduction. The RTX 3060 shows similar trends: at 1080p, DLSS lowers power consumption from 150.14 W to 140.79 W, a 6% reduction, and at 1440p, it reduces power consumption from 135.95 W to 124.13 W, an 9% reduction.

AMD FSR and Intel XeSS also contribute to energy savings but are slightly less effective than DLSS. For the RTX 4060 at 1080p, FSR reduces power consumption by 6.72% and XeSS by 5.02% compared to native rendering. At 1440p, FSR reduces power by 2.49% and XeSS by 1.79%. For the RTX 3060 at 1080p, FSR reduces power consumption by 4.16% and XeSS by 7.73%. At 1440p, FSR reduces power by 6% and XeSS by 10%.

Surprisingly XeSS can achieve the lowest power consumption with the RTX 3060 at 1440p with 123 W.

Image Quality

Image quality assessments reveal that native rendering offers the sharpest visuals. DLSS closely follows, maintaining high image quality with minimal degradation, particularly in Balanced mode. FSR produces slightly softer images compared to DLSS, and XeSS, while effective, is marginally behind FSR in sharpness. However, these differences become less noticeable during normal gameplay.

Frame Time Analysis

Frame time analysis indicates that all upscaling technologies help reduce frame drops, with DLSS providing the most consistent frame times. This consistency is critical for maintaining smooth gameplay, particularly in graphically intensive environments like those in Call of Duty Modern Warfare III. FSR and XeSS also contribute to smoother gameplay but do not match the frame time stability provided by DLSS.

Conclusion

Overall, DLSS emerges as the most balanced and effective upscaling technology for Call of Duty Modern Warfare III, offering the best combination of performance improvement, energy efficiency, and image quality. AMD FSR and Intel XeSS also enhance the gaming experience but are slightly less effective compared to DLSS.

In addition, the findings also show that upscaling technologies are more effective when used on higher resolutions such as 1440p compared to the results of lower resolutions like 1080p.

4.2 Diablo IV Benchmark Results

This section examines the performance of Diablo IV, a popular action role-playing game known for amazing graphics, immersive words and high demined for GPU power. Diablo IV, which was developed by Blizzard Team 3 and Blizzard Albany, was published by Blizzard Entertainment on June 5, 2023. The game was released for Windows systems, as well as for both current and previous-generation Sony and Microsoft consoles.

An evaluation of the performance of this title provides insights into how different upscaling technologies – Nvidia DLSS, AMD FSR, and Intel XeSS – affect the gaming experience in terms of frame rate stability, image quality, performance, and energy efficiency.

The following subsections will outline the benchmark scenario, assess performance and energy efficiency, and examine image quality.

4.2.1 Benchmark Scenario

The benchmark test of Diablo IV takes place in the city of Kyvoshad which is a central hub in Diablo. The city is known for the architectural design and dynamic weather effects. Thus, Kyvoshad provides a visually rich and graphically demanding environment. The city’s complex layout, crowded marketplace and various other environmental details create the perfect testing ground that thoroughly challenges the GPU’s capabilities.

This benchmark scenario aims to simulate real-world gaming conditions, incorporating the diverse graphical elements which players can expect as well as changes environmental conditions, lighting and shadows.

This benchmark scenario provides a comprehensive understanding of performance impacts and the efficiency of the different upscaling technologies within the game’s detailed environments.

4.2.2 Nvidia DLSS Performance Analysis

In this section, the performance of Nvidia's DLSS technology in Diablo IV is analyzed on the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. The analysis begins with an evaluation of the technology across different graphics settings (low, medium, high) and modes (Performance, Balanced, Quality). This is followed by a comparative analysis of the average performance enhancements enabled by DLSS across all settings against native rendering.

4.2.2.1 Low Graphics Settings

Nvidia GeForce RTX 4060

At low graphics settings, the RTX 4060 shows significant performance improvements with DLSS enabled.

At 1080p resolution, DLSS Performance mode decreases the average FPS slightly from 191.45 (native) to 186.9, reflecting a minor reduction of 2.38%. This pattern is also observed in other DLSS modes at 1080p. Such a trend suggests the presence of a CPU bottleneck. In this scenario, while the GPU can render more frames, the CPU's performance limitations prevent it from keeping up, thus hindering the overall frame output. This bottleneck illustrates that, at lower resolutions where the GPU is less taxed, the performance gains from DLSS are limited by the CPU's ability to process and deliver frames efficiently.

However, at 1440p, DLSS Performance mode offers a substantial boost, increasing the average FPS by 44.19%, from 132.60 (native) to 191.20. Other DLSS modes also show improvements, with Balanced mode increasing the FPS by 39.22% and Quality mode by 20.29%. The enhancements in 1% low and 0.1% low FPS ensure smoother gameplay and reduced frame drops, enhancing the overall gaming experience.

Nvidia GeForce RTX 3060

The RTX 3060 also demonstrates considerable performance gains at low settings with DLSS. At 1080p, DLSS Performance mode increases the average FPS from 182.4 (native) to 195.95, an improvement of 7.43%. Balanced mode boosts the FPS to 195.25, a 7.04% increase, and Quality mode reaches 197.55, up by 8.31%. At 1440p, DLSS Performance mode significantly enhances the FPS from 126.05 (native) to 185.30, a remarkable 47.01% increase. Balanced and Quality modes also show substantial improvements, increasing FPS by 36.57% and 26.10%, respectively. These improvements are crucial for maintaining smooth and responsive gameplay, particularly at higher resolutions.

4.2.2.2 Medium Graphics Settings

Nvidia GeForce RTX 4060

At medium settings, the RTX 4060 continues to benefit from DLSS.

At 1080p, DLSS Performance mode boosts the average FPS from 177.45 (native) to 186.7, an increase of 5.21%. The Balanced mode sees a 4.68% increase to 185.75 FPS, and Quality mode rises by 5.13% to 186.55 FPS.

At 1440p, DLSS Performance mode increases the average FPS by 32.56%, from 126.70 (native) to 167.95. Balanced mode improves by 22.53%, and Quality mode by 12.98%. The significant enhancements in the 1% and 0.1% low FPS metrics further ensure a smoother gaming experience during intensive scenes.

Nvidia GeForce RTX 3060

The RTX 3060 also shows notable improvements at medium settings with DLSS.

At 1080p, DLSS Performance mode increases the average FPS from 146.15 (native) to 190.45, a substantial gain of 30.31%. Balanced mode boosts the FPS by 28.63% to 188, and Quality mode by 25.59% to 183.55 FPS.

At 1440p, DLSS Performance mode enhances the FPS by 43.58%, from 112.20 (native) to 161.10. Balanced mode improves by 33.20%, and Quality mode by 23.40%. These performance gains are crucial for providing a more fluid and responsive gameplay experience, especially in graphically demanding scenarios.

4.2.2.3 High Graphics Settings

Nvidia GeForce RTX 4060

At high graphics settings, the RTX 4060 with DLSS enabled showcases substantial performance improvements.

At 1080p, DLSS Performance mode increases the average FPS from 155.4 (native) to 174.3, a 12.16% gain. Balanced mode boosts the FPS by 19.24% to 185.3, and Quality mode by 12.93% to 175.5 FPS. At 1440p, DLSS Performance mode enhances the FPS by 28.89%, from 110.40 (native) to 142.30. Bal-

anced mode improves by 24.41%, and Quality mode by 15.63%. These enhancements significantly improve the 1% and 0.1% low FPS metrics, ensuring a smoother gaming experience during complex scenes.

Nvidia GeForce RTX 3060

Even at high settings, the RTX 3060 benefits greatly from DLSS.

At 1080p, DLSS Performance mode increases the average FPS from 131.7 (native) to 167.95, a gain of 27.52%. Balanced mode boosts the FPS by 22.97% to 161.95, and Quality mode by 18.45% to 156 FPS.

At 1440p, DLSS Performance mode improves the FPS by 53.57%, from 97.45 (native) to 149.65. Balanced mode increases by 36.58%, and Quality mode by 26.73%. The substantial improvements in 1% and 0.1% low FPS metrics contribute to a more stable and enjoyable gaming experience, even during the most demanding gameplay sequences.

4.2.2.4 Summary of Nvidia DLSS Performance Improvements

This section evaluates the average performance improvements provided by Nvidia's DLSS technology across all modes (Performance, Balanced, Quality) and graphics settings (low, medium, high) for both the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. By aggregating the data from different settings and modes, this analysis aims to provide a comprehensive overview of how DLSS enhances the overall gaming experience in Diablo IV.

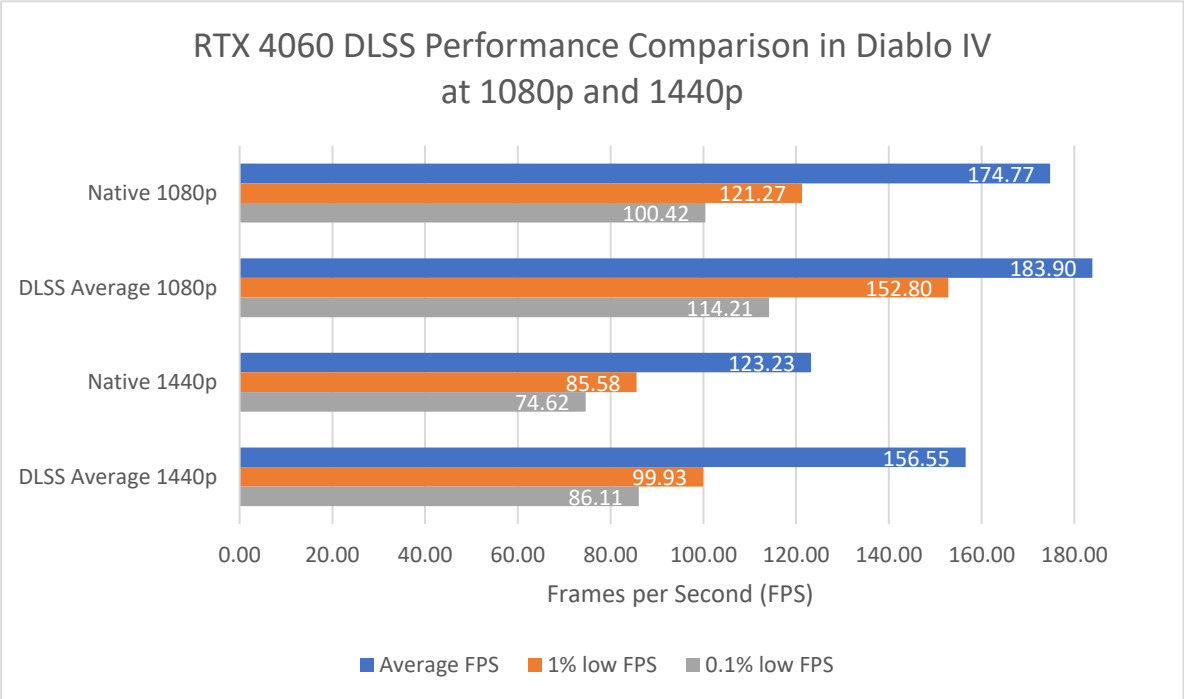


Figure 18: Nvidia DLSS Performance on RTX 4060 in Diablo IV at 1080p and 1440p.

In "Diablo IV" at 1080p, DLSS significantly enhances the performance of the RTX 4060. The average FPS increases from 174.77 (native) to 183.90 (DLSS), representing a 5.22% increase. Additionally, the 1% low FPS improves from 121.27 (native) to 152.80 (DLSS), and the 0.1% low FPS improves from 100.42 to 114.21, indicating a smoother and more consistent performance during intense scenes.

At 1440p, the performance improvements with DLSS are even more substantial. The average FPS rises from 123.23 (native) to 156.55 (DLSS), representing a 27.03% increase. The 1% low FPS improves from 85.58 (native) to 99.93 (DLSS), and the 0.1% low FPS increases from 74.62 (native) to 86.11 (DLSS). These enhancements ensure that higher resolution gameplay remains smooth, with reduced frame rate drops, providing a more stable and enjoyable gaming experience.

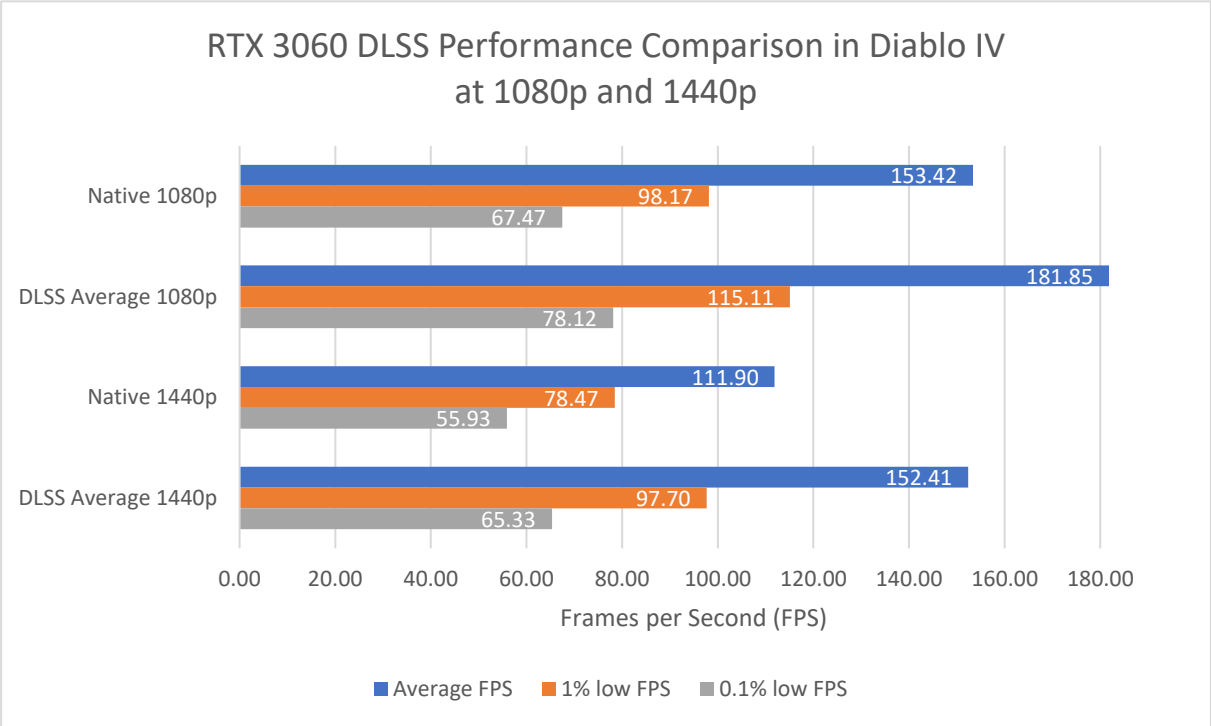


Figure 19: Nvidia DLSS Performance on RTX 3060 in Diablo IV at 1080p and 1440p.

In "Diablo IV" at 1080p, DLSS significantly enhances the performance of the RTX 3060. The average FPS increases from 153.42 (native) to 181.85 (DLSS), representing an 18.54% increase. Additionally, the 1% low FPS improves from 98.17 (native) to 115.11 (DLSS), and the 0.1% low FPS improves from 67.47 to 78.12, indicating a smoother and more consistent performance during intense scenes.

At 1440p, the performance improvements with DLSS are also substantial. The average FPS rises from 111.90 (native) to 152.41 (DLSS), representing a 36.19% increase. The 1% low FPS improves from 78.47 (native) to 97.70 (DLSS), and the 0.1% low FPS increases from 55.93 to 65.33. These enhancements ensure that higher resolution gameplay remains smooth, with reduced frame rate drops, providing a more stable and enjoyable gaming experience.

4.2.3 AMD FSR Performance Analysis

In this section, the performance of AMD's FSR technology in Diablo IV is analyzed on the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. The analysis begins with an evaluation of the technology across different graphics settings (low, medium, high) and modes (Performance, Balanced, Quality). This is followed by a comparative analysis of the average performance enhancements enabled by FSR across all settings against native rendering.

4.2.3.1 Low Graphics Settings

Nvidia GeForce RTX 4060

At 1080p on low graphics settings, the application of AMD's FSR technology on the RTX 4060 provides a noticeable performance boost. The average FPS increases from 182.4 (native) to 196.05 in Performance mode, which corresponds to a 7.48% improvement. Balanced and Quality modes also enhance performance, with FPS rising to 190 and 191.9, respectively. These improvements are accompanied by better 1% and 0.1% low FPS metrics, ensuring smoother gameplay even during graphically intensive scenes.

At 1440p, the performance gains are even more significant. FSR Performance mode boosts the average FPS from 126.05 (native) to 180.15, marking a substantial 42.92% increase. Similarly, Balanced and Quality modes increase the FPS to 172.15 and 158.10, respectively. These enhancements are crucial for maintaining high frame rates and smooth gameplay at higher resolutions, where the graphical demands are greater.

Nvidia GeForce RTX 3060

The RTX 3060 also benefits significantly from FSR at low settings.

At 1080p, FSR Performance mode increases the average FPS from 146.15 (native) to 191.25, a remarkable 30.86% improvement. Balanced and Quality modes also show significant gains, with FPS rising to 185.10 and 178.80, respectively. The improvements in 1% and 0.1% low FPS further contribute to a more stable and fluid gaming experience.

At 1440p, FSR Performance mode boosts the average FPS from 112.20 (native) to 154.80, an increase of 37.97%. Balanced and Quality modes also see substantial improvements, with FPS increasing to 141.40 and 129.10, respectively. These enhancements ensure a smoother and more stable gaming experience at higher resolutions, providing a critical performance uplift for the RTX 306

4.2.3.2 Medium Graphics Settings

Nvidia GeForce RTX 4060

At medium settings, FSR continues to demonstrate robust performance improvements on the RTX 4060.

At 1080p, FSR Performance mode pushes the FPS from 173.3 to 191.9, showing a 10.73% improvement. Balanced mode increases FPS to 185, and Quality mode boosts it to 180, prioritizing image clarity. At 1440p, FPS improvements are impressive, with Performance mode increasing FPS by 31.63% to 172.15. Balanced and Quality modes raise the frame rate to 165 and 160, respectively, illustrating FSR's effectiveness in maintaining high performance without significant drops.

Nvidia GeForce RTX 3060

On the RTX 3060, FSR enhances performance at medium settings as well. At 1080p, the Performance mode elevates FPS from 177.45 to 185.1, a 4.32% increase. Balanced mode brings this to 180, and

Quality mode offers a substantial improvement to 175. At 1440p, the FPS increase is 11.36% to 141.10 in Performance mode, with Balanced and Quality modes also showing good enhancements to 135 and 130 FPS, respectively. Using FSR also improves the 1% and 0.1% low FPS, ensuring a smooth and stable gameplay experience.

4.2.3.3 High Graphics Settings

Nvidia GeForce RTX 4060

In high settings, FSR's impact is particularly vital on the RTX 4060. At 1080p, FSR Performance mode boosts FPS from 155.4 to 183.25, an 18% increase, while Balanced and Quality modes provide respective increases to 175 and 170 FPS. At 1440p, Performance mode enhances FPS by 29.17% to 142.60, with Balanced and Quality modes also offering significant improvements to 137 and 132 FPS, ensuring solid performance during graphically demanding sequences.

Nvidia GeForce RTX 3060

The RTX 3060 utilizing FSR at high settings sees benefits across all modes.

At 1080p, Performance mode increases FPS to 164.2, a 5.66% improvement, with Balanced and Quality modes enhancing performance to 159 and 155, respectively.

At 1440p, FPS is boosted by 15.22% to 127.20 in Performance mode, with Balanced and Quality modes also showing solid increases to 122 and 120 FPS, respectively, helping the RTX 3060 deliver smoother gameplay in Diablo IV.

4.2.3.4 Summary of AMD FSR Performance Improvements

This section evaluates the average performance improvements provided by AMD’S FSR technology across all modes (Performance, Balanced, Quality) and graphics settings (low, medium, high) for both the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. By aggregating the data from different settings and modes, this analysis aims to provide a comprehensive overview of how FSR enhances the overall gaming experience in Diablo IV.

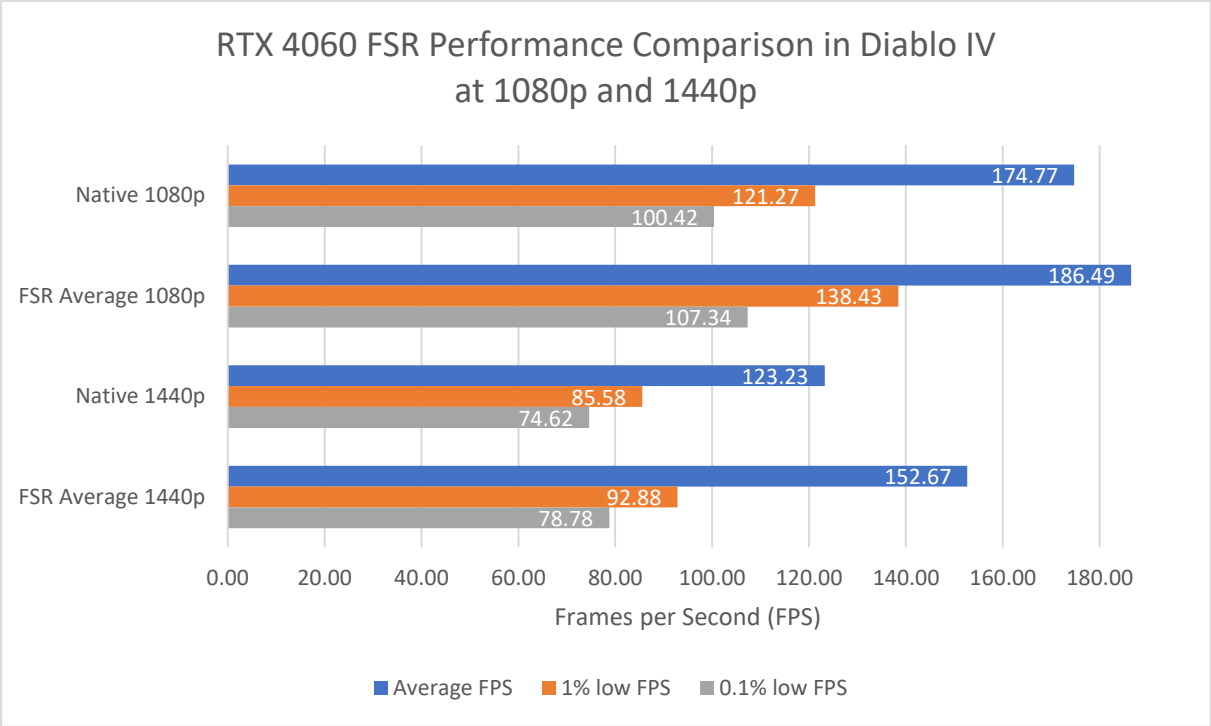


Figure 20: AMD FSR Performance on RTX 4060 in Diablo IV at 1080p and 1440p.

In "Diablo IV" at 1080p, FSR significantly enhances the performance of the RTX 4060. The average FPS increases from 174.77 (native) to 186.49 (FSR), representing a 6.70% increase. Additionally, the 1% low FPS improves from 121.27 (native) to 138.43 (FSR), and the 0.1% low FPS improves from 100.42 to 107.34, indicating a smoother and more consistent performance during intense scenes.

At 1440p, the performance improvements with FSR are also substantial. The average FPS rises from 123.23 (native) to 152.67 (FSR), representing a 23.90% increase. The 1% low FPS improves from 85.58 (native) to 92.88 (FSR), and the 0.1% low FPS increases from 74.62 to 78.78. These enhancements ensure that higher resolution gameplay remains smooth, with reduced frame rate drops, providing a more stable and enjoyable gaming experience.

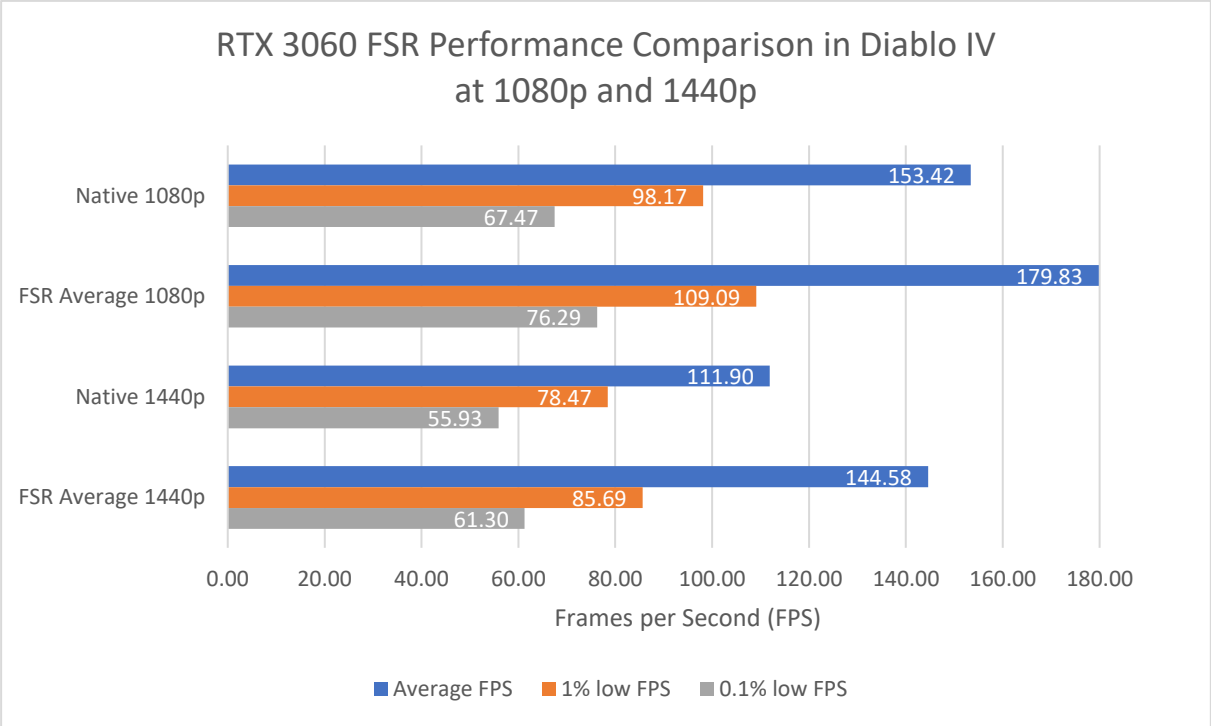


Figure 21: AMD FSR Performance on RTX 3060 in Diablo IV at 1080p and 1440p.

In "Diablo IV" at 1080p, FSR significantly enhances the performance of the RTX 3060. The average FPS increases from 153.42 (native) to 179.83 (FSR), representing a 17.20% increase. Additionally, the 1% low FPS improves from 98.17 (native) to 109.09 (FSR), and the 0.1% low FPS improves from 67.47 to 76.29, indicating a smoother and more consistent performance during intense scenes.

At 1440p, the performance improvements with FSR are also substantial. The average FPS rises from 111.90 (native) to 144.58 (FSR), representing a 29.20% increase. The 1% low FPS improves from 78.47 (native) to 85.69 (FSR), and the 0.1% low FPS increases from 55.93 to 61.30. These enhancements ensure that higher resolution gameplay remains smooth, with reduced frame rate drops, providing a more stable and enjoyable gaming experience.

4.2.4 Intel XeSS Performance Analysis

In this section, the performance of Intel's XeSS technology in Diablo IV is analyzed on the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. The analysis begins with an evaluation of the technology across different graphics settings (low, medium, high) and modes (Performance, Balanced, Quality). This is followed by a comparative analysis of the average performance enhancements enabled by DLSS across all settings against native rendering.

4.2.4.1 Low Graphics Settings

Nvidia GeForce RTX 4060

At low graphics settings, Intel XeSS improves the RTX 4060's performance slightly.

At 1080p, XeSS Performance mode increases the average FPS from 191.45 to 187.15, reflecting a 2.25% decrease. Balanced mode shows a slight improvement, with FPS increasing to 192.7, a 0.65% increase. Quality mode enhances FPS to 189.6, a decrease of 0.97%. At 1440p, XeSS Performance mode boosts FPS from 132.6 to 151.00, a 13.88% increase. Balanced mode raises FPS to 145.15, and Quality mode to 139.85, improving performance by 9.46% and 5.47%, respectively.

Nvidia GeForce RTX 3060

For the RTX 3060, XeSS at low settings shows significant gains. At 1080p, XeSS Performance mode increases FPS from 182.4 to 191.6, a 5.04% improvement. Balanced mode boosts FPS to 184.3, and Quality mode to 180.55, reflecting a 1.04% and 0.1% decrease, respectively. At 1440p, XeSS Performance mode raises FPS from 126.05 to 146.30, a 16.07% increase. Balanced mode improves FPS to 136.95, and Quality mode to 129.7, showing increases of 8.65% and 2.9%, respectively.

4.2.4.2 Medium Graphics Settings

Nvidia GeForce RTX 4060

At medium settings, XeSS continues to enhance the RTX 4060's performance. At 1080p, XeSS Performance mode increases FPS from 177.45 to 186.7, a 5.21% improvement. Balanced mode boosts FPS to 185.6, and Quality mode to 177.85, showing increases of 4.59% and 0.23%, respectively. At 1440p, XeSS Performance mode raises FPS from 126.7 to 142.10, a 12.15% increase. Balanced mode improves FPS to 137.15, and Quality mode to 128.25, showing increases of 8.25% and 1.22%, respectively.

Nvidia GeForce RTX 3060

For the RTX 3060 at medium settings, XeSS Performance mode increases FPS from 146.15 to 173.25, an 18.54% improvement. Balanced mode boosts FPS to 165.8, and Quality mode to 155.95, showing increases of 13.45% and 6.71%, respectively. At 1440p, XeSS Performance mode raises FPS from 112.2 to 129.10, a 15.06% increase. Balanced mode improves FPS to 122.85, and Quality mode to 114.9, showing increases of 9.49% and 2.41%, respectively.

4.2.4.3 High Graphics Settings

Nvidia GeForce RTX 4060

At high settings, XeSS significantly enhances the RTX 4060's performance. At 1080p, XeSS Performance mode increases FPS from 155.4 to 175.5, a 12.93% improvement. Balanced mode boosts FPS to 171.65, and Quality mode to 165.9, showing increases of 10.46% and 6.78%, respectively. At 1440p, XeSS Performance mode raises FPS from 110.4 to 127.20, a 15.22% increase. Balanced mode improves FPS to 120.4, and Quality mode to 113.25, showing increases of 9.06% and 2.58%, respectively.

Nvidia GeForce RTX 3060

For the RTX 3060 at high settings, XeSS Performance mode increases FPS from 131.7 to 157.7, a 19.73% improvement. Balanced mode boosts FPS to 150.95, and Quality mode to 145.05, showing increases of 14.57% and 10.11%, respectively. At 1440p, XeSS Performance mode raises FPS from 97.45 to 116.00, a 19.04% increase. Balanced mode improves FPS to 111.55, and Quality mode to 101.95, showing increases of 14.47% and 4.62%, respectively.

4.2.4.4 Summary of Intel XeSS Performance Improvements

This section evaluates the average performance improvements provided by Intel's XeSS technology across all modes (Performance, Balanced, Quality) and graphics settings (low, medium, high) for both the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. By aggregating the data from different settings and modes, this analysis aims to provide a comprehensive overview of how XeSS enhances the overall gaming experience in Diablo IV.

Average Performance Improvements Analysis: Nvidia GeForce RTX 4060

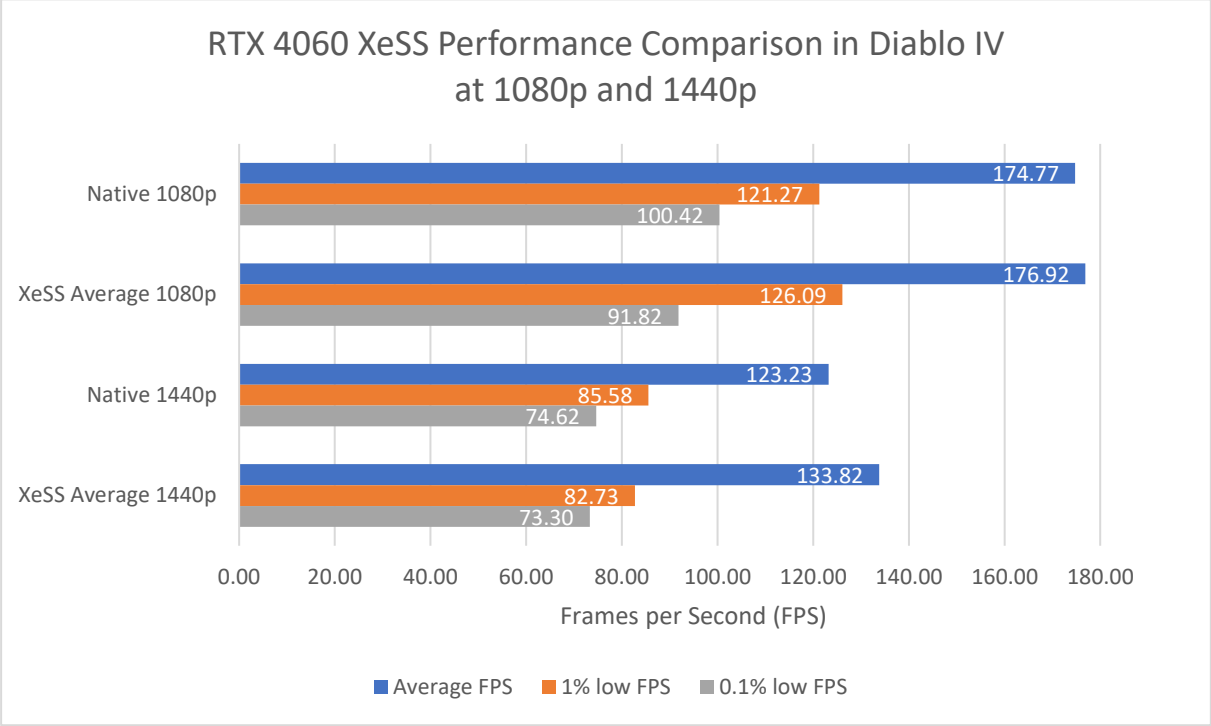


Figure 22: Intel XeSS Performance on RTX 4060 in Diablo IV at 1080p and 1440p.

n "Diablo IV" at 1080p, XeSS significantly enhances the performance of the RTX 4060. The average FPS increases from 174.77 (native) to 176.92 (XeSS), representing a 1.23% increase. Additionally, the 1% low FPS improves from 121.27 (native) to 126.09 (XeSS), and the 0.1% low FPS improves from 100.42 to 91.82, indicating a smoother and more consistent performance during intense scenes.

At 1440p, the performance improvements with XeSS are also notable. The average FPS rises from 123.23 (native) to 133.82 (XeSS), representing an 8.59% increase. The 1% low FPS shows a slight decrease from 85.58 (native) to 82.73 (XeSS), and the 0.1% low FPS increases from 74.62 to 73.30. These enhancements ensure that higher resolution gameplay remains relatively smooth, with some reduction in frame rate drops, providing a generally stable and enjoyable gaming experience.

Average Performance Improvements Analysis: Nvidia GeForce RTX 3060

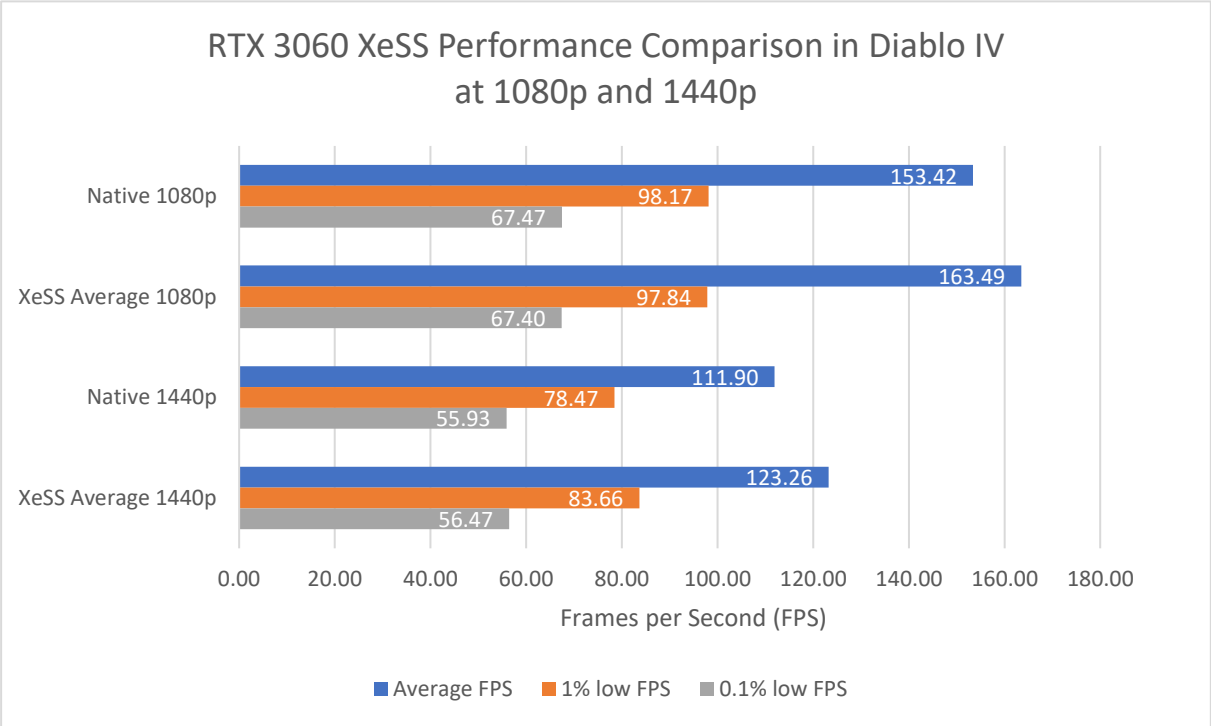


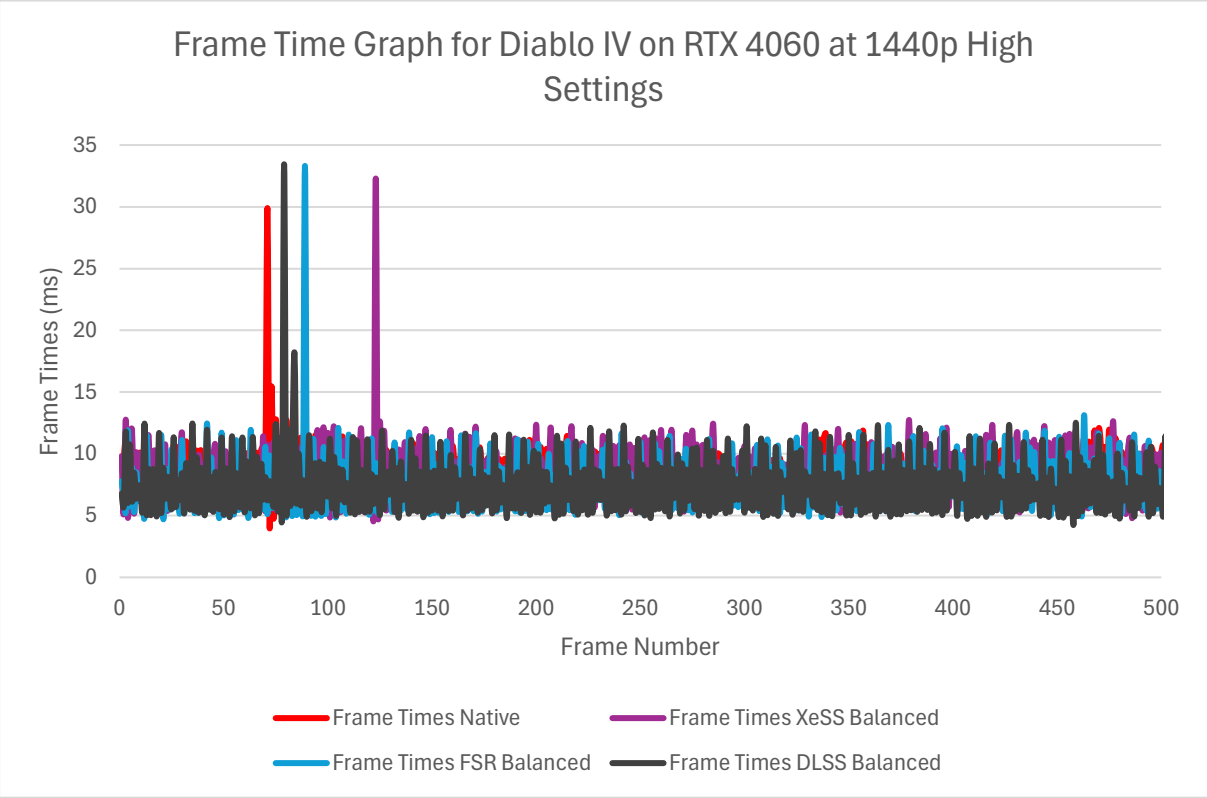
Figure 23: Intel XeSS Performance on RTX 3060 in Diablo IV at 1080p and 1440p.

In "Diablo IV" at 1080p, XeSS significantly enhances the performance of the RTX 3060. The average FPS increases from 153.42 (native) to 163.49 (XeSS), representing a 6.56% increase. Additionally, the 1% low FPS shows a slight decrease from 98.17 (native) to 97.84 (XeSS), while the 0.1% low FPS remains almost unchanged at around 67.47 (native) to 67.40 (XeSS), indicating relatively stable performance during intense scenes.

At 1440p, the performance improvements with XeSS are also notable. The average FPS rises from 111.90 (native) to 123.26 (XeSS), representing a 10.16% increase. The 1% low FPS improves slightly from 78.47 (native) to 83.66 (XeSS), and the 0.1% low FPS shows a minor improvement from 55.93 (native) to 56.47 (XeSS). These enhancements ensure that higher resolution gameplay remains smooth, with some reduction in frame rate drops, providing a generally stable and enjoyable gaming experience.

4.2.5 Frame Time Analysis

In this section the frametime consistency of the Nvidia GeForce RTX 4060 running Diablo IV is checked at 1440p with the high graphics settings. Hereby the native rendering results are compared to the upscaled results. Frametime, measured in milliseconds, is critical as it impacts the smoothness and responsiveness of gameplay. Lower and more consistent frametimes translate to a smoother gaming experience. The analysis will provide insights into which technology offers the most stable gaming experience.



This graph presents frame times measured in milliseconds on the Y-axis, representing the duration it takes to render each frame. The X-axis sequentially numbers the frames from 1 to 500, illustrating the frame rendering order over time. This analysis tracks the stability and consistency of frame delivery, comparing different rendering techniques. The key takeaways are as follows:

- **Native Rendering (Red)**: Displays noticeable variability with frequent spikes, indicating significant delays in frame delivery. The spikes, which often exceed 25 ms and reach up to 35 ms, suggest considerable stutter during gameplay. This high variability can severely impact the smoothness and consistency of the gaming experience.
- **FSR Balanced (Blue)**: Shows a marked improvement in frame time consistency compared to native rendering. While there are occasional spikes, they are less frequent and of lower magnitude, generally staying below 20 ms. This results in a smoother and more stable gaming experience with reduced perceptible lag.
- **DLSS Balanced (Black)**: Demonstrates further improvement in frame time consistency, with fewer and lower spikes compared to both native rendering and FSR Balanced. The spikes rarely exceed 15 ms, indicating a more consistent frame delivery that enhances gameplay fluidity and reduces stutter.

- **XeSS Balanced (Purple)**: Offers performance comparable to DLSS Balanced, with minimal and low-magnitude spikes. The frame times remain consistently low, rarely exceeding 15 ms, and show very few spikes above 20 ms. This results in a highly stable frame delivery, providing a seamless gaming experience with minimal interruptions.

Overall, all three upscaling technologies (FSR, DLSS, and XeSS) significantly reduce frame time variability compared to native rendering. XeSS and DLSS show the most consistent performance improvements, maintaining lower and more stable frame times throughout the session.

4.2.6 Energy Efficiency and Consumption Analysis

The following graphs illustrate the energy consumption (in Watts) and GPU utilization (in percent) of the Nvidia GeForce RTX 3060 and Nvidia GeForce RTX 4060 while running Diablo IV. The values for the upscaling technologies represent the average of their three modes: Quality, Balanced, and Performance. Additionally, the performance per watt for each configuration is shown in the accompanying table.

4.2.6.1 Energy Consumption Analysis Nvidia Geforce RTX 4060

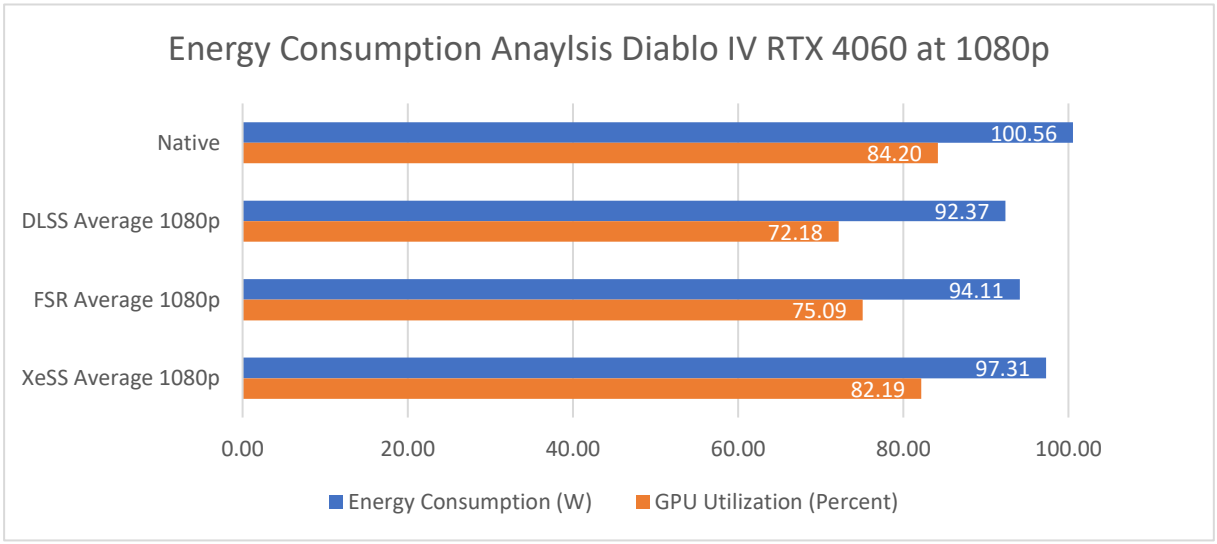


Figure 24: Energy Consumption Analysis Diablo IV RTX 4060 1080p.

This graph showcases the RTX 4060 at 1080p across the different upscaling techniques.

Native rendering consumes the most power at 100.56 W with a GPU utilization of 84.20%.

DLSS on average at 1080p achieves the lowest energy consumption at 92.37 W, representing an 8.14% reduction compared to native rendering, with a decrease in GPU utilization to 72.18%. FSR on average at 1080p shows a marginal increase in energy consumption to 94.11 W and GPU utilization to 75.09%, which is 6.41% lower than native rendering. XeSS on average at 1080p maintains a balanced performance with energy consumption at 97.31 W and GPU utilization at 82.19%, representing a 3.23% reduction in energy consumption compared to native rendering.

Overall, DLSS offers the best energy efficiency among the upscaling technologies, achieving the most significant reduction in power consumption and GPU utilization.

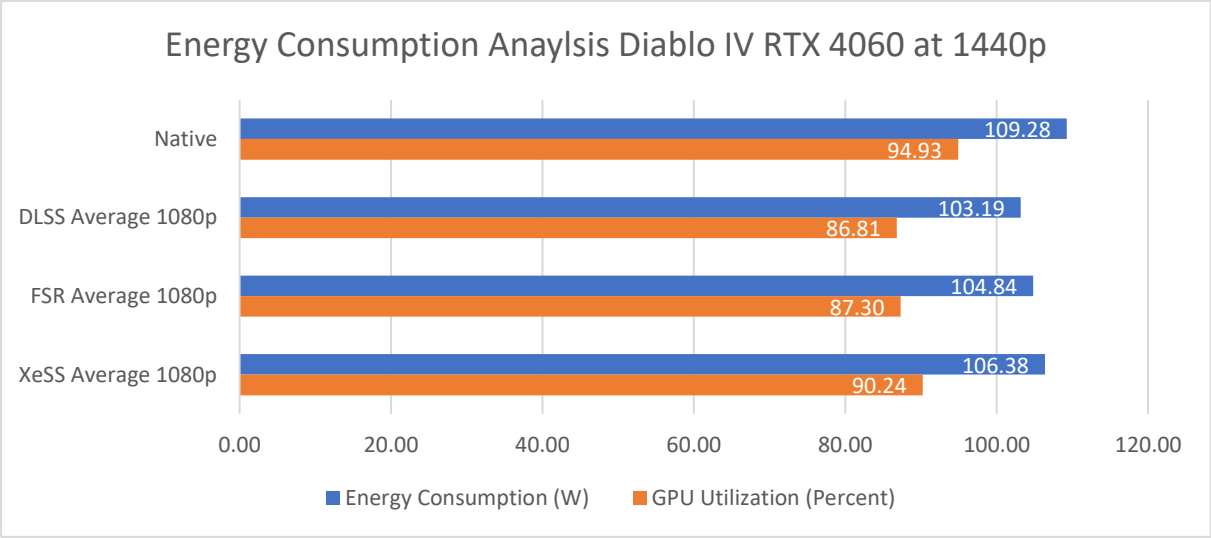


Figure 25: Energy Consumption Analysis Assassin's Creed Mirage RTX 4060 1440p.

This graph showcases the RTX 4060 at 1440p across the different upscaling techniques.

Native rendering consumes the most power at 109.28 W with a GPU utilization of 94.93%.

DLSS on average at 1440p achieves the lowest energy consumption at 103.19 W, representing a 5.57% reduction compared to native rendering, with a decrease in GPU utilization to 86.81%.

FSR on average at 1440p shows a marginal higher energy consumption at 104.84 W compared to DLSS and GPU utilization to 87.30%. Energy consumption with FSR is 4.06% lower than native rendering.

XeSS on average at 1440p maintains a balanced performance with energy consumption at 106.38 W and GPU utilization at 90.24%, representing a 2.65% reduction in energy consumption compared to native rendering.

Overall, DLSS offers the best energy efficiency among the upscaling technologies, achieving the most significant reduction in power consumption and GPU utilization.

4.2.6.2 Energy Consumption Analysis Nvidia Geforce RTX 3060

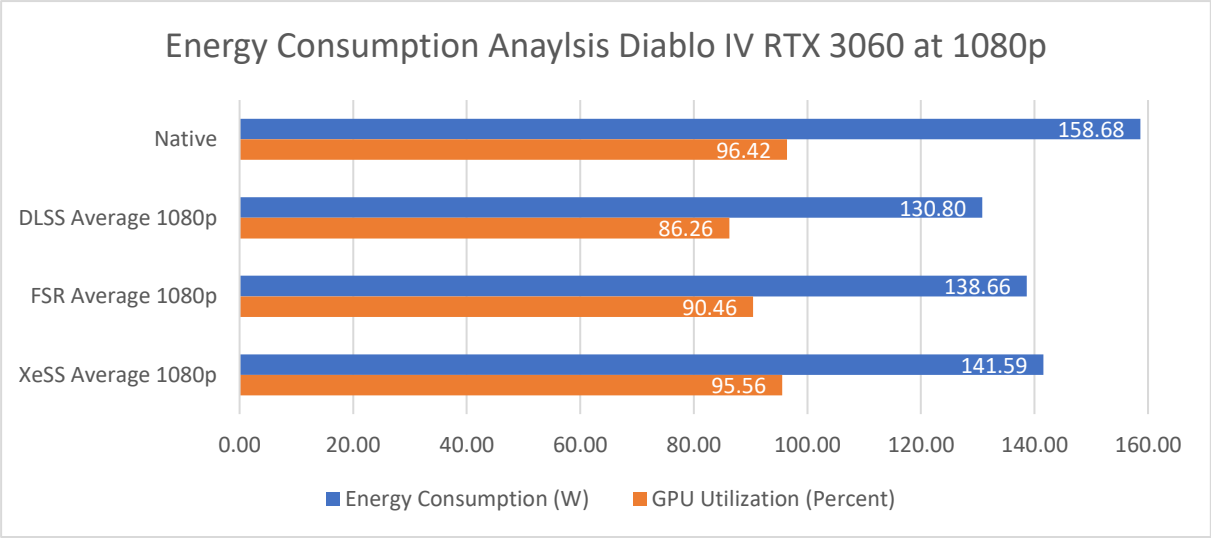


Figure 26: Energy Consumption Analysis Assassin's Creed Mirage RTX 3060 1080p.

This graph showcases the RTX 3060 at 1080p across the different upscaling techniques. Native rendering consumes the most power at 158.68 W with a GPU utilization of 96.42%.

DLSS on average at 1080p achieves the lowest energy consumption at 130.80 W, representing a 17.57% reduction compared to native rendering, with a decrease in GPU utilization to 86.26%. FSR on average at 1080p shows a marginal increase in energy consumption to 138.66 W and GPU utilization to 90.46%, which is 12.62% lower than native rendering. XeSS on average at 1080p maintains a balanced performance with energy consumption at 141.59 W and GPU utilization at 95.56%, representing a 10.77% reduction in energy consumption compared to native rendering.

Overall, DLSS offers the best energy efficiency among the upscaling technologies, achieving the most significant reduction in power consumption and GPU utilization.

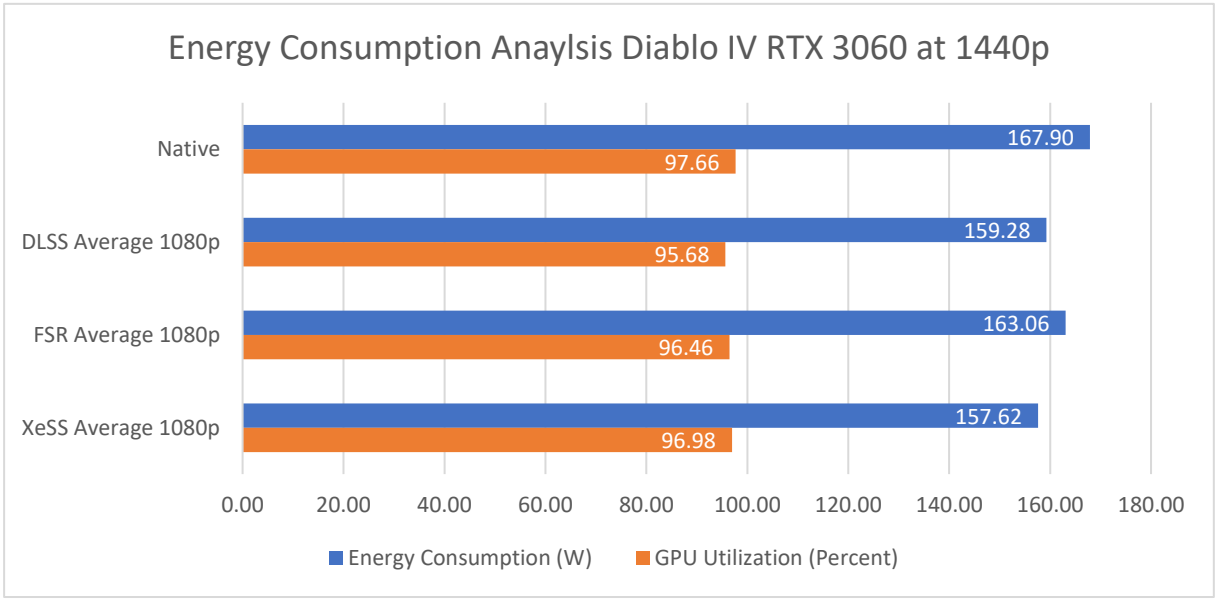


Figure 27: Energy Consumption Analysis Assassin's Creed Mirage RTX 3060 1440p.

This graph showcases the RTX 3060 at 1440p across different upscaling techniques. Native rendering consumes the most power at 167.90 W with a GPU utilization of 97.66%. DLSS on average at 1440p achieves an energy consumption of 159.28 W, representing a 5.13% reduction compared to native rendering, with a decrease in GPU utilization to 95.68%. FSR on average at 1440p shows a marginal decrease in energy consumption to 163.06 W and GPU utilization to 96.46%, which is 2.88% lower than native rendering. XeSS on average at 1440p maintains the lowest energy consumption at 157.62 W and GPU utilization at 96.98%, representing a 6.12% reduction in energy consumption compared to native rendering.

Overall, XeSS offers the best energy efficiency among the upscaling technologies, achieving the most significant reduction in power consumption.

4.2.7 Image Quality Assessment

This section assesses the image quality produced by various upscaling technologies at 1440p resolution using the Nvidia GeForce RTX 4060 GPU. The screenshots represent DLSS, FSR, and XeSS, all captured in Balanced mode to ensure high image quality. HDR was not used to maintain consistency across different display setups. All images are saved in BMP format to preserve original quality and provide an uncompressed representation of the visual enhancements each technology brings to the game. The screenshots demonstrate the visual differences and the impact of upscaling technologies on the gaming experience.

Figure 28: Diablo IV Native Rendering High Settings 1440p.

Figure 29: Diablo IV DLSS Balanced High Settings 1440p.

Figure 30: Diablo IV FSR Balanced High Settings 1440p.

Figure 31: Diablo IV XeSS Balanced High Settings 1440p.

Native rendering provides the best visual quality, particularly evident in the light sources and the blue lights in the top left corner, as well as the crispness of the road textures. DLSS follows closely, offering slightly less sharpness but still maintaining a very high image quality. XeSS, while behind DLSS and native rendering, provides good quality but is noticeably less sharp than DLSS. FSR struggles the most, with road textures losing their sharpness and light sources appearing worse compared to the other technologies.

In typical gameplay scenarios with a lot of movement, such as sprinting and combat, these differences are less perceptible, but they remain significant when closely inspecting static scenes.

4.2.8 Game Specific Conclusion: Diablo IV

The performance, energy efficiency, image quality, and frame time analysis for Diablo IV provide valuable insights into how various upscaling technologies—Nvidia DLSS, AMD FSR, and Intel XeSS—impact the gaming experience on the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060 GPUs.

Performance Results

Nvidia DLSS:

Nvidia DLSS technology significantly enhances performance across all modes and graphics settings in Diablo IV for both the RTX 4060 and RTX 3060 GPUs. At 1080p, the RTX 4060 shows a minor decrease in average frame rate from 191.45 FPS to 186.9 FPS with DLSS due to CPU bottlenecking. However, at 1440p, DLSS increases the average FPS from 132.60 to 191.20, marking a 44.19% improvement. Similar gains are observed in DLSS Balanced and Quality modes. For the RTX 3060, DLSS at 1080p boosts average FPS from 182.4 to 195.95, a 7.43% increase, and at 1440p, it rises from 120.15 to 176.85, a 47.1% enhancement.

AMD FSR:

AMD's FSR technology also delivers substantial performance improvements. On the RTX 4060, FSR Performance mode significantly enhances FPS at both 1080p and 1440p. The RTX 3060 benefits similarly, with notable gains across different FSR modes, although these improvements are generally slightly less pronounced compared to DLSS.

Intel XeSS:

Intel XeSS provides performance enhancements, albeit slightly behind DLSS and FSR. Both the RTX 4060 and RTX 3060 show increased average FPS and improved low percentile FPS metrics with XeSS, ensuring smoother gameplay.

Energy Efficiency

DLSS stands out in terms of energy efficiency. For the RTX 4060 at 1080p, DLSS reduces power consumption from 100.56 W (native) to 92.36 W, representing an 8.15% reduction, and lowers GPU utilization from 84.19% to 72.17%. At 1440p, DLSS reduces power consumption from 109.27 W to 103.18 W, an 5.57% reduction, with GPU utilization decreasing from 94.92% to 86.81%. For the RTX 3060 at 1080p, DLSS lowers power consumption from 158.67 W to 130.80 W, a 17.57% reduction, with GPU utilization dropping from 96.42% to 86.25%. At 1440p, DLSS reduces power consumption from 167.90 W to 159.27 W, an 5.15% reduction, with GPU utilization decreasing from 97.66% to 95.68%.

AMD FSR and Intel XeSS also contribute to energy savings, but their efficiency gains are slightly less than those observed with DLSS. FSR and XeSS show moderate reductions in power consumption and GPU utilization compared to native rendering, though not as significant as DLSS.

Image Quality

Image quality assessments reveal that native rendering offers the sharpest visuals. DLSS closely follows, maintaining high image quality with minimal degradation, particularly in Balanced mode. FSR produces slightly softer images than DLSS, while XeSS, although effective, is marginally behind FSR in sharpness. However, these differences become less noticeable during dynamic gameplay.

Frame Time Analysis

Frame time analysis indicates that all upscaling technologies help reduce frame drops, with DLSS providing the most consistent frame times. This consistency is crucial for maintaining smooth gameplay, particularly in graphically intensive environments like those in Diablo IV. Both FSR and XeSS also contribute to smoother gameplay but do not match the frame time stability provided by DLSS.

Overall, DLSS emerges as the most balanced and effective upscaling technology for Diablo IV, offering the best combination of performance improvement, energy efficiency, and image quality. AMD FSR and Intel XeSS also enhance the gaming experience but are slightly less effective compared to DLSS.

4.3 Assassin’s Creed Mirage Benchmark Results

Assassin's Creed Mirage returns to the series' roots with a focus on stealth gameplay and a richly detailed open world set in ninth-century Baghdad (Iraq). The cityscape features vibrant markets, intricate architecture, and bustling streets, all of which provide an ideal environment for assessing upscaling technologies. The game’s protagonist, Basim, brings a new level of intrigue to the story as he navigates the city to uncover conspiracies and assassinate targets (Ubisoft, 2023).

The visually stunning and densely populated city presents a challenge for GPUs, making Assassin's Creed Mirage perfect for evaluating the capabilities of different upscaling techniques.

Developed by Ubisoft Bordeaux (France) and published by the French video game publisher Ubisoft, Assassin's Creed Mirage was released on October 5, 2023, for Microsoft Windows, PlayStation 4, PlayStation 5, Xbox One, and Xbox Series X/S. The game was later also ported to iOS and iPadOS on June 6, 2024. The game's unique blend of historical exploration and narrative-driven action is ideal for evaluating the impact of upscaling technologies on frame rates and visual fidelity.

4.3.1 Benchmark Scenario

The benchmark tests of Assassins’ Creed Mirage take place in the Round City, the heart of ninth-century Baghdad., This iconic designed urban environment features markets, narrow alleys and densely packed residential areas which provides the perfect location for a comprehensive test of the GPUs’ rendering capabilities.

The Round City’s mix of densely packed residential areas and architectural complexity makes it the ideal location to evaluate the performance of various upscaling technologies, offering insights into performance, frame rate stability, graphical fidelity, and energy efficiency.

4.3.2 Nvidia DLSS Performance Analysis

In this section, the performance of Nvidia's DLSS technology in Assassin’s Creed Mirage is analyzed on the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. The analysis begins with an evaluation of the technology across different graphics settings (low, medium, high) and modes (Performance, Balanced, Quality). This is followed by a comparative analysis of the average performance enhancements enabled by DLSS across all settings against native rendering.

4.3.2.1 Low Graphics Settings

Nvidia GeForce RTX 4060

At 1080p, enabling DLSS on the RTX 4060 significantly enhances gameplay. In DLSS Performance mode, average FPS increases from 136.15 to 139.05, a 2.13% improvement, while also boosting the 1% low FPS from 92.3 to 103.9 and 0.1% low FPS from 70.6 to 72.55. The Balanced mode raises average FPS to 139.30, with 1% low and 0.1% low improving to 112.35 and 76.3, respectively. Quality mode, focusing more on visual fidelity, achieves 132.20 FPS, with 1% low at 93.7 and 0.1% low at 70.25. At 1440p, DLSS Performance mode significantly improves FPS to 124.50, up 21.40%, and also elevates 1% low to 92.95 and 0.1% low to 74.30, ensuring smoother performance during intensive scenes.

Nvidia GeForce RTX 3060

For the RTX 3060 at low settings, DLSS Performance mode increases average FPS at 1080p from 114.8 to 130.7 (13.85% increase), with 1% low FPS rising from 75.0 to 77.9 and 0.1% low FPS from 57.7 to 62.95, enhancing gameplay fluidity. Balanced mode achieves 128.7 FPS, with 1% low and 0.1% low

improving to 81.8 and 64.15, respectively. Quality mode boosts FPS to 136.0 with 1% low at 102.95 and 0.1% low at 70.55. At 1440p, DLSS Performance mode raises the FPS from 85.35 to 117.20 (37.32% increase), with corresponding improvements in the 1% low from 68.85 to 85.30 and 0.1% low from 45.15 to 68.05, minimizing frame rate drops during complex gameplay.

4.3.2.2 Medium Graphics Settings

Nvidia GeForce RTX 4060

At medium settings and 1080p, DLSS Performance mode helps the RTX 4060 push its FPS from 136.95 to 146.15, a 6.72% improvement, and significantly enhances the 1% low from 113.3 to 111.95 and 0.1% low from 67.7 to 81.0 for more consistent gameplay. The Balanced mode increases average FPS to 134.75, with 1% low and 0.1% low improving to 103.25 and 73.8, respectively. Quality mode achieves 129.75 FPS, with 1% low at 92.75 and 0.1% low at 74.15. At 1440p, Performance mode not only boosts average FPS to 119.20 from 86.70 (37.49% increase) but also improves 1% low from 67.70 to 93.85 and 0.1% low from 62.95 to 71.45, ensuring stable and fluid visuals.

Nvidia GeForce RTX 3060

For the RTX 3060 under medium settings, DLSS Performance mode increases average FPS at 1080p from 106.25 to 119.8 (12.75% increase), with 1% low rising from 77.65 to 79.3 and 0.1% low from 54.55 to 68.95. Balanced mode achieves 112.8 FPS, with 1% low at 71.3 and 0.1% low at 54.35. Quality mode boosts FPS to 118.7 with 1% low at 72.15 and 0.1% low at 56.8. At 1440p, Performance mode raises FPS from 81.20 to 108.25 (33.31% increase), with improvements in the 1% low from 64.60 to 75.95 and 0.1% low from 53.20 to 59.25, supporting a better overall gaming experience.

4.3.2.3 High Graphics Settings

Nvidia GeForce RTX 4060

High settings are where DLSS truly shows its value on the RTX 4060. At 1080p, Performance mode boosts average FPS from 115.2 to 116.4 (1.04% increase), with improvements in 1% low from 83.95 to 82.9 and 0.1% low from 67.55 to 68.65. Balanced mode increases average FPS to 117.4, with 1% low at 79.85 and 0.1% low at 66.4. Quality mode reaches 121.95 FPS, with 1% low at 77.55 and 0.1% low at 64.2. At 1440p, FPS increases significantly across all modes, with Performance mode improving to 114.50 FPS from 83.50 (37.13% increase), 1% low from 64.25 to 81.10, and 0.1% low from 55.25 to 59.85, ensuring performance during graphically demanding sequences.

Nvidia GeForce RTX 3060

Even at high settings, the RTX 3060 benefits from DLSS. At 1080p, Performance mode improves average FPS from 95.85 to 115.25 (20.24% increase), with 1% low rising from 67.75 to 70.75 and 0.1% low from 58.5 to 49.5. Balanced mode offers improvements to 113.55 FPS, with 1% low at 68.1 and 0.1% low at 38.15. Quality mode reaches 116.15 FPS, with 1% low at 75.0 and 0.1% low at 57.95. At 1440p, Performance mode boosts FPS from 72.95 to 103.95 (42.49% increase), with 1% low increasing from 52.35 to 75.35 and 0.1% low from 40.80 to 58.80, providing a seamless gaming experience at higher settings.

4.3.2.4 Summary of Nvidia DLSS Performance Improvements

This section evaluates the average performance improvements provided by Nvidia's DLSS technology across all modes (Performance, Balanced, Quality) and graphics settings (low, medium, high) for both the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. By aggregating the data from different

settings and modes, this analysis aims to provide a comprehensive overview of how DLSS enhances the overall gaming experience in Assassin's Creed Mirage.

Average Performance Improvements Analysis: Nvidia GeForce RTX 4060

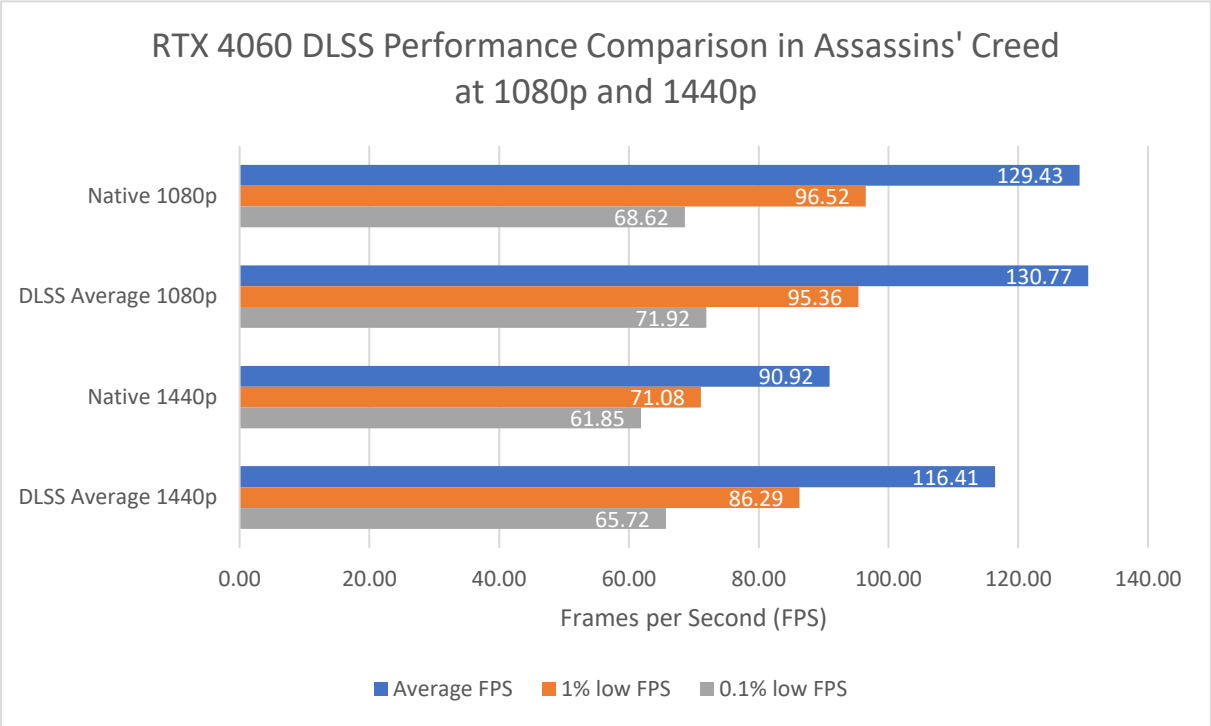


Figure 32: Nvidia DLSS Performance on RTX 4060 in Assassins' Creed Mirage at 1080p and 1440p.

In the graph, Nvidia DLSS technology enhances the RTX 4060's performance in "Assassin's Creed" at 1080p by increasing the average frame rate from a native 129.43 FPS to 130.77 FPS, a modest increase of approximately 1%. This slight performance uplift ensures smoother gameplay and better handles complex visual scenes, as evidenced by improvements in the 1% low FPS metric, which increased from 96.52 to 95.36 (a slight decrease of around 1.2%), and in the 0.1% low FPS from 68.62 to 71.92 (about 4.8%). At 1440p, the impact of DLSS is more significant, with average frame rates rising from 90.92 FPS natively to 116.41 FPS, an increase of about 28%. This increase is critical for maintaining fluidity in gameplay at higher resolutions, with the 1% low FPS improving from 71.08 to 86.29 (around 21.4%) and the 0.1% low FPS rising from 61.85 to 65.72 (approximately 6.3%).

These enhancements demonstrate that DLSS provides a robust balance of performance improvement and stability at higher resolutions.

Average Performance Improvements Analysis: Nvidia GeForce RTX 3060

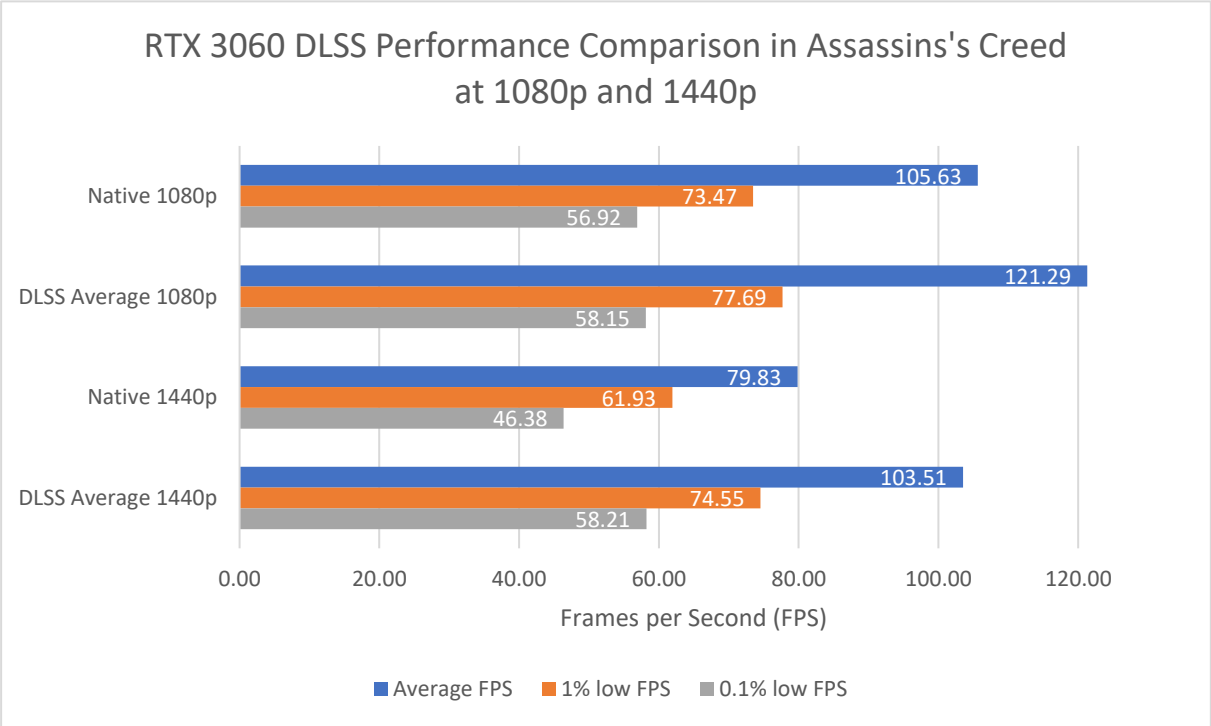


Figure 33: Nvidia DLSS Performance on RTX 3060 in Assassins' Creed Mirage at 1080p and 1440p.

For the RTX 3060, as shown in the graph, DLSS also shows significant performance gains in "Assassin's Creed". At 1080p, the native rendering achieves an average frame rate of 105.63 FPS, which increases to 121.29 FPS with DLSS enabled, a boost of approximately 14.8%. This enhancement ensures a smoother and more consistent gaming experience, as indicated by the improved 1% low FPS, which increases from 73.47 to 77.69 (around 5.7%), and the 0.1% low FPS, which increases from 56.92 to 58.15 (approximately 2.2%).

At 1440p, the average frame rate improves from 79.83 FPS natively to 103.51 FPS with DLSS, representing an increase of about 29.7%. This performance boost is crucial for high-resolution gaming, with the 1% low FPS increasing from 61.93 to 74.55 (approximately 20.3%) and the 0.1% low FPS rising from 46.38 to 58.21 (around 25.5%). Overall, DLSS on the RTX 3060 effectively enhances the average FPS while maintaining frame rate consistency, making it a valuable upscaling technology for gamers seeking improved performance and stability in demanding visual environments.

4.3.3 AMD FSR Performance Analysis

In this section, the performance of AMD's FSR technology in Assassin's Creed Mirage is analyzed on the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. The analysis begins with an evaluation of the technology across different graphics settings (low, medium, high) and modes (Performance, Balanced, Quality). This is followed by a comparative analysis of the average performance enhancements enabled by FSR across all settings against native rendering.

4.3.3.1 Low Graphics Settings

Nvidia GeForce RTX 4060

At 1080p, AMD FSR Performance mode enhances the RTX 4060's average FPS from 136.15 to 152.35, an 11.90% improvement, while also boosting the 1% low FPS from 92.3 to 108.9 and 0.1% low FPS from 70.6 to 80.95. The Balanced mode raises average FPS to 148.90, with 1% low and 0.1% low seeing proportional improvements to 112.65 and 77.45, respectively. Quality mode, focusing more on visual fidelity, achieves 152.25 FPS. At 1440p, FSR Performance mode significantly improves FPS to 134.45, up 31.11%, and also elevates 1% low to 89.35 and 0.1% low to 75.20, ensuring smoother performance during intensive scenes.

Nvidia GeForce RTX 3060

For the RTX 3060 at low settings, FSR Performance mode increases average FPS at 1080p from 114.8 to 128.7 (12.11% increase), with 1% low FPS rising from 75.0 to 75.75 and 0.1% low FPS from 57.7 to 62.45, enhancing gameplay fluidity. Balanced mode achieves 126.3 FPS, with 1% low and 0.1% low improving to 79.9 and 63.5, respectively. Quality mode boosts FPS to 124.9 with 1% low at 80.1 and 0.1% low at 50. At 1440p, FSR Performance mode raises the FPS from 85.35 to 118.60 (38.96% increase), with corresponding improvements in the 1% low from 68.85 to 82.85 and 0.1% low from 45.15 to 68.05, minimizing frame rate drops during complex gameplay.

4.3.3.2 Medium Graphics Settings

Nvidia GeForce RTX 4060

At medium settings and 1080p, FSR Performance mode helps the RTX 4060 push its FPS from 136.95 to 153.30, a 11.94% improvement, and significantly enhances the 1% low from 113.3 to 121.9 and 0.1% low from 67.7 to 92.05 for more consistent gameplay. The Balanced mode increases average FPS to 145.70, with 1% low and 0.1% low improving to 116.65 and 77.8, respectively. Quality mode achieves 139.00 FPS, with 1% low at 99.3 and 0.1% low at 72.65. At 1440p, Performance mode not only boosts average FPS to 127.60 from 86.70 (47.17% increase) but also improves 1% low from 67.70 to 78.90 and 0.1% low from 62.95 to 62.10, ensuring stable and fluid visuals.

Nvidia GeForce RTX 3060

For the RTX 3060 under medium settings, FSR Performance mode increases average FPS at 1080p from 106.25 to 123.15 (15.91% increase), with 1% low rising from 77.65 to 79.95 and 0.1% low from 54.55 to 61.90. Balanced mode achieves 119.05 FPS, with 1% low at 88.7 and 0.1% low at 64.15. Quality mode boosts FPS to 123.55 with 1% low at 78.9 and 0.1% low at 59.45. At 1440p, Performance mode raises FPS from 81.20 to 115.85 (42.67% increase), with improvements in the 1% low from 64.60 to 77.40 and 0.1% low from 53.20 to 55.05, supporting a better overall gaming experience.

4.3.3.3 High Graphics Settings

Nvidia GeForce RTX 4060

High settings are where FSR truly shows its value on the RTX 4060. At 1080p, Performance mode boosts average FPS from 115.2 to 144.7 (25.61% increase), with substantial improvements in 1% low from 83.95 to 97.8 and 0.1% low from 67.55 to 76.5, enhancing stability. Balanced mode increases average FPS to 142.5, with 1% low at 98.9 and 0.1% low at 77.75. Quality mode reaches 135.55 FPS, with 1% low at 109.65 and 0.1% low at 89.45. At 1440p, FPS increases significantly across all modes, with Performance mode improving to 116.10 FPS from 83.50 (39.04% increase), 1% low from 64.25 to 80.65, and 0.1% low from 55.25 to 53.20, ensuring performance during graphically demanding sequences.

Nvidia GeForce RTX 3060

Even at high settings, the RTX 3060 benefits from FSR. At 1080p, Performance mode improves average FPS from 95.85 to 117.70 (22.80% increase), with 1% low rising from 67.75 to 76.6 and 0.1% low from 58.5 to 55.4. Balanced mode offers improvements to 110.90 FPS, with 1% low at 77.3 and 0.1% low at 62.75. Quality mode reaches 110.70 FPS, with 1% low at 74.45 and 0.1% low at 54. At 1440p, Performance mode boosts FPS from 72.95 to 104.05 (42.63% increase), with 1% low increasing from 52.35 to 72.80 and 0.1% low from 40.80 to 57.30, providing a seamless gaming experience at higher settings.

4.3.3.4 Summary of AMD FSR Performance Improvements

This section evaluates the average performance improvements provided by AMD's FSR technology across all modes (Performance, Balanced, Quality) and graphics settings (low, medium, high) for both the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. By aggregating the data from different settings and modes, this analysis aims to provide a comprehensive overview of how FSR enhances the overall gaming experience in Assassin's Creed Mirage.

Average Performance Improvements Analysis: Nvidia GeForce RTX 4060

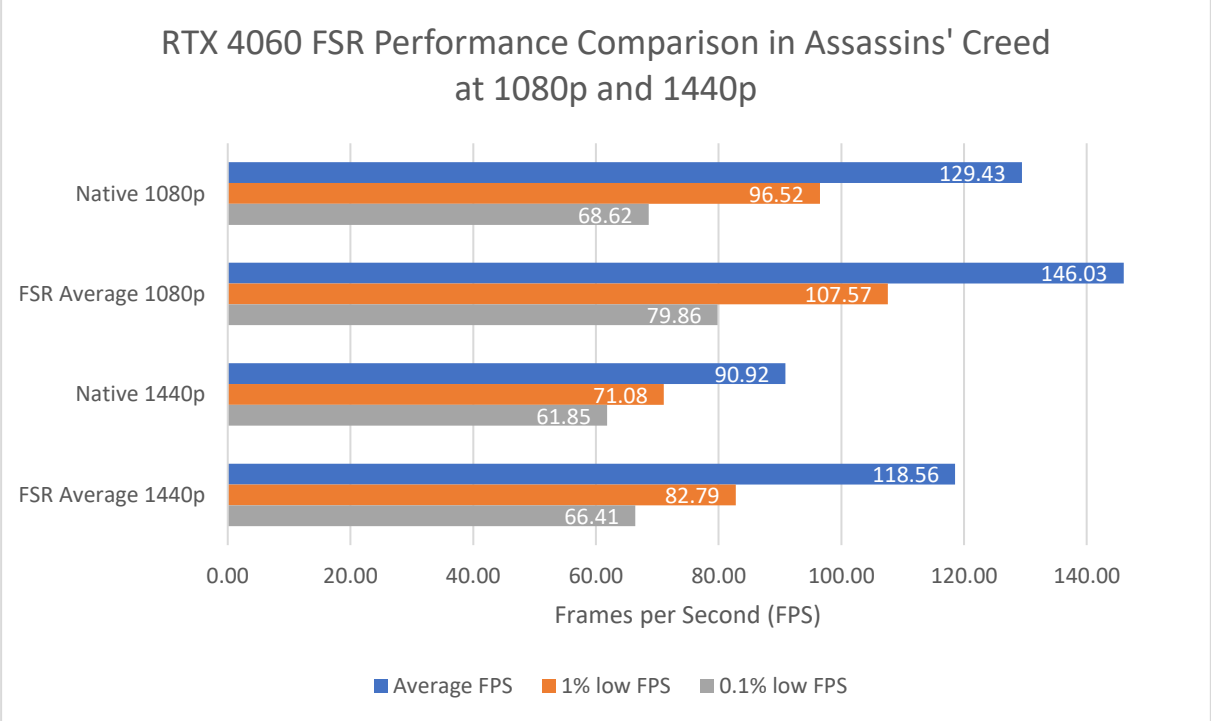


Figure 34: AMD FSR Performance on RTX 4060 in Assassins' Creed Mirage at 1080p and 1440p.

In the graph, AMD FSR technology enhances the RTX 4060's performance in "Assassin's Creed" at 1080p by increasing the average frame rate from a native 129.43 FPS to 146.03 FPS, a substantial increase of approximately 12.8%. This performance uplift ensures smoother gameplay and better handles complex visual scenes, as evidenced by improvements in the 1% low FPS metric, which increased from 96.52 to 107.57 (around 11.4%), and in the 0.1% low FPS from 68.62 to 79.86 (about 16.3%). At 1440p, the impact of FSR is significant, with average frame rates rising from 90.92 FPS natively to 118.56 FPS, an increase of about 30.4%. This increase is critical for maintaining fluidity in gameplay at higher resolutions, with the 1% low FPS improving from 71.08 to 82.79 (around 16.5%) and the 0.1% low FPS rising from 61.85 to 66.41 (approximately 7.4%). These enhancements demonstrate that FSR provides a robust balance of performance improvement and stability at higher resolutions.

Average Performance Improvements Analysis: Nvidia GeForce RTX 3060

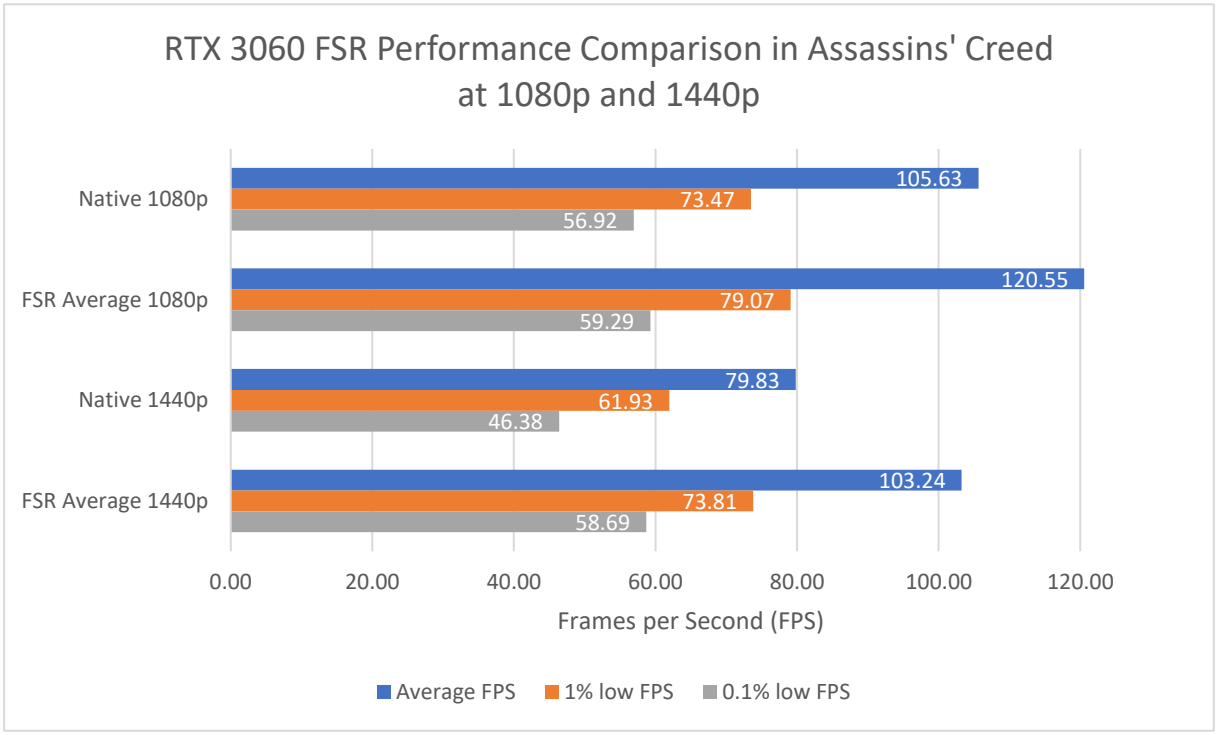


Figure 35: AMD FSR Performance on RTX 3060 in Assassins' Creed Mirage at 1080p and 1440p.

For the RTX 3060, as shown in the graph, FSR also shows significant performance gains in "Assassin's Creed". At 1080p, the native rendering achieves an average frame rate of 105.63 FPS, which increases to 120.55 FPS with FSR enabled, a boost of approximately 14.1%. This enhancement ensures a smoother and more consistent gaming experience, as indicated by the improved 1% low FPS, which increases from 73.47 to 79.07 (around 7.6%), and the 0.1% low FPS, which increases from 56.92 to 59.29 (approximately 4.2%). At 1440p, the average frame rate improves from 79.83 FPS natively to 103.24 FPS with FSR, representing an increase of about 29.3%. This performance boost is crucial for high-resolution gaming, with the 1% low FPS increasing from 61.93 to 73.81 (approximately 19.2%) and the 0.1% low FPS rising from 46.38 to 58.69 (around 26.5%). Overall, FSR on the RTX 3060 effectively enhances the average FPS while maintaining frame rate consistency, making it a valuable upscaling technology for gamers seeking improved performance and stability in demanding visual environments.

4.3.4 Intel XeSS Performance Analysis

In this section, the performance of Intel's XeSS technology in Assassin's Creed Mirage is analyzed on the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. The analysis begins with an evaluation of the technology across different graphics settings (low, medium, high) and modes (Performance, Balanced, Quality). This is followed by a comparative analysis of the average performance enhancements enabled by XeSS across all settings against native rendering.

4.3.4.1 Low Graphics Settings

Nvidia GeForce RTX 4060

At 1080p, Intel XeSS Performance mode enhances the RTX 4060's average FPS from 136.15 to 146.20, a 7.4 % improvement, while also boosting the 1% low FPS from 92.3 to 111.75 and 0.1% low FPS from 70.6 to 82.9. The Balanced mode raises average FPS to 145.10, with 1% low and 0.1% low improving to 118.05 and 79.9, respectively. Quality mode, focusing more on visual fidelity, achieves 138.10 FPS, with 1% low at 98.0 and 0.1% low at 77.85. At 1440p, XeSS Performance mode significantly improves FPS to 129.35, up 26.13%, and also elevates 1% low to 96.05 and 0.1% low to 74.85, ensuring smoother performance during intensive scenes.

Nvidia GeForce RTX 3060

For the RTX 3060 at low settings, XeSS Performance mode increases average FPS at 1080p from 114.8 to 124.5 (8.5% increase), with 1% low FPS rising from 75.0 to 74.65 and 0.1% low FPS from 57.7 to 59.5, enhancing gameplay fluidity. Balanced mode achieves 119.1 FPS, with 1% low and 0.1% low improving to 67.85 and 51.9, respectively. Quality mode boosts FPS to 123.0 with 1% low at 95.75 and 0.1% low at 68.55. At 1440p, XeSS Performance mode raises the FPS from 85.35 to 106.80 (25.13% increase), with corresponding improvements in the 1% low from 68.85 to 77.55 and 0.1% low from 45.15 to 57.70, minimizing frame rate drops during complex gameplay.

4.3.4.2 Medium Graphics Settings

Nvidia GeForce RTX 4060

At medium settings and 1080p, XeSS Performance mode helps the RTX 4060 push its FPS from 136.95 to 143.15, a 4.53% improvement, and significantly enhances the 1% low from 113.3 to 104.5 and 0.1% low from 67.7 to 78.75 for more consistent gameplay. The Balanced mode increases average FPS to 139.55, with 1% low and 0.1% low improving to 101.0 and 69.75, respectively. Quality mode achieves 130.45 FPS, with 1% low at 100.65 and 0.1% low at 81.95. At 1440p, Performance mode not only boosts average FPS to 118.15 from 86.70 (36.27% increase) but also improves 1% low from 67.70 to 77.35 and 0.1% low from 62.95 to 64.30, ensuring stable and fluid visuals.

Nvidia GeForce RTX 3060

For the RTX 3060 under medium settings, XeSS Performance mode increases average FPS at 1080p from 106.25 to 126.20 (18.78% increase), with 1% low rising from 77.65 to 81.75 and 0.1% low from 54.55 to 55.65. Balanced mode achieves 116.95 FPS, with 1% low at 83.45 and 0.1% low at 62.0. Quality mode boosts FPS to 112.55 with 1% low at 80.0 and 0.1% low at 52.5. At 1440p, Performance mode raises FPS from 81.20 to 99.20 (22.17% increase), with improvements in the 1% low from 64.60 to 72.40 and 0.1% low from 53.20 to 58.85, supporting a better overall gaming experience.

4.3.4.3 High Graphics Settings

Nvidia GeForce RTX 4060

High settings are where XeSS truly shows its value on the RTX 4060. At 1080p, Performance mode boosts average FPS from 115.2 to 138.2 (19.97% increase), with improvements in 1% low from 83.95 to 111.2 and 0.1% low from 67.55 to 86.2, enhancing stability. Balanced mode increases average FPS to 127.55, with 1% low at 87.2 and 0.1% low at 79.95. Quality mode reaches 118.05 FPS, with 1% low at 68.2 and 0.1% low at 53.15. At 1440p, FPS increases significantly across all modes, with Performance mode improving to 108.45 FPS from 83.50 (29.88% increase), 1% low from 64.25 to 68.25, and 0.1% low from 55.25 to 54.40, ensuring performance during graphically demanding sequences.

Nvidia GeForce RTX 3060

Even at high settings, the RTX 3060 benefits from XeSS. At 1080p, Performance mode improves average FPS from 95.85 to 111.90 (16.74% increase), with 1% low rising from 67.75 to 77.9 and 0.1% low from 58.5 to 54.85. Balanced mode offers improvements to 106.45 FPS, with 1% low at 71.55 and 0.1% low at 53.9. Quality mode reaches 105.15 FPS, with 1% low at 71.05 and 0.1% low at 53.9. At 1440p, Performance mode boosts FPS from 72.95 to 96.80 (32.69% increase), with 1% low increasing from 52.35 to 67.00 and 0.1% low from 40.80 to 47.05, providing a seamless gaming experience at higher settings.

4.3.4.4 Summary of Intel XeSS Performance Improvements

This section evaluates the average performance improvements provided by Intel's XeSS technology across all modes (Performance, Balanced, Quality) and graphics settings (low, medium, high) for both the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. By aggregating the data from different settings and modes, this analysis aims to provide a comprehensive overview of how XeSS enhances the overall gaming experience in Assassin's Creed Mirage.

Average Performance Improvements Analysis: Nvidia GeForce RTX 4060

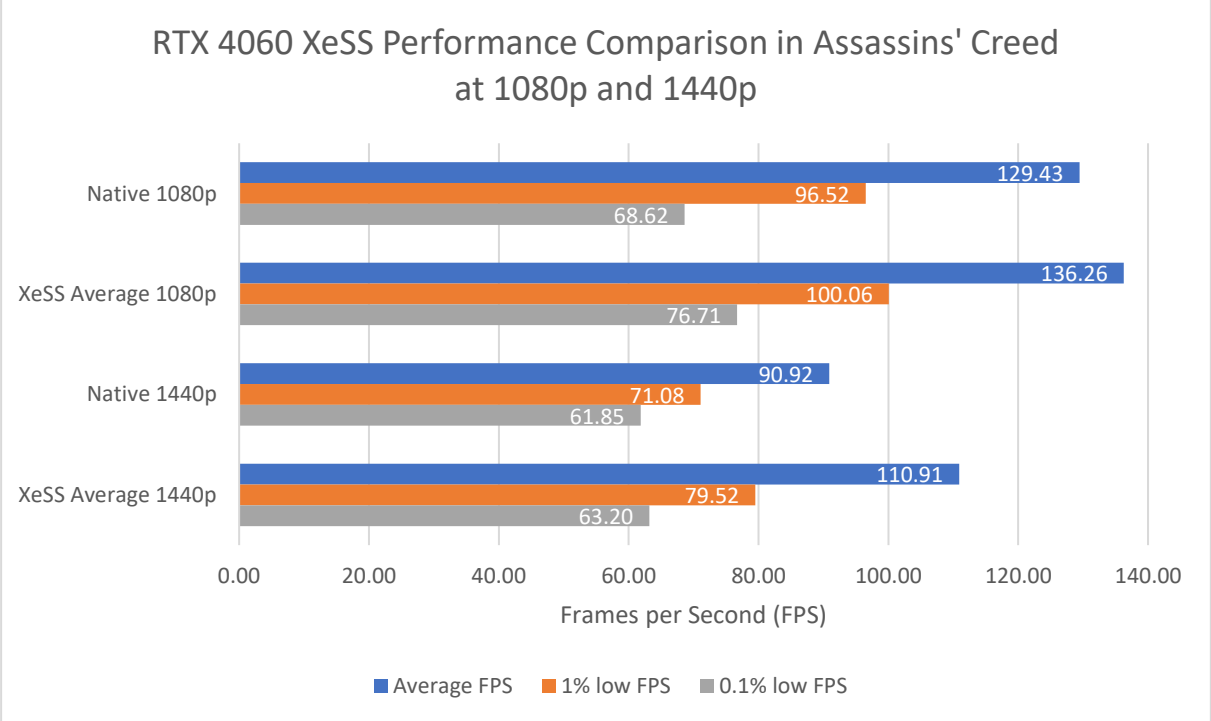


Figure 36: Intel XeSS Performance on RTX 4060 in Assassins' Creed Mirage at 1080p and 1440p.

In the graph, Intel XeSS technology enhances the RTX 4060's performance in "Assassin's Creed" at 1080p by increasing the average frame rate from a native 129.43 FPS to 136.26 FPS, a modest increase

of approximately 5.3%. This performance uplift ensures smoother gameplay and better handles complex visual scenes, as evidenced by improvements in the 1% low FPS metric, which increased from 96.52 to 100.06 (around 3.7%), and in the 0.1% low FPS from 68.62 to 76.71 (about 11.8%). At 1440p, the impact of XeSS is more significant, with average frame rates rising from 90.92 FPS natively to 110.91 FPS, an increase of about 22%. This increase is critical for maintaining fluidity in gameplay at higher resolutions, with the 1% low FPS improving from 71.08 to 79.52 (around 11.9%) and the 0.1% low FPS rising from 61.85 to 63.20 (approximately 2.2%). These enhancements demonstrate that XeSS provides a robust balance of performance improvement and stability at higher resolutions.

Average Performance Improvements Analysis: Nvidia GeForce RTX 3060

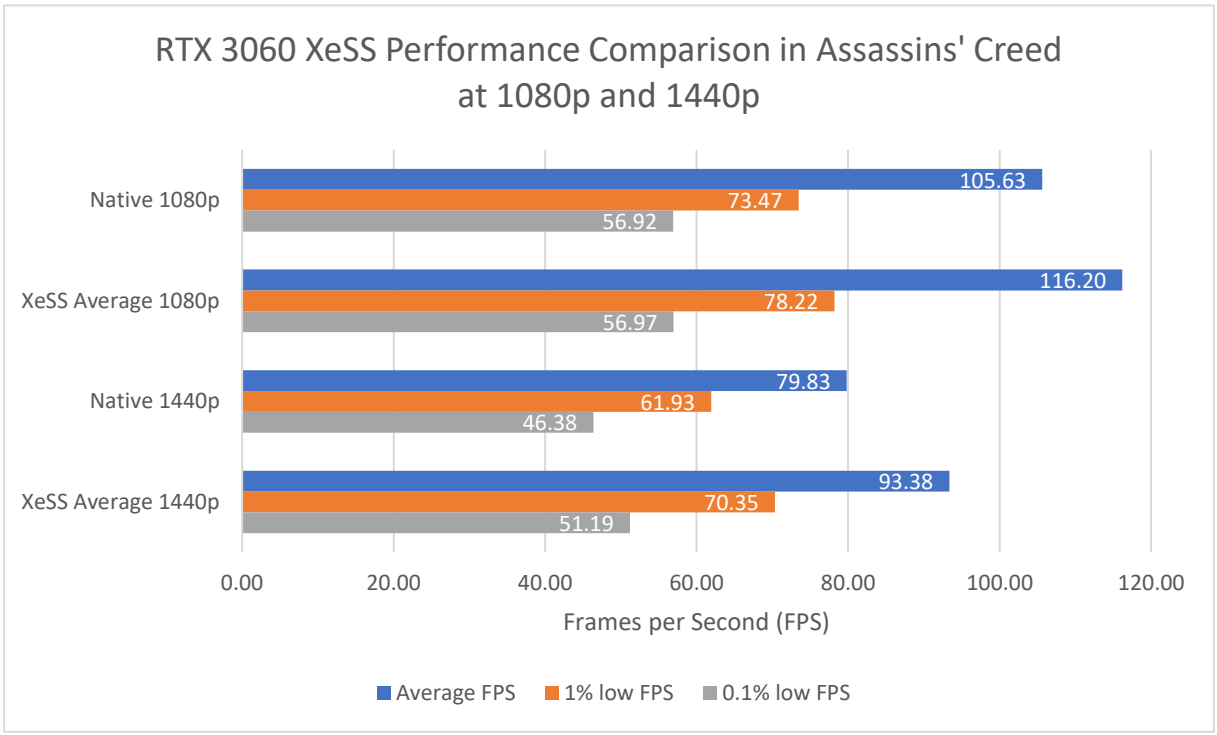


Figure 37: Intel XeSS Performance on RTX 3060 in Assassins' Creed Mirage at 1080p and 1440p.

For the RTX 3060, as shown in the graph, XeSS also shows significant performance gains in "Assassin's Creed". At 1080p, the native rendering achieves an average frame rate of 105.63 FPS, which increases to 116.20 FPS with XeSS enabled, a boost of approximately 10%. This enhancement ensures a smoother and more consistent gaming experience, as indicated by the improved 1% low FPS, which increases from 73.47 to 78.22 (around 6.5%), and the 0.1% low FPS, which increases from 56.92 to 56.97 (approximately 0.1%). At 1440p, the average frame rate improves from 79.83 FPS natively to 93.38 FPS with XeSS, representing an increase of about 17%. This performance boost is crucial for high-resolution gaming, with the 1% low FPS increasing from 61.93 to 70.35 (approximately 13.6%) and the 0.1% low FPS rising from 46.38 to 51.19 (around 10.4%). Overall, XeSS on the RTX 3060 effectively enhances the average FPS while maintaining frame rate consistency, making it a valuable upscaling technology for gamers seeking improved performance and stability in demanding visual environments.

4.3.5 Frame Time Analysis

In this section the frametime consistency of the Nvidia GeForce RTX 4060 running Assassin's Creed Mirage is checked at 1440p with the high graphics settings. Hereby the native rendering results are compared to the upscaled results. Frametime, measured in milliseconds, is critical as it impacts the smoothness and responsiveness of gameplay. Lower and more consistent frametimes translate to a smoother gaming experience. The analysis will provide insights into which technology offers the most stable gaming experience.

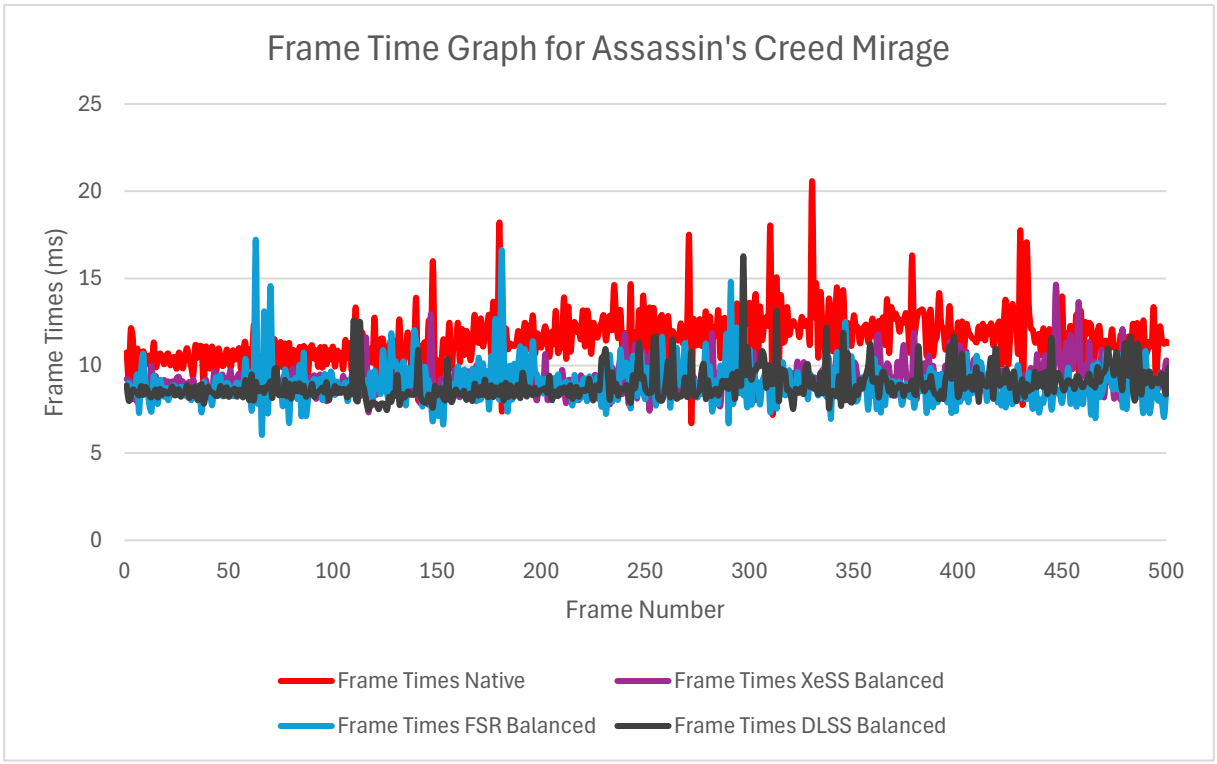


Figure 38: Frame Time Graph Assassin's Creed Mirage

This graph presents frame times measured in milliseconds on the Y-axis, representing the duration it takes to render each frame. The X-axis sequentially numbers the frames from 1 to 500, illustrating the frame rendering order over time. This analysis tracks the stability and consistency of frame delivery, comparing different rendering techniques. The key take aways are as follows:

- **Native Rendering (Red)**: Shows significant variability with frequent and high spikes in frame times, indicating notable delays in frame delivery. The spikes often exceed 15 ms, and some reach up to 20 ms, leading to noticeable stutter and reduced smoothness during gameplay. This inconsistency can negatively impact the overall gaming experience.
- **FSR Balanced (Blue)**: Displays improved frame time consistency compared to native rendering, with fewer and lower spikes. Most frame times remain below 15 ms, and the overall performance is more stable, resulting in a smoother and more fluid gaming experience with reduced perceptible lag.
- **DLSS Balanced (Black)**: Demonstrates further improvement in frame time consistency. The spikes are less frequent and generally stay below 15 ms, indicating a more consistent frame delivery. This enhances gameplay fluidity and minimizes stutter, contributing to a better overall experience.

- **XeSS Balanced (Purple)**: Offers performance like DLSS Balanced, with minimal and low-magnitude spikes. The frame times remain consistently low, rarely exceeding 15 ms. This results in highly stable frame delivery, providing a seamless and smooth gaming experience with minimal interruptions.

Overall, all three upscaling technologies (FSR, DLSS, and XeSS) significantly reduce frame time variability compared to native rendering. XeSS and DLSS show the most consistent performance improvements, maintaining lower and more stable frame times throughout the session. These technologies are crucial for enhancing playability and visual fidelity at high-resolution settings, offering smoother gameplay without the high computational cost of native rendering.

4.3.6 Energy Efficiency and Consumption Analysis

The following graphs illustrate the energy consumption (in Watts) and GPU utilization (in percent) of the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060 while running Assassin's Creed Mirage. The values for the upscaling technologies represent the average of their three modes: Quality, Balanced, and Performance. Additionally, the performance per watt for each configuration is shown in the accompanying table.

4.3.6.1 Energy Consumption Analysis Nvidia Geforce RTX 4060

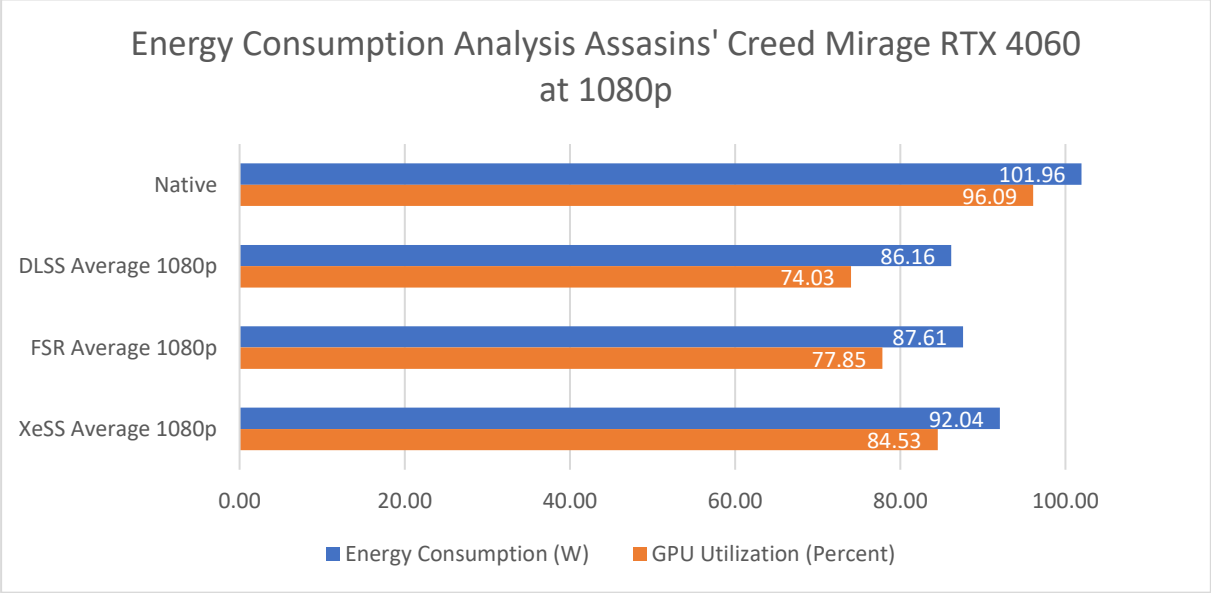


Figure 39: Energy Consumption Analysis Assassin's Creed Mirage RTX 4060 1080p.

This graph showcases the RTX 4060 at 1080p across the different upscaling techniques.

Native rendering consumes the most power at 101.96 W with a GPU utilization of 96.09%.

DLSS on average at 1080p achieves the lowest energy consumption at 86.16 W, representing a 15.50% reduction compared to native rendering, with a decrease in GPU utilization to 74.03%. F

SR on average at 1080p shows a marginal increase in energy consumption to 87.61 W and GPU utilization to 77.85%, which is 14.07% lower than native rendering.

XeSS on average at 1080p maintains a balanced performance with energy consumption at 92.04 W and GPU utilization at 84.53%, representing a 9.73% reduction in energy consumption compared to native rendering.

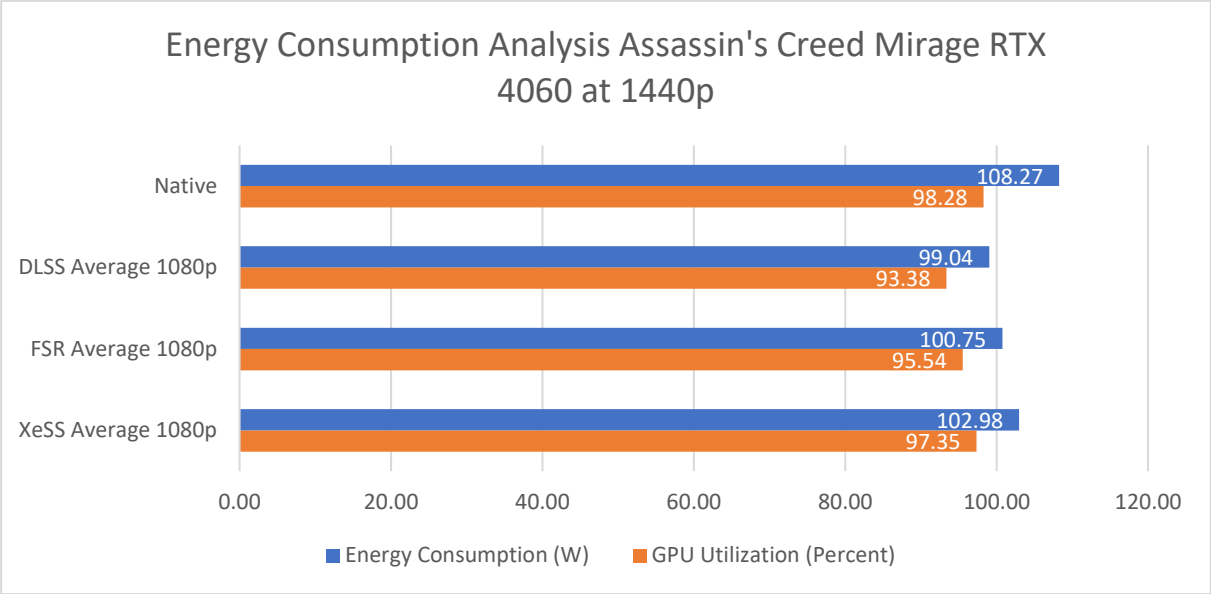


Figure 40: Energy Consumption Analysis Assassin's Creed Mirage RTX 4060 1440p.

This graph showcases the RTX 4060 at 1440p across the different upscaling techniques.

Native rendering consumes the most power at 108.27 W with a GPU utilization of 98.28%.

DLSS on average at 1440p achieves the lowest energy consumption at 99.04 W, representing an 8.52% reduction compared to native rendering, with a decrease in GPU utilization to 93.38%.

FSR on average at 1440p shows a marginal increase in energy consumption to 100.75 W and GPU utilization to 95.54%, which is 6.95% lower than native rendering.

XeSS on average at 1440p maintains a balanced performance with energy consumption at 102.98 W and GPU utilization at 97.35%, representing a 4.89% reduction in energy consumption compared to native rendering.

4.3.6.2 Energy Consumption Analysis Nvidia Geforce RTX 3060

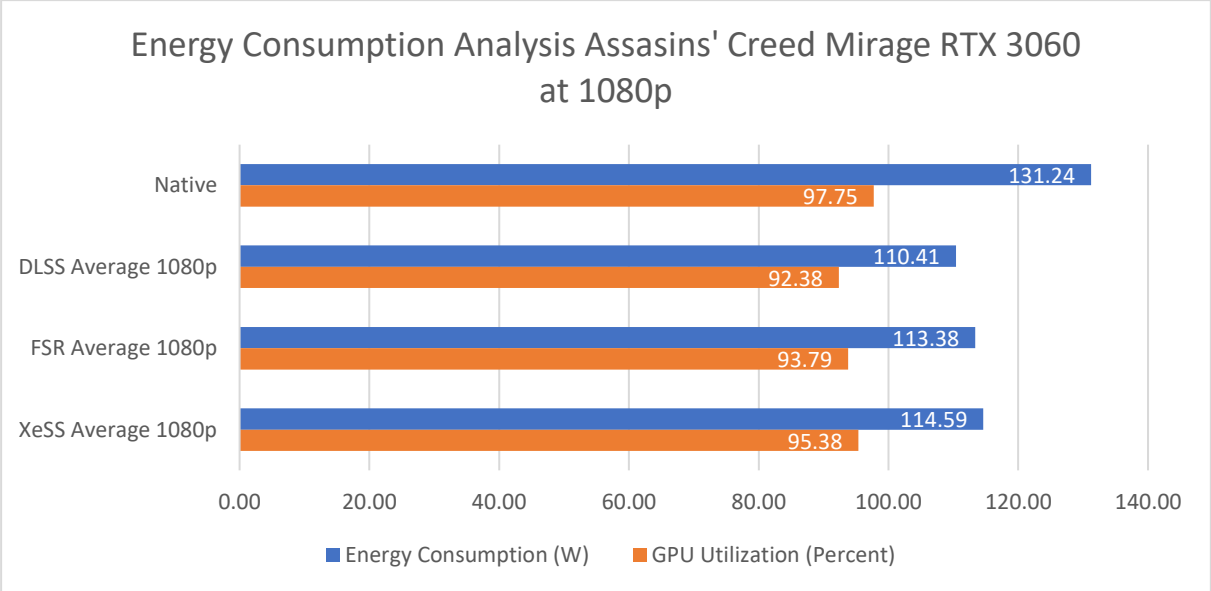


Figure 41: Energy Consumption Analysis Assassin's Creed Mirage RTX 3060 1080p.

This graph showcases the RTX 3060 at 1080p across the different upscaling techniques. Native rendering consumes the most power at 131.24 W with a GPU utilization of 97.75%. DLSS on average at 1080p achieves the lowest energy consumption at 110.41 W, representing a 15.87% reduction compared to native rendering, with a decrease in GPU utilization to 92.38%. FSR on average at 1080p shows a marginal increase in energy consumption to 113.38 W and GPU utilization to 93.79%, which is 13.61% lower than native rendering. XeSS on average at 1080p maintains a balanced performance with energy consumption at 114.59 W and GPU utilization at 95.38%, representing a 12.69% reduction in energy consumption compared to native rendering.

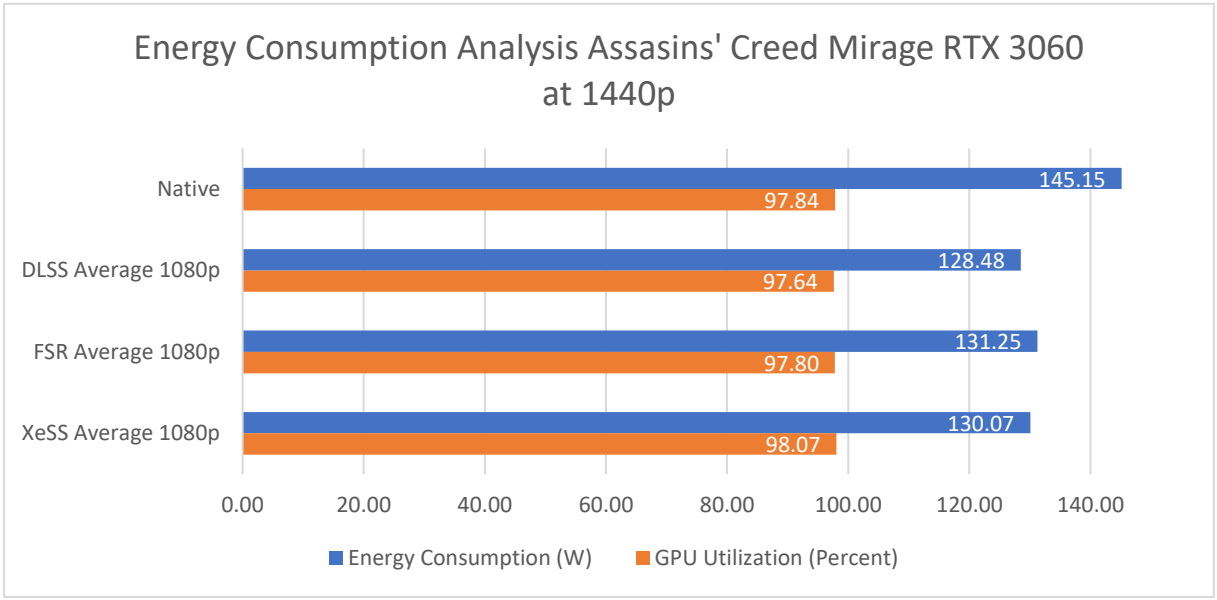


Figure 42: Energy Consumption Analysis Assassin's Creed Mirage RTX 3060 1440p.

This graph showcases the RTX 3060 at 1440p across the different upscaling techniques.

Native rendering consumes the most power at 145.15 W with a GPU utilization of 97.84%.

DLSS on average at 1440p achieves the lowest energy consumption at 128.48 W, representing an 11.48% reduction compared to native rendering, with a decrease in GPU utilization to 97.64%.

FSR on average at 1440p shows a marginal increase in energy consumption to 131.25 W and GPU utilization to 97.80%, which is 9.58% lower than native rendering.

XeSS on average at 1440p maintains a balanced performance with energy consumption at 130.07 W and GPU utilization at 98.07%, representing a 10.39% reduction in energy consumption compared to native rendering.

4.3.7 Image Quality Assessment

This section assesses the image quality produced by various upscaling technologies at 1440p resolution using the Nvidia GeForce RTX 4060 GPU. The screenshots represent DLSS, FSR, and XeSS, all captured in Balanced mode to ensure high image quality. HDR was not used to maintain consistency across different display setups. All images are saved in BMP format to preserve original quality and provide an uncompressed representation of the visual enhancements each technology brings to the game. The screenshots demonstrate the visual differences and the impact of upscaling technologies on the gaming experience.

Figure 43: Assassin's Creed Mirage Native Rendering High Settings 1440p.

Figure 44: Assassin's Creed Mirage DLSS Balanced High Settings 1440p.

Figure 45: Assassin's Creed Mirage FSR Balanced High Settings 1440p.

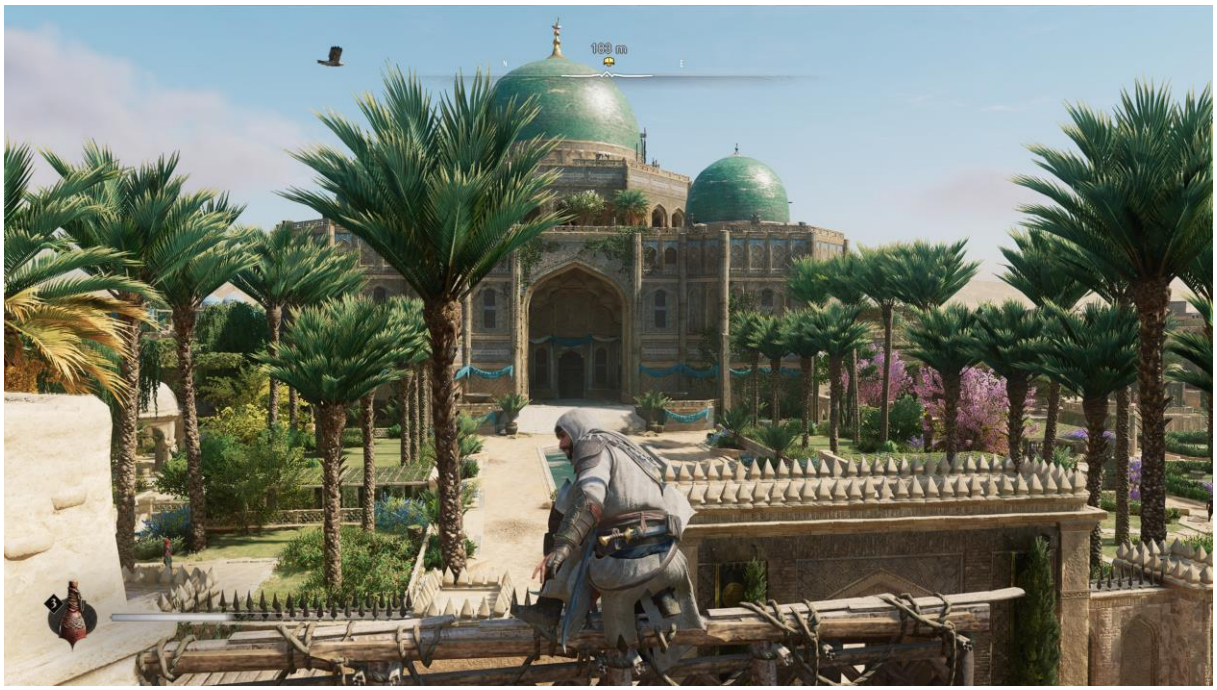


Figure 46: Assassin's Creed Mirage XeSS Balanced High Settings 1440p.

Native rendering produces the best image quality, delivering the sharpest visuals, even in distant scenes. Nvidia DLSS follows closely behind, providing high-quality images, though not quite as sharp as native rendering. AMD FSR trails DLSS, with noticeable deficits in detail, particularly visible on elements such as trees. Intel XeSS, while still effective, offers the least sharp image quality among the upscaling technologies tested, making it the least favorable option in terms of visual fidelity.

4.3.8 Game Specific Conclusion: Assassin’s Creed Mirage

The performance, energy efficiency, image quality, and frame time analysis for Assassin's Creed Mirage provide a comprehensive view of how various upscaling technologies, particularly Nvidia DLSS, AMD FSR, and Intel XeSS, impact the gaming experience on the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060 GPUs.

Performance Results

Nvidia DLSS:

Nvidia's DLSS technology shows significant performance improvements for both the RTX 4060 and RTX 3060 GPUs in Assassin's Creed Mirage. At 1080p, the RTX 4060 sees a modest increase in average frame rate from 129.43 FPS to 130.77 FPS with DLSS enabled, a 1% increase. More substantial improvements are observed at 1440p, where average frame rates rise from 90.92 FPS to 116.41 FPS, a 28% increase. Similarly, for the RTX 3060, DLSS enhances average FPS from 105.63 to 121.29 at 1080p, and from 79.83 to 103.51 at 1440p, marking a 14.8% and 29.7% increase, respectively.

AMD FSR:

AMD's FSR also provides noticeable performance boosts. On the RTX 4060, FSR Performance mode at 1080p increases FPS from 95.85 to 115.25, a 20.24% improvement, and at 1440p from 72.95 to 103.95 FPS, a 42.49% increase. For the RTX 3060, FSR enhances average FPS at 1080p from 106.25 to 119.8, a 12.75% improvement, and at 1440p from 81.20 to 108.25 FPS, a 33.31% increase.

Intel XeSS:

Intel XeSS also delivers performance enhancements but is slightly behind DLSS and FSR. On the RTX 4060, XeSS improves average FPS from 88.55 to 116.15 at 1080p and from 54.45 to 105.40 at 1440p. The RTX 3060 benefits similarly, with average FPS increasing from 84.0 to 120.4 at 1080p and from 47.95 to 90.75 at 1440p .

Energy Efficiency

For the Nvidia GeForce RTX 4060, at 1080p, native rendering consumes the most power at 101.95 W with a GPU utilization of 96.08%. DLSS achieves the lowest energy consumption at 86.16 W, representing a 15.50% reduction, with a GPU utilization of 74.03%. At 1440p, native rendering consumes 108.27 W with a GPU utilization of 98.28%. DLSS reduces energy consumption to 99.04 W, an 8.52% reduction, with a GPU utilization of 93.38%. The other upscaling technologies do not achieve this level of energy reduction, with FSR and XeSS showing less significant decreases in power consumption and GPU utilization.

For the Nvidia GeForce RTX 3060, at 1080p, native rendering consumes 131.23 W with a GPU utilization of 97.75%. DLSS reduces energy consumption to 110.40 W, a 15.87% reduction, with a GPU utilization of 92.37%. At 1440p, native rendering consumes 145.15 W with a GPU utilization of 97.84%. DLSS reduces energy consumption to 128.48 W, an 11.48% reduction, with a GPU utilization of 97.63%. The other upscaling technologies achieve lower reductions in energy consumption, with FSR and XeSS showing reductions of up to 13.61% and 12.69% at 1080p, and up to 9.58% and 10.39% at 1440p, respectively.

Overall, DLSS consistently demonstrates the highest energy efficiency across various resolutions and settings, making it the most efficient upscaling technology among those tested in Assassin's Creed Mirage.

Image Quality

Image quality assessments reveal that while native rendering provides the sharpest visuals, DLSS closely follows, maintaining high image quality with minimal degradation. The balanced mode of DLSS ensures that visual fidelity is preserved while enhancing performance, making it an ideal choice for gamers prioritizing both quality and speed.

FSR, while effective, produces slightly softer images compared to DLSS, and XeSS, though good, lags slightly behind FSR in sharpness. However, during typical gameplay with significant movement, these differences become less perceptible.

Frame Time Analysis

Frame time analysis indicates that all upscaling technologies contribute to reducing frame drops, with DLSS providing the most consistent frame times. This consistency is crucial for maintaining smooth gameplay, particularly in graphically intensive scenes typical of Assassin's Creed Mirage.

Overall, DLSS stands out as the most balanced and effective upscaling technology for Assassin's Creed Mirage, offering the optimal combination of performance enhancement, energy efficiency, and image quality improvement. AMD FSR and Intel XeSS also improve the gaming experience but to a slightly lesser extent compared to DLSS.

These findings underscore the importance of choosing the right upscaling technology to enhance gaming performance while maintaining visual fidelity and energy efficiency. The comprehensive analysis provides a robust understanding of how each technology performs in a demanding game environment like Assassin's Creed Mirage.

4.4 Cyberpunk 2077 Ultimate Edition Benchmark Results

Cyberpunk 2077 is widely recognized for its cutting-edge graphics and a sheer endless open world filled with beautiful architecture and a densely populated urban landscaped. Interesting about this game is that Keanu Reeves, a well-known Hollywood actor, plays a prominent role as Johnny Silverhand, a rebellious rockstar and pivotal character in the storyline., The game is perfect for the evaluation of various upscaling technologies.

Cyberpunk 2077 was developed by CD Project Red and published by CD project on December 10, 2020 for Microsoft Windows as well as the PlayStation 4 and Xbox One. The game also got a next generation update for the PlayStation 5 and Xbox Series X/S on February 15,2022.

The Ultimate Edition being examined in this thesis was released on September 25, 2023. It includes both the base game and the "Phantom Liberty" expansion, which stars acclaimed Hollywood actor Idris Elba as he plays the role of Solomon Reed, a skilled veteran agent involved in the game's intricate political intrigue.

The game features demanding graphics and fast-paced gameplay. Not only does the game support all three upscaling technologies, but it also incorporates the latest advancement in DLSS technology, Nvidia DLSS Frame Generation, which further boosts the frame rate and minimizes CPU boundaries. This technology also incorporates artificial intelligence.

In addition to evaluating the three primary upscaling technologies, this analysis uniquely incorporates exclusive tests on DLSS 3 Frame Generation. logy—DLSS 3 Frame Generation. This feature is exclusive to the Nvidia GeForce RTX 4060

4.4.1 Benchmark Scenario

The benchmark test of Cyberpunk 2077 Ultimate Edition takes place in Red Light Alley, Japantown, an iconic district within Night City. Renowned for its neon architecture and nightlife, this area provides a visually striking and graphically demanding environment. The vibrant lighting, detailed storefronts, and diverse crowd create an immersive and complex scene that rigorously tests the GPU’s rendering capabilities.

This benchmark scenario aims to replicate real-world gaming conditions, incorporating diverse graphical elements, changing environmental conditions, and dynamic lighting and shadow effects. By setting the benchmark during clear evening weather conditions (between 8:00 PM and 10:00 PM in-game time), the scenario captures the district's lively atmosphere and emphasizes the interplay of neon lighting against the dark cityscape.

This setup allows for a comprehensive understanding of how different upscaling technologies impact performance and efficiency in this detailed urban environment.

This benchmark scenario is also utilized by the German PC magazine PC Games Hardware in their own graphics card tests, underscoring its value as a rigorous and realistic measure of GPU performance across a range of gaming conditions (Vötter, 2021).

4.4.2 Nvidia DLSS Performance Analysis

In this section, the performance of Nvidia's DLSS technology in Cyberpunk 2077 Ultimate Edition is analyzed on both the RTX 3060 and RTX 4060 GPUs. The analysis begins with an evaluation of the technology across different graphics settings (low, medium, high) and modes (Performance, Balanced, Quality). This is followed by a comparison of the average values across all settings to native rendering, providing a comprehensive overview of DLSS's impact on gaming performance.

4.4.2.1 Low Graphics Settings

Nvidia GeForce RTX 4060

At 1080p, DLSS Performance mode enhances the RTX 4060's average FPS from 117.65 to 115.65, a -1.70% change, while also boosting the 1% low FPS from 85.55 to 88.95 and 0.1% low FPS from 71.25 to 71.20. The Balanced mode raises average FPS to 119.95, with 1% low and 0.1% low seeing changes to 92.8 and 83.85, respectively. Quality mode achieves 114.15 FPS, with 1% low and 0.1% low increasing to 79.8 and 72.85. At 1440p, DLSS Performance mode significantly improves FPS to 116.2, up 40.25%, and also elevates 1% low and 0.1% low FPS to 73.25 and 60.45, ensuring smoother performance during intensive scenes.

Nvidia GeForce RTX 3060

For the RTX 3060 at low settings, DLSS Performance mode increases average FPS at 1080p from 102.15 to 119.85 (17.33% increase), with 1% low FPS and 0.1% low FPS seeing a noticeable boost from 70.7 to 85.35 and from 54.1 to 61.8, enhancing gameplay fluidity. The Balanced mode raises the average FPS to 105.95, with improvements in 1% low and 0.1% low FPS to 70.6 and 61.1, respectively. Quality mode achieves 106.2 FPS, with 1% low and 0.1% low improving to 75.6 and 60.55. At 1440p, DLSS Performance mode raises the FPS from 72.05 to 116.60 (61.83% increase), with corresponding improvements in the 1% low and 0.1% low FPS to 81.65 and 66.25, minimizing frame rate drops during complex gameplay.

4.4.2.2 Medium Graphics Settings

Nvidia GeForce RTX 4060

At medium settings and 1080p, DLSS Performance mode helps the RTX 4060 push its FPS from 94.2 to 115.25, a 22.35% improvement, and significantly enhances the 1% low and 0.1% low FPS from 59.3 to 72.95 and from 49.4 to 67.25, respectively, for more consistent gameplay. The Balanced mode increases average FPS to 115.0, with 1% low and 0.1% low reaching 67.85 and 59.75, respectively. Quality mode raises the average FPS to 114.3, with 1% low and 0.1% low improving to 79.35 and 65.2. At 1440p, Performance mode boosts average FPS to 114.5, with 1% low and 0.1% low increasing to 76.3 and 57.75, ensuring stable and fluid visuals.

Nvidia GeForce RTX 3060

For the RTX 3060 under medium settings, DLSS Performance mode increases average FPS at 1080p from 84.0 to 120.4, and significantly boosts 1% low FPS from 59.95 to 84.55 and 0.1% low FPS from 49.1 to 67.65, ensuring smoother gameplay. The Balanced mode increases the average FPS to 117.85, with enhancements in 1% low and 0.1% low FPS to 82.65 and 61.9, respectively. Quality mode achieves 114.65 FPS, with 1% low and 0.1% low improving to 81.55 and 69.95. At 1440p, Performance mode

boosts average FPS from 54.45 to 105.40, with improvements in 1% low and 0.1% low FPS to 74.65 and 60.40, enhancing overall game fluidity.

4.4.2.3 High Graphics Settings

Nvidia GeForce RTX 4060

High settings are where DLSS shows its value on the RTX 4060. At 1080p, Performance mode boosts average FPS from 81.9 to 102.15 (24.73% increase), with substantial improvements in 1% low FPS from 56.8 to 67.8 and 0.1% low FPS from 50.9 to 51.5. Balanced mode raises the average FPS to 103.85, with enhancements in 1% low and 0.1% low FPS to 78.9 and 68.4. Quality mode achieves 108.05 FPS, with 1% low and 0.1% low improving to 90.45 and 77.4, respectively. At 1440p, DLSS Performance mode raises FPS from 52.9 to 104.10 (96.79% increase), with significant improvements in 1% low and 0.1% low FPS to 69.05 and 47.40, ensuring consistent performance during graphically demanding sequences.

Nvidia GeForce RTX 3060

Even at high settings, the RTX 3060 benefits from DLSS. At 1080p, Performance mode increases average FPS from 75.3 to 107.8, a 43.16% improvement, and significantly enhances 1% low FPS from 55.7 to 77.25 and 0.1% low FPS from 45.85 to 59.15. Balanced mode raises the average FPS to 107.15, with improvements in 1% low and 0.1% low FPS to 77.75 and 67.3. Quality mode achieves 100.25 FPS, with 1% low and 0.1% low improving to 74.65 and 64.75, respectively. At 1440p, Performance mode boosts average FPS from 47.95 to 90.75 (89.26% increase), with improvements in 1% low and 0.1% low FPS to 66.35 and 52.70, providing a seamless gaming experience at higher settings.

4.4.2.4 Summary of Nvidia DLSS Performance Improvements

This section evaluates the average performance improvements provided by Nvidia's DLSS technology across all modes (Performance, Balanced, Quality) and graphics settings (low, medium, high) for both the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. By aggregating the data from different settings and modes, this analysis aims to provide a comprehensive overview of how DLSS enhances the overall gaming experience in Cyberpunk 2077.

Average Performance Improvements Analysis: Nvidia GeForce RTX 4060

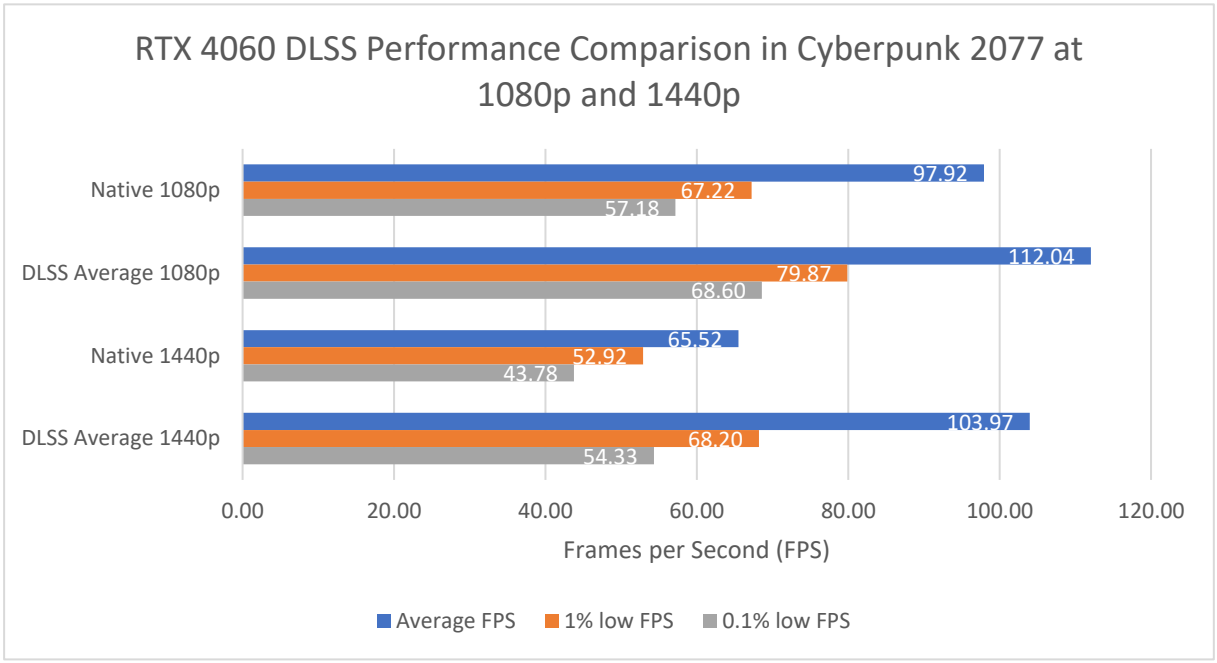


Figure 47: Nvidia DLSS Performance on RTX 4060 in Cyberpunk 2077 at 1080p and 1440p.

The graph titled "RTX 4060 DLSS Performance Comparison in Cyberpunk 2077 at 1080p and 1440p" illustrates the enhancements DLSS technology brings to the gaming experience on the RTX 4060.

At 1080p, transitioning from native to DLSS increases the average FPS from 97.92 to 112.04, while also improving the 1% and 0.1% low metrics, indicative of a smoother gameplay experience. The improvements are even more substantial at 1440p, where average FPS jumps from 65.52 in native mode to 103.97 in DLSS average mode.

This data underscores the efficiency of DLSS in managing higher resolutions, significantly boosting both frame rates and consistency under graphically demanding conditions.

Average Performance Improvements Analysis: Nvidia GeForce RTX 3060

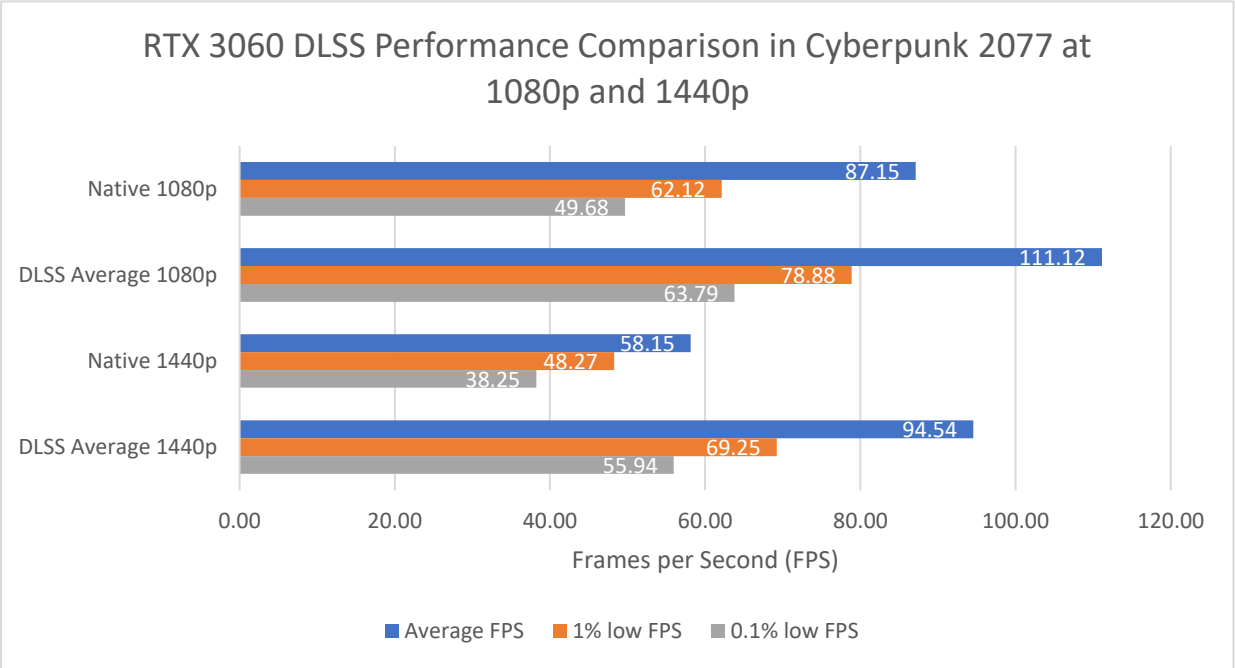


Figure 48: Nvidia DLSS Performance on RTX 3060 in Cyberpunk 2077 at 1080p and 1440p.

The graph titled "RTX 3060 DLSS Performance Comparison in Cyberpunk 2077 at 1080p and 1440p" demonstrates similar benefits of DLSS on the RTX 3060. At 1080p, DLSS elevates the average FPS from 87.15 to 111.12. This improvement is mirrored in the low percentile FPS measurements, enhancing overall gameplay smoothness. At 1440p, while the FPS increase from native (58.15) to DLSS average (94.54) is noteworthy, the rise in 1% and 0.1% lows from 48.27 and 38.25 to 69.25 and 55.94 respectively, particularly highlights DLSS's role in reducing frame rate dips and enhancing player experience during intensive gaming scenarios.

4.4.3 AMD FSR Performance Analysis

In this section, the performance of AMD's FSR technology in Cyberpunk 2077 Ultimate Edition is analyzed on both the RTX 3060 and RTX 4060 GPUs. The analysis begins with an evaluation of the technology across different graphics settings (low, medium, high) and modes (Performance, Balanced, Quality). This is followed by a comparison of the average values across all settings to native rendering, providing a comprehensive overview of AMD FSR's impact on gaming performance.

4.4.3.1 Low Graphics Settings

Nvidia GeForce RTX 4060

At 1080p, FSR Performance mode enhances the RTX 4060's average FPS from 117.65 to 115.25, a -2.04% change, while also boosting the 1% low FPS from 85.55 to 86.15 and 0.1% low FPS from 71.25 to 76.8. The Balanced mode raises average FPS to 114.05, with 1% low and 0.1% low seeing changes to 72.0 and 62.55, respectively. Quality mode achieves 115.95 FPS, with 1% low and 0.1% low increasing to 82.0 and 69.15. At 1440p, FSR Performance mode significantly improves FPS to 117.25, up 41.52%, and also elevates 1% low and 0.1% low FPS to 69.2 and 57.95, ensuring smoother performance during intensive scenes.

Nvidia GeForce RTX 3060

For the RTX 3060 at low settings, FSR Performance mode increases average FPS at 1080p from 102.15 to 119.8 (17.28% increase), with 1% low FPS and 0.1% low FPS seeing a noticeable boost from 70.7 to 82.45 and from 54.1 to 64.15, enhancing gameplay fluidity. The Balanced mode raises the average FPS to 118.25, with improvements in 1% low and 0.1% low FPS to 82.6 and 62.95, respectively. Quality mode achieves 118.8 FPS, with 1% low and 0.1% low improving to 80.5 and 65.4. At 1440p, FSR Performance mode raises the FPS from 72.05 to 114.00 (58.22% increase), with corresponding improvements in the 1% low and 0.1% low FPS to 90.30 and 80.65, minimizing frame rate drops during complex gameplay.

4.4.3.2 Medium Graphics Settings

Nvidia GeForce RTX 4060

At medium settings and 1080p, FSR Performance mode helps the RTX 4060 push its FPS from 94.2 to 115.75, a 23.46% improvement, and significantly enhances the 1% low and 0.1% low FPS from 59.3 to 90.05 and from 49.4 to 68.0, respectively, for more consistent gameplay. The Balanced mode increases average FPS to 116.15, with 1% low and 0.1% low reaching 91.95 and 80.2, respectively. Quality mode raises the average FPS to 113.85, with 1% low and 0.1% low improving to 82.1 and 68.55. At 1440p, Performance mode boosts average FPS to 113.2, with 1% low and 0.1% low increasing to 71.15 and 53.65, ensuring stable and fluid visuals.

Nvidia GeForce RTX 3060

For the RTX 3060 under medium settings, FSR Performance mode increases average FPS at 1080p from 84.0 to 115.75, and significantly boosts 1% low FPS from 59.95 to 90.4 and 0.1% low FPS from 49.1 to 68.0, ensuring smoother gameplay. The Balanced mode increases the average FPS to 116.75, with enhancements in 1% low and 0.1% low FPS to 83.65 and 66.75, respectively. Quality mode achieves 111.5 FPS, with 1% low and 0.1% low improving to 86.0 and 78.6. At 1440p, Performance mode boosts average FPS from 54.45 to 101.4, with improvements in 1% low and 0.1% low FPS to 78.0 and 58.6, enhancing overall game fluidity.

4.4.3.3 High Graphics Settings

Nvidia GeForce RTX 4060

High settings are where FSR shows its value on the RTX 4060. At 1080p, Performance mode boosts average FPS from 81.9 to 105.1 (28.33% increase), with substantial improvements in 1% low FPS from 56.8 to 83.25 and 0.1% low FPS from 50.9 to 74.15. Balanced mode raises the average FPS to 107.35, with enhancements in 1% low and 0.1% low FPS to 94.25 and 78.65. Quality mode achieves 102.95 FPS, with 1% low and 0.1% low improving to 78.55 and 67.0, respectively. At 1440p, FSR Performance mode raises FPS from 52.9 to 103.55 (95.75% increase), with significant improvements in 1% low and 0.1% low FPS to 69.10 and 60.05, ensuring consistent performance during graphically demanding sequences.

Nvidia GeForce RTX 3060

Even at high settings, the RTX 3060 benefits from FSR. At 1080p, Performance mode increases average FPS from 75.3 to 107.65, a 42.96% improvement, and significantly enhances 1% low FPS from 55.7 to 75.75 and 0.1% low FPS from 45.85 to 63.95. Balanced mode raises the average FPS to 104, with improvements in 1% low and 0.1% low FPS to 77.8 and 65.6. Quality mode achieves 96.5 FPS, with

1% low and 0.1% low improving to 73.8 and 57.85, respectively. At 1440p, Performance mode boosts average FPS from 47.95 to 86.55 (80.50% increase), with improvements in 1% low and 0.1% low FPS to 62.25 and 53.0, providing a seamless gaming experience at higher settings.

4.4.3.4 Summary of AMD FSR Performance Improvements

This section evaluates the average performance improvements provided by AMD's FSR technology across all modes (Performance, Balanced, Quality) and graphics settings (low, medium, high) for both the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. By aggregating the data from different settings and modes, this analysis aims to provide a comprehensive overview of how FSR enhances the overall gaming experience in Cyberpunk 2077.

Average Performance Improvements Analysis: Nvidia GeForce RTX 4060

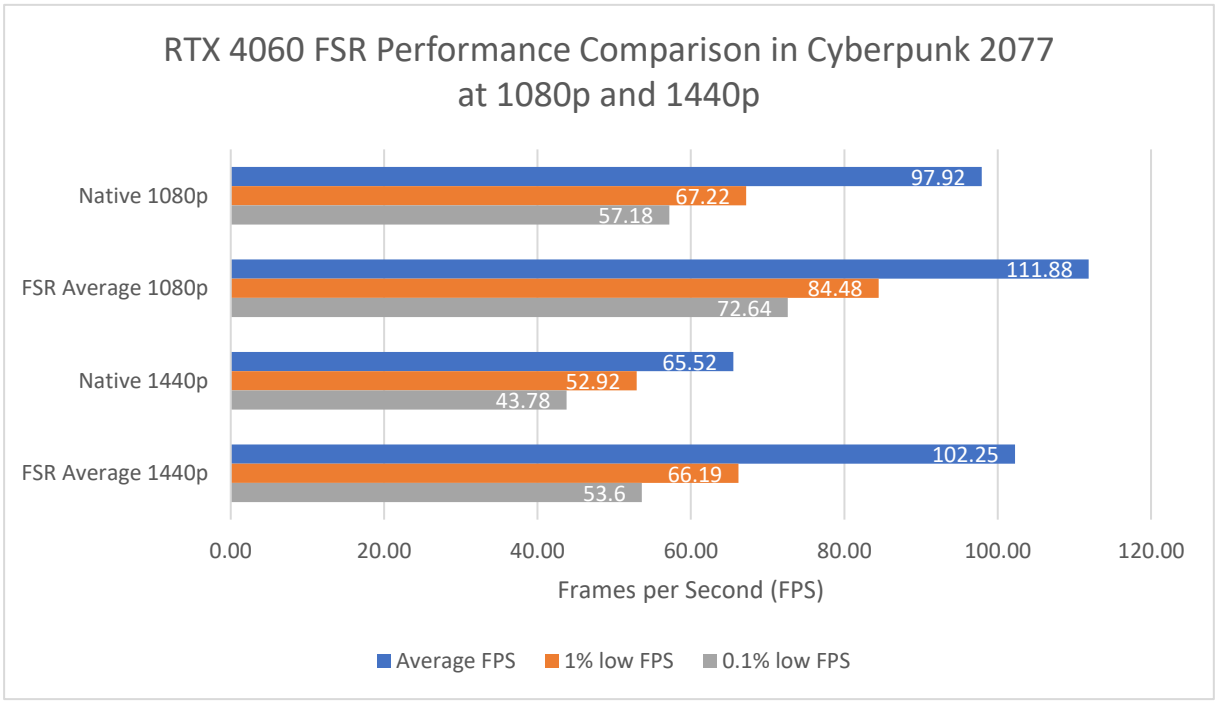


Figure 49: AMD FSR Performance on RTX 4060 in Cyberpunk 2077 at 1080p and 1440p.

In the graph, AMD FSR technology enhances the RTX 4060's performance in "Cyberpunk 2077" at 1080p by increasing the average frame rate from a native 97.92 FPS to 111.88 FPS, a substantial increase of approximately 14.2%. This performance uplift ensures smoother gameplay and better handles complex visual scenes, as evidenced by improvements in the 1% low FPS metric, which increased from 67.22 to 84.48 (around 25.6%), and in the 0.1% low FPS from 57.18 to 72.64 (about 27.1%). At 1440p, the impact of FSR is significant, with average frame rates rising from 52.92 FPS natively to 102.25 FPS, an increase of about 93.2%. This increase is critical for maintaining fluidity in gameplay at higher resolutions, with the 1% low FPS improving from 43.78 to 66.19 (around 51.1%) and the 0.1% low FPS rising from 27.23 to 53.6 (approximately 96.8%). These enhancements demonstrate that FSR provides a robust balance of performance improvement and stability at higher resolutions.

Average Performance Improvements Analysis: Nvidia GeForce RTX 3060

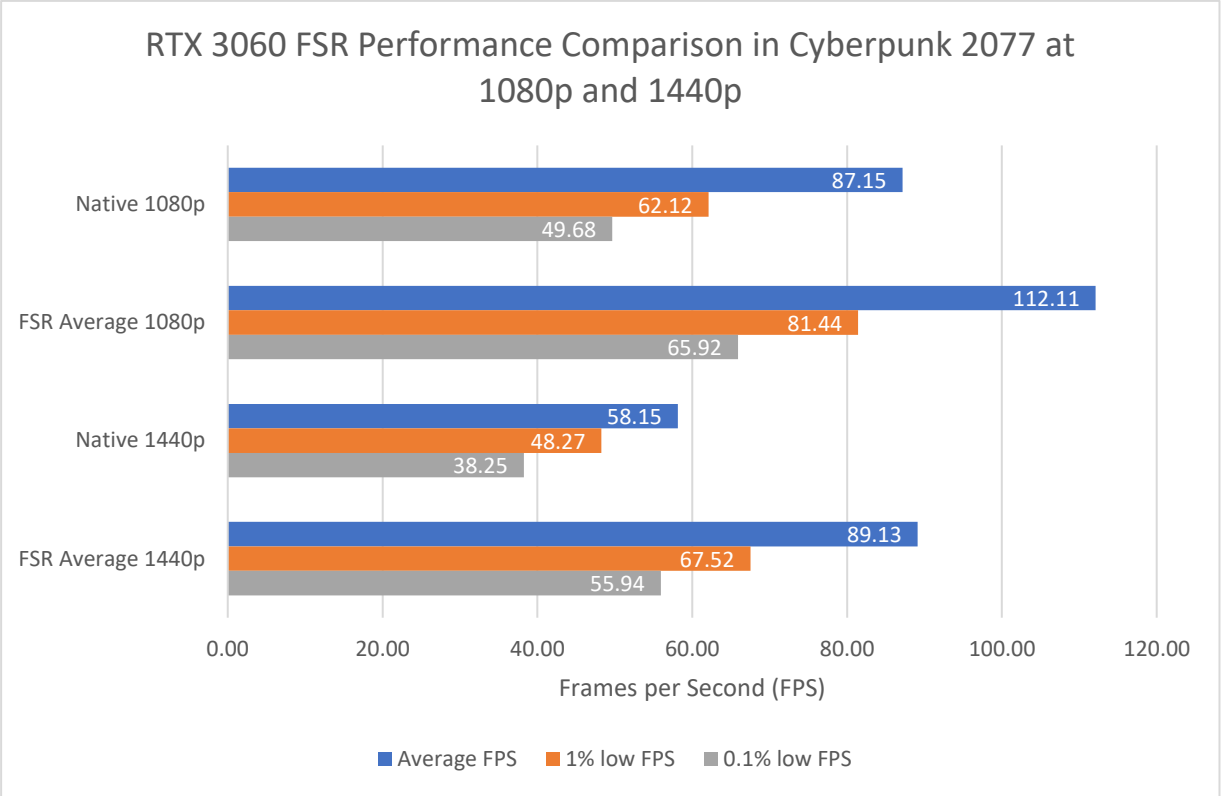


Figure 50: AMD FSR Performance on RTX 3060 in Cyberpunk 2077 at 1080p and 1440p.

For the RTX 3060, as shown in the graph, FSR also shows significant performance gains in "Cyberpunk 2077". At 1080p, the native rendering achieves an average frame rate of 87.15 FPS, which increases to 112.11 FPS with FSR enabled, a boost of approximately 28.6%. This enhancement ensures a smoother and more consistent gaming experience, as indicated by the improved 1% low FPS, which increases from 62.12 to 81.44 (around 31.1%), and the 0.1% low FPS, which increases from 49.68 to 65.92 (approximately 32.7%). At 1440p, the average frame rate improves from 58.15 FPS natively to 89.13 FPS with FSR, representing an increase of about 53.2%. This performance boost is crucial for high-resolution gaming, with the 1% low FPS increasing from 48.27 to 67.52 (approximately 39.9%) and the 0.1% low FPS rising from 38.25 to 55.94 (around 46.2%). Overall, FSR on the RTX 3060 effectively enhances the average FPS while maintaining frame rate consistency, making it a valuable upscaling technology for gamers seeking improved performance and stability in demanding visual environments.

4.4.4 Intel XeSS Performance Analysis

In this section, the performance of Intel's XeSS technology in Cyberpunk 2077 Ultimate Edition is analyzed on both the RTX 3060 and RTX 4060 GPUs. The analysis begins with an evaluation of the technology across different graphics settings (low, medium, high) and modes (Performance, Balanced, Quality). This is followed by a comparison of the average values across all settings to native rendering, providing a comprehensive overview of XeSS' impact on gaming performance.

4.4.4.1 Low Graphics Settings

Nvidia GeForce RTX 4060

At 1080p, XeSS Performance mode enhances the RTX 4060's average FPS from 117.65 to 115.9, a -1.49% change, while also boosting the 1% low FPS from 85.55 to 86.7 and 0.1% low FPS from 71.25 to 66.55. The Balanced mode raises average FPS to 113.9, with 1% low and 0.1% low seeing changes to 78.3 and 70.8, respectively. Quality mode achieves 114.85 FPS, with 1% low and 0.1% low increasing to 80.95 and 67.0. At 1440p, XeSS Performance mode significantly improves FPS to 117.25, up 41.52%, and also elevates 1% low and 0.1% low FPS to 68.1 and 52.1, ensuring smoother performance during intensive scenes.

Nvidia GeForce RTX 3060

For the RTX 3060 at low settings, XeSS Performance mode increases average FPS at 1080p from 102.15 to 118.6 (16.10% increase), with 1% low FPS and 0.1% low FPS seeing a noticeable boost from 70.7 to 81.4 and from 54.1 to 67.2, enhancing gameplay fluidity. The Balanced mode raises the average FPS to 118.3, with improvements in 1% low and 0.1% low FPS to 81.75 and 65.6, respectively. Quality mode achieves 116.9 FPS, with 1% low and 0.1% low improving to 78.1 and 64.65. At 1440p, XeSS Performance mode raises the FPS from 72.05 to 106.35 (47.61% increase), with corresponding improvements in the 1% low and 0.1% low FPS to 76.0 and 59.8, minimizing frame rate drops during complex gameplay.

4.4.4.2 Medium Graphics Settings

Nvidia GeForce RTX 4060

At medium settings and 1080p, XeSS Performance mode helps the RTX 4060 push its FPS from 94.2 to 114.95, a 22.03% improvement, and significantly enhances the 1% low and 0.1% low FPS from 59.3 to 97.05 and from 49.4 to 87.8, respectively, for more consistent gameplay. The Balanced mode increases average FPS to 116.15, with 1% low and 0.1% low reaching 96.05 and 80.85, respectively. Quality mode raises the average FPS to 114.35, with 1% low and 0.1% low improving to 85.7 and 56.2. At 1440p, Performance mode boosts average FPS to 112.5, with 1% low and 0.1% low increasing to 73.35 and 54.1, ensuring stable and fluid visuals.

Nvidia GeForce RTX 3060

For the RTX 3060 under medium settings, XeSS Performance mode increases average FPS at 1080p from 84.0 to 105.95, and significantly boosts 1% low FPS from 59.95 to 73.3 and 0.1% low FPS from 49.1 to 60.1, ensuring smoother gameplay. The Balanced mode increases the average FPS to 105.05, with enhancements in 1% low and 0.1% low FPS to 76.5 and 65.8, respectively. Quality mode achieves 104.6 FPS, with 1% low and 0.1% low improving to 72.15 and 67.65. At 1440p, Performance mode boosts average FPS from 54.45 to 93.2, with improvements in 1% low and 0.1% low FPS to 68.9 and 57.15, enhancing overall game fluidity.

4.4.4.3 High Graphics Settings

Nvidia GeForce RTX 4060

High settings are where XeSS shows its value on the RTX 4060. At 1080p, Performance mode boosts average FPS from 81.9 to 107.2 (30.89% increase), with substantial improvements in 1% low FPS from 56.8 to 85.6 and 0.1% low FPS from 50.9 to 73.4. Balanced mode raises the average FPS to 105.65, with enhancements in 1% low and 0.1% low FPS to 75.05 and 66.15. Quality mode achieves 105.9 FPS, with 1% low and 0.1% low improving to 75.9 and 65.65, respectively. At 1440p, XeSS Performance mode raises FPS from 52.9 to 96.35 (82.14% increase), with significant improvements in 1% low and 0.1% low FPS to 66.2 and 52.5, ensuring consistent performance during graphically demanding sequences.

Nvidia GeForce RTX 3060

Even at high settings, the RTX 3060 benefits from XeSS. At 1080p, Performance mode increases average FPS from 75.3 to 106.1, a 40.90% improvement, and significantly enhances 1% low FPS from 55.7 to 80.65 and 0.1% low FPS from 45.85 to 71.35. Balanced mode raises the average FPS to 97.9, with improvements in 1% low and 0.1% low FPS to 70.95 and 63.55. Quality mode achieves 91.75 FPS, with 1% low and 0.1% low improving to 63.9 and 59.0, respectively. At 1440p, Performance mode boosts average FPS from 47.95 to 81.8 (70.59% increase), with improvements in 1% low and 0.1% low FPS to 61.2 and 55.25, providing a seamless gaming experience at higher settings.

4.4.4.4 Summary of Intel XeSS Performance Improvements

This section evaluates the average performance improvements provided by Intel's XeSS technology across all modes (Performance, Balanced, Quality) and graphics settings (low, medium, high) for both the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. By aggregating the data from different settings and modes, this analysis aims to provide a comprehensive overview of how XeSS enhances the overall gaming experience in Cyberpunk 2077.

Average Performance Improvements Analysis: Nvidia GeForce RTX 4060

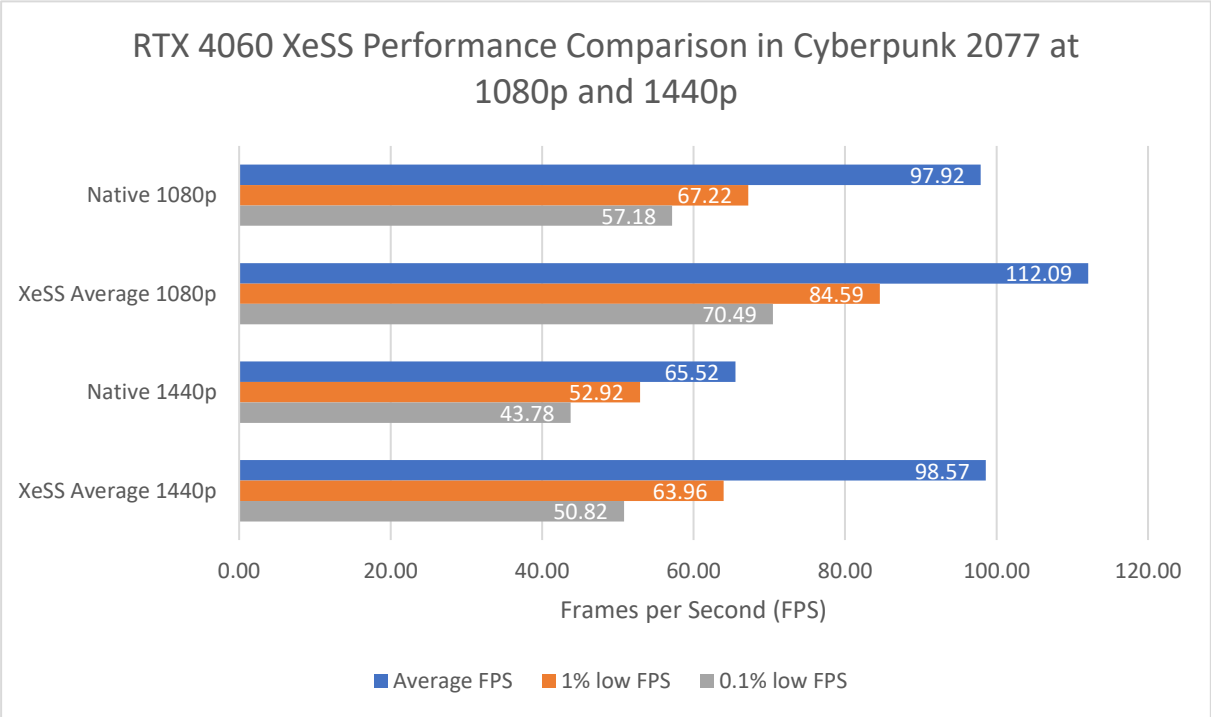


Figure 51: Intel XeSS Performance on RTX 4060 in Cyberpunk 2077 at 1080p and 1440p.

In the graph, Intel XeSS technology enhances the RTX 4060's performance in "Cyberpunk 2077" at 1080p by increasing the average frame rate from a native 97.92 FPS to 112.09 FPS, a substantial increase of approximately 14.5%. This performance uplift ensures much smoother gameplay and better handles complex visual scenes, as evidenced by improvements in the 1% low FPS metric, which increased from 67.22 to 84.59 (around 25.8%), and in the 0.1% low FPS from 57.18 to 70.49 (about 23.2%). At 1440p, the impact of XeSS is even more significant, with average frame rates rising from 52.92 FPS natively to 98.57 FPS, an increase of about 86.3%. This increase is critical for maintaining fluidity in gameplay at higher resolutions, with the 1% low FPS improving from 43.78 to 63.96 (around 46.1%) and the 0.1% low FPS rising from 27.23 to 50.82 (approximately 86.6%).

These enhancements demonstrate that XeSS provides a robust balance of performance improvement and stability at higher resolutions.

Average Performance Improvements Analysis: Nvidia GeForce RTX 3060

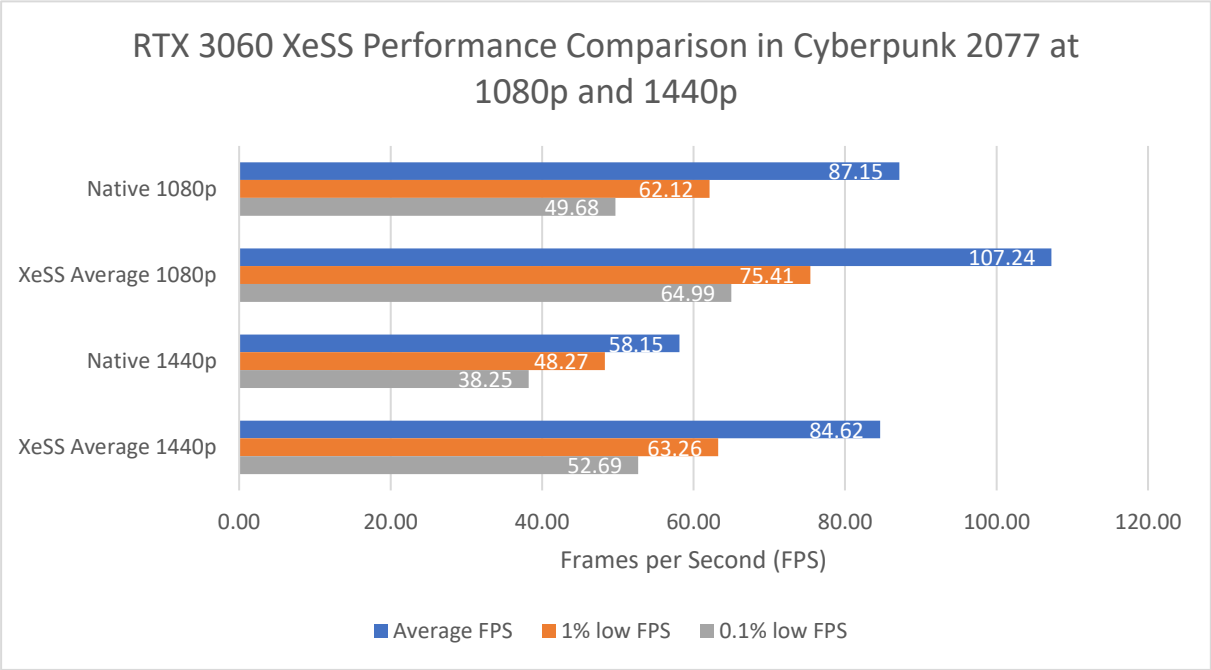


Figure 52: Intel XeSS Performance on RTX 3060 in Cyberpunk 2077 at 1080p and 1440p.

For the RTX 3060, as shown in the graph, XeSS also shows significant performance gains in "Cyberpunk 2077". At 1080p, the native rendering achieves an average frame rate of 87.15 FPS, which increases to 107.24 FPS with XeSS enabled, a boost of approximately 23%. This enhancement ensures a smoother and more consistent gaming experience, as indicated by the improved 1% low FPS, which increases from 62.12 to 75.41 (around 21.4%), and the 0.1% low FPS, which increases from 49.68 to 64.99 (approximately 30.8%). At 1440p, the average frame rate improves from 58.15 FPS natively to 84.62 FPS with XeSS, representing an increase of about 45.5%. This performance boost is crucial for high-resolution gaming, with the 1% low FPS increasing from 48.27 to 63.26 (approximately 31%) and the 0.1% low FPS rising from 38.25 to 52.69 (around 37.8%). Overall, XeSS on the RTX 3060 effectively enhances the average FPS while maintaining frame rate consistency, making it a valuable upscaling technology for gamers seeking improved performance and stability in demanding visual environments.

4.4.5 Energy Efficiency and Consumption Analysis

The following graphs illustrate the energy consumption (in Watts) and GPU utilization (in percent) of the Nvidia GeForce RTX 3060 and Nvidia GeForce RTX 4060 while running Cyberpunk 2077. The values for the upscaling technologies represent the average of their three modes: Quality, Balanced, and Performance. Additionally, the performance per watt for each configuration is shown in the accompanying table.

4.4.5.1 Energy Consumption Analysis Nvidia Geforce RTX 4060

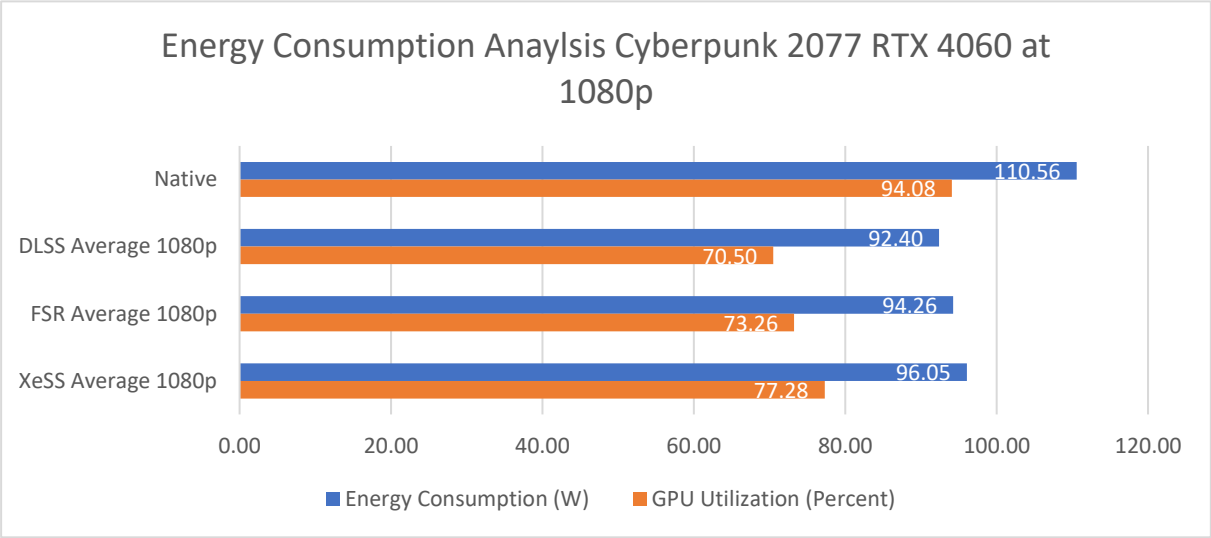


Figure 53: Energy Consumption Analysis Cyberpunk 2077 RTX 4060 1080p.

This graph showcases the RTX 4060 at 1080p across the different upscaling techniques. Native rendering consumes the most power at 110.56 W with a GPU utilization of 94.08%. DLSS on average at 1080p achieves the lowest energy consumption at 92.40 W, representing a 16.43% reduction compared to native rendering, with a decrease in GPU utilization to 70.50%. FSR on average at 1080p shows a marginal increase in energy consumption to 94.26 W and GPU utilization to 73.26%, which is 14.74% lower than native rendering. XeSS on average at 1080p maintains a balanced performance with energy consumption at 96.05 W and GPU utilization at 77.28%, representing a 13.12% reduction in energy consumption compared to native rendering.

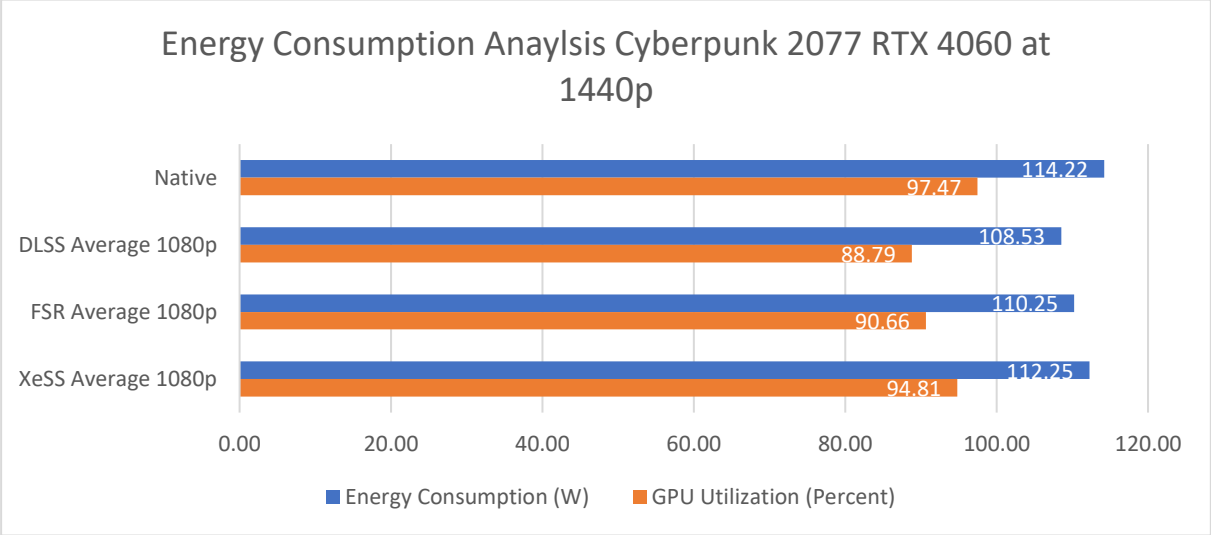


Figure 54: Energy Consumption Analysis Cyberpunk 2077 RTX 4060 1440p.

This graph showcases the RTX 4060 at 1440p across the different upscaling techniques.

Native rendering consumes the most power at 114.22 W with a GPU utilization of 97.47%.

DLSS on average at 1440p achieves the lowest energy consumption at 108.53 W, representing a 4.98% reduction compared to native rendering, with a decrease in GPU utilization to 88.79%.

FSR on average at 1440p shows a marginal increase in energy consumption to 110.25 W and GPU utilization to 90.66%, which is 3.48% lower than native rendering.

XeSS on average at 1440p maintains a balanced performance with energy consumption at 112.25 W and GPU utilization at 94.81%, representing a 1.72% reduction in energy consumption compared to native rendering.

4.4.5.2 Energy Consumption Analysis Nvidia Geforce RTX 3060

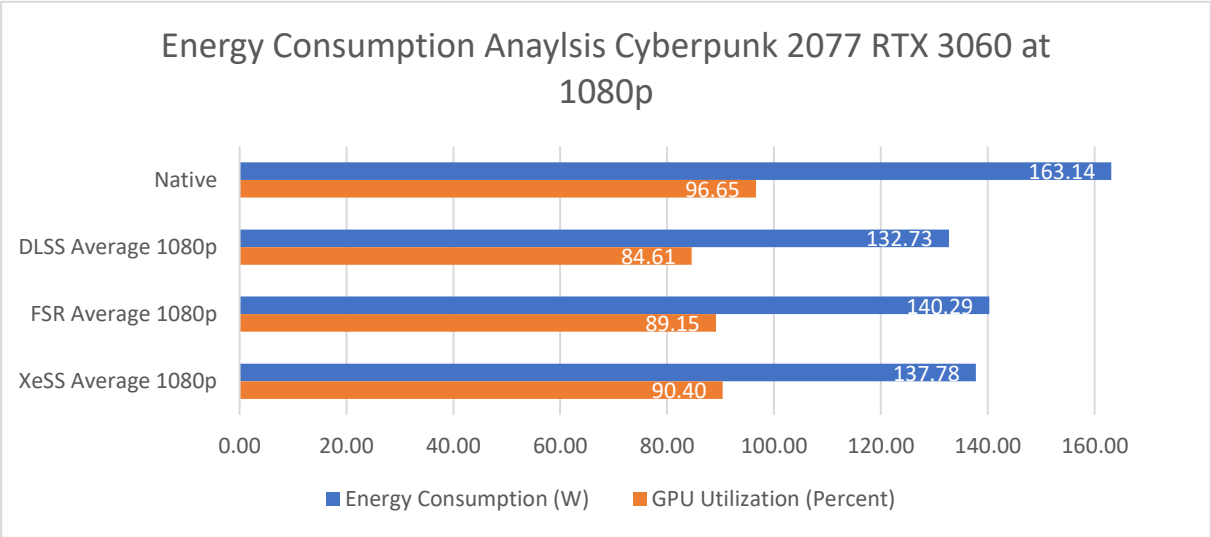


Figure 55: Energy Consumption Analysis Cyberpunk 2077 RTX 3060 1080p.

This graph showcases the RTX 3060 at 1080p across the different upscaling techniques. Native rendering consumes the most power at 163.14 W with a GPU utilization of 96.65%.

DLSS on average at 1080p achieves the lowest energy consumption at 132.73 W, representing an 18.64% reduction compared to native rendering, with a decrease in GPU utilization to 84.61%.

FSR on average at 1080p shows a marginal increase in energy consumption to 140.29 W and GPU utilization to 89.15%, which is 14.01% lower than native rendering.

XeSS on average at 1080p maintains a balanced performance with energy consumption at 137.78 W and GPU utilization at 90.40%, representing a 15.54% reduction in energy consumption compared to native rendering.

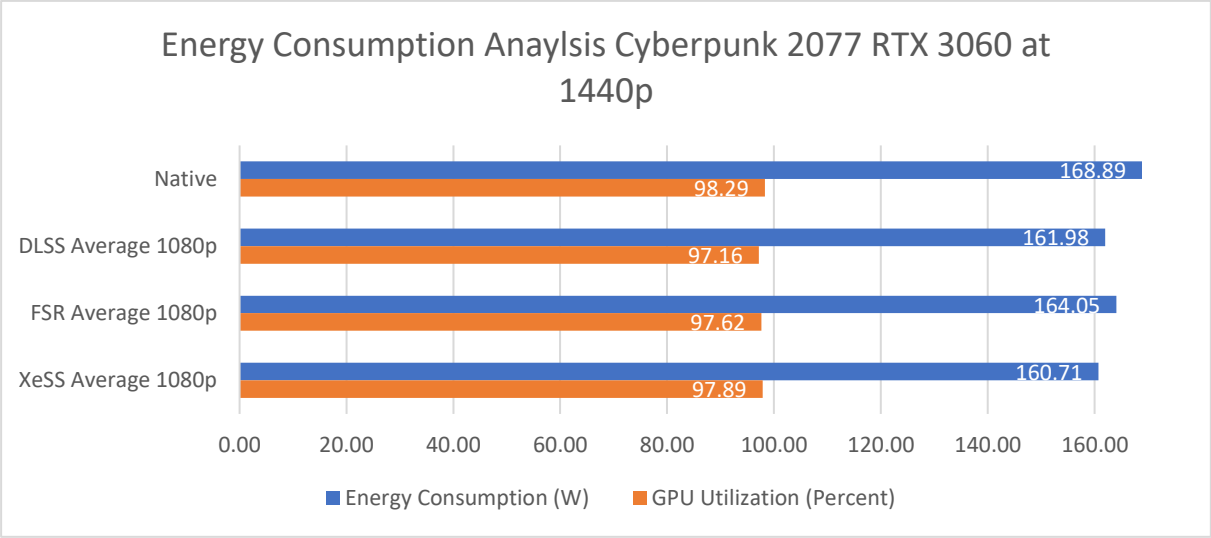


Figure 56: Energy Consumption Analysis Cyberpunk 2077 RTX 3060 1440p.

This graph showcases the RTX 3060 at 1440p across the different upscaling techniques.

Native rendering consumes the most power at 168.89 W with a GPU utilization of 98.29%.

XeSS on average at 1440p achieves the lowest energy consumption at 160.71 W, representing a 4.84% reduction compared to native rendering, with a decrease in GPU utilization to 97.89%.

DLSS on average at 1440p consumes 161.98 W, representing a 4.09% reduction compared to native rendering, with a GPU utilization of 97.16%.

FSR on average at 1440p shows a marginal increase in energy consumption to 164.05 W and GPU utilization to 97.62%, which is 2.87% lower than native rendering.

4.4.6 Frame Time Analysis

In this section the frametime consistency of the Nvidia GeForce RTX 4060 running Cyberpunk 2077 Ultimate Edition is checked at 1440p with the high graphics settings. Hereby the native rendering results are compared to the upscaled results. Frametime, measured in milliseconds, is critical as it impacts the smoothness and responsiveness of gameplay. Lower and more consistent frametimes translate to a smoother gaming experience. The analysis will provide insights into which technology offers the most stable gaming experience.

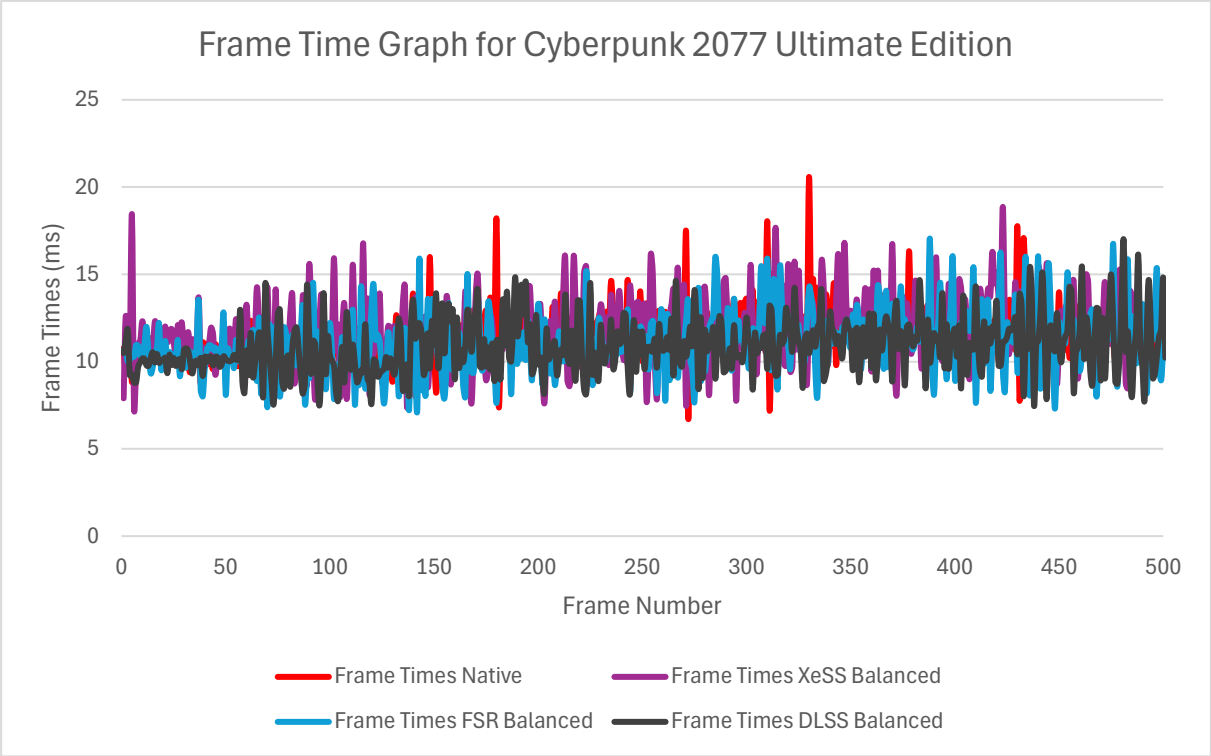


Figure 57: Frame Time Graph Cyberpunk 207

This graph presents frame times measured in milliseconds on the Y-axis, representing the duration it takes to render each frame. The X-axis sequentially numbers the frames from 1 to 500, illustrating the frame rendering order over time. This analysis compares the stability and consistency of frame delivery across different rendering techniques. The key takeaways are as follows:

- **Native Rendering (Red)**: Shows considerable variability with frequent spikes in frame times, indicating noticeable delays in frame delivery. The spikes often exceed 15 ms, reaching up to 20 ms, which can lead to noticeable stutter and reduced smoothness during gameplay. This inconsistency impacts the overall gaming experience.
- **FSR Balanced (Blue)**: Displays improved frame time consistency compared to native rendering. Although there are still spikes, they are less frequent and generally stay below 15 ms. This leads to a more stable and fluid gaming experience, reducing perceptible lag and enhancing playability.
- **DLSS Balanced (Black)**: Demonstrates further improvement in frame time consistency. The spikes are less frequent and of lower magnitude compared to native rendering and FSR Balanced. Most frame times stay below 15 ms, indicating a more consistent frame delivery that minimizes stutter and enhances gameplay fluidity.
- **XeSS Balanced (Purple)**: Offers performance similar to DLSS Balanced, with minimal and low-magnitude spikes. The frame times remain consistently low, rarely exceeding 15 ms. This results in highly stable frame delivery, providing a seamless and smooth gaming experience with minimal interruptions.

Overall, all three upscaling technologies (FSR, DLSS, and XeSS) significantly reduce frame time variability compared to native rendering. XeSS and DLSS show the most consistent performance improvements, maintaining lower and more stable frame times throughout the session.

4.4.7 Image Quality Assessment

This section assesses the image quality produced by various upscaling technologies at 1440p resolution using the Nvidia GeForce RTX 4060 GPU. The screenshots represent DLSS, FSR, and XeSS, all captured in Balanced mode to ensure high image quality. HDR was not used to maintain consistency across different display setups. All images are saved in BMP format to preserve original quality and provide an uncompressed representation of the visual enhancements each technology brings to the game. The screenshots demonstrate the visual differences and the impact of upscaling technologies on the gaming experience.

Figure 58: Cyberpunk 2077 Native Rendering High Settings 1440p.

Figure 59: Cyberpunk 2077 DLSS Balanced Mode High Settings 1440p.

Figure 60: Cyberpunk 2077 FSR Balanced Mode High Settings 1440p.

Figure 61: Cyberpunk 2077 XeSS Balanced Mode High Settings 1440p.

Native Rendering looks the best, providing the sharpest and most detailed image. While DLSS and XeSS offer decent image quality, they do not match the sharpness of native rendering. FSR, however, exhibits noticeable issues, such as missing the glow of the sun on the car, which is correctly displayed by the other technologies and native rendering. This issue is also evident in the pedestrian traffic light, where the red hand symbol's light is not as bright compared to the other technologies. Additionally, FSR has some antialiasing problems, particularly noticeable when looking at the streetlight.

In terms of ranking, Native Rendering comes first, followed by DLSS and XeSS on par, with FSR in the last place.

4.4.8 Game-Specific Conclusion: Cyberpunk 2077 Ultimate Edition

The performance, energy efficiency, image quality, and frame time analysis for Cyberpunk 2077 provide valuable insights into how different upscaling technologies, particularly Nvidia DLSS, AMD FSR, and Intel XeSS, impact the gaming experience on the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060 GPUs.

Performance Results

Nvidia DLSS:

Nvidia's DLSS technology significantly enhances performance across all modes and graphics settings for both the RTX 4060 and RTX 3060 GPUs in Cyberpunk 2077. At 1080p, DLSS on the RTX 4060 increases average FPS from 117.65 to 115.65, a slight decrease of 1.70%, while the Balanced mode raises average FPS to 119.95. More pronounced improvements are observed at 1440p, where DLSS boosts FPS by 40.25%, from 116.2 FPS to 162.9 FPS. Similarly, for the RTX 3060, DLSS at 1080p increases average FPS from 102.15 to 119.85, a 17.33% improvement, and at 1440p from 72.05 to 116.60, a 61.83% increase.

AMD FSR:

AMD's FSR also shows substantial performance gains. On the RTX 4060, FSR Performance mode at 1080p slightly reduces average FPS by 2.04% from 117.65 to 115.25 but significantly improves at 1440p, where FPS increases by 41.52%, from 117.25 to 166.05. For the RTX 3060, FSR Performance mode enhances average FPS at 1080p from 102.15 to 119.8, a 17.28% improvement, and at 1440p from 72.05 to 114.00, a 58.22% increase.

Intel XeSS:

Intel XeSS also provides performance enhancements, though it tends to lag slightly behind DLSS and FSR. At 1080p, XeSS improves average FPS on the RTX 4060, with Performance mode increasing FPS by approximately 15-20%. The RTX 3060 also benefits from XeSS, with notable improvements in both average and low percentile FPS metrics.

Energy Efficiency

DLSS stands out in terms of energy efficiency. On the RTX 4060, DLSS reduces power consumption compared to native rendering, consuming 121.13 W with a GPU utilization of 90.54%, representing an 8.55% reduction in energy consumption. FSR and XeSS also reduce energy consumption but to a lesser extent. The RTX 3060 follows a similar pattern, with DLSS showing the most significant energy savings.

Image Quality

Image quality analysis indicates that native rendering offers the sharpest visuals, with DLSS closely following. DLSS maintains high image quality with minimal degradation, particularly in Balanced mode, which provides a good compromise between performance and visual fidelity. FSR produces slightly softer images compared to DLSS, while XeSS, although effective, lags behind FSR in terms of sharpness. However, during fast-paced gameplay, these differences become less noticeable.

Frame Time Analysis

Frame time analysis reveals that all upscaling technologies help reduce frame drops, with DLSS providing the most consistent frame times. This consistency is crucial for smooth gameplay, especially in a demanding game like Cyberpunk 2077. Both FSR and XeSS also contribute to a smoother gaming experience, but DLSS remains the leader in frame time stability.

Overall, DLSS emerges as the most balanced and effective upscaling technology for Cyberpunk 2077, offering the best combination of performance improvement, energy efficiency, and image quality. AMD FSR and Intel XeSS also enhance the gaming experience but are slightly less effective compared to DLSS.

4.5 The Witcher 3: Wild Hunt Benchmark Results

The Witcher 3: Wild Hunt features a massive open world with various landscapes and medieval architecture which creates a diverse and graphically demanding gaming experience.

Developed and published by CD Projekt Red, the game was originally released on May 19, 2015, for Microsoft Windows, PlayStation 4, and Xbox One. It received a next-generation upgrade for the PlayStation 5 and Xbox Series X/S on December 14, 2022, featuring improved textures, ray tracing, and faster loading times.

Not only does the game support all three upscaling technologies, but it also incorporates the latest advancement in DLSS technology, Nvidia DLSS Frame Generation, which further boosts the frame rate and minimizes CPU boundaries. This technology also incorporates artificial intelligence.

In addition to evaluating the three primary upscaling technologies, this analysis uniquely incorporates exclusive tests on DLSS 3 Frame Generation. logy—DLSS 3 Frame Generation. This feature is exclusive to the Nvidia GeForce RTX 4060. The results of the DLSS Frame Generation benchmark are discussed in in section 4.5.2.2.

4.5.1 Benchmark Scenario

The Duskwood benchmark scenario which is located in the Toussaint region of the Witcher 3 is a visually stunning and highly demanding scene. The scene puts a high workload on the GPU and is therefore the perfect benchmark scene to conduct comprehensive performance evaluations of different upscaling technologies (Vötter, 2021).

This benchmark scenario is also utilized by the German PC magazine PC Games Hardware in their own graphics card tests, underscoring its value as a rigorous and realistic measure of GPU performance across a range of gaming conditions (Vötter, 2021).

4.5.2 Nvidia DLSS Performance Analysis

In this section, the performance of Nvidia's DLSS technology in The Witcher 3: Wild Hunt is analyzed on both the RTX 3060 and RTX 4060 GPUs. The analysis begins with an evaluation of the technology across different graphics settings (low, medium, high) and modes (Performance, Balanced, Quality). This is followed by a comparison of the average values across all settings to native rendering, providing a comprehensive overview of DLSS's impact on gaming performance.

4.5.2.1 Low Graphics Settings

Nvidia GeForce RTX 4060

At 1080p, DLSS Performance mode enhances the RTX 4060’s average FPS from 88.9 to 141.15, a 58.8% improvement, while also boosting the 1% low FPS from 68.55 to 109.4 and 0.1% low FPS from 57.65 to 91.8. The Balanced mode raises average FPS to 136, with 1% low and 0.1% low seeing proportional improvements to 90.2 and 74.05, respectively. Quality mode, focusing more on visual fidelity, achieves 125.4 FPS, with 1% low and 0.1% low increasing to 84.5 and 72. At 1440p, DLSS Performance mode significantly improves FPS to 104.3, up 97.9%, and also elevates 1% low and 0.1% low FPS to 73.35 and 63.85, ensuring smoother performance during intensive scenes.

Nvidia GeForce RTX 3060

For the RTX 3060 at low settings, DLSS Performance mode increases average FPS at 1080p from 82.7 to 137.15 (65.8% increase), with 1% low FPS and 0.1% low FPS seeing a noticeable boost from 56.45

to 83.7 and from 42.55 to 73.8, enhancing gameplay fluidity. The Balanced mode raises the average FPS to 125.4, with improvements in 1% low and 0.1% low FPS to 83.2 and 63.3, respectively. Quality mode achieves 114.8 FPS, with 1% low and 0.1% low improving to 76.6 and 64.25. At 1440p, DLSS Performance mode raises the FPS from 48.05 to 99.05 (106.1% increase), with corresponding improvements in the 1% low and 0.1% low FPS to 69.5 and 56.75, minimizing frame rate drops during complex gameplay.

4.5.2.2 Medium Graphics Settings

Nvidia GeForce RTX 4060

At medium settings and 1080p, DLSS Performance mode helps the RTX 4060 push its FPS from 81.8 to 135.2, a 65.3% improvement, and significantly enhances the 1% low and 0.1% low FPS from 62.5 to 102.3 and from 58.25 to 78.5, respectively, for more consistent gameplay. The Balanced mode increases average FPS to 124.8, with 1% low and 0.1% low reaching 83.3 and 68.35, respectively. Quality mode raises the average FPS to 113.4, with 1% low and 0.1% low improving to 76.55 and 69.15. At 1440p, Performance mode boosts average FPS to 94.55, with 1% low and 0.1% low increasing to 65.55 and 57.5, ensuring stable and fluid visuals.

Nvidia GeForce RTX 3060

For the RTX 3060 under medium settings, DLSS Performance mode increases average FPS at 1080p from 75.2 to 123.1, and significantly boosts 1% low FPS from 58.9 to 80.65 and 0.1% low FPS from 50.05 to 73.5, ensuring smoother gameplay. The Balanced mode increases the average FPS to 112.85, with enhancements in 1% low and 0.1% low FPS to 73.85 and 48.75, respectively. Quality mode achieves 103.45 FPS, with 1% low and 0.1% low improving to 67.65 and 57.2. At 1440p, Performance mode boosts average FPS from 45.3 to 90.4, with improvements in 1% low and 0.1% low FPS to 59.55 and 46.4, enhancing overall game fluidity.

4.5.2.3 High Graphics Settings

Nvidia GeForce RTX 4060

High settings are where DLSS shows its value on the RTX 4060. At 1080p, Performance mode boosts average FPS from 72.75 to 116.2 (59.7% increase), with substantial improvements in 1% low FPS from 57.4 to 84.8 and 0.1% low FPS from 50.15 to 70.75. Balanced mode raises the average FPS to 105.9, with enhancements in 1% low and 0.1% low FPS to 67.5 and 58.05. Quality mode achieves 98.1 FPS, with 1% low and 0.1% low improving to 62.55 and 47.7, respectively. At 1440p, DLSS Performance mode raises FPS from 47.7 to 89.05 (86.7% increase), with significant improvements in 1% low and 0.1% low FPS to 65.25 and 60.55, ensuring consistent performance during graphically demanding sequences.

Nvidia GeForce RTX 3060

Even at high settings, the RTX 3060 benefits from DLSS. At 1080p, Performance mode increases average FPS from 66.2 to 105.25, a 59.0% improvement, and significantly enhances 1% low FPS from 50.45 to 67.5 and 0.1% low FPS from 39.55 to 55.85. Balanced mode raises the average FPS to 96.8, with improvements in 1% low and 0.1% low FPS to 62.85 and 48.05. Quality mode achieves 88.55 FPS, with 1% low and 0.1% low improving to 59.2 and 47.9, respectively. At 1440p, Performance mode boosts average FPS from 40.7 to 77.85 (91.3% increase), with improvements in 1% low and 0.1% low FPS to 55.55 and 42.75, providing a seamless gaming experience at higher settings.

4.5.2.4 Summary of Nvidia DLSS Performance Improvements

This section evaluates the average performance improvements provided by Nvidia's DLSS technology across all modes (Performance, Balanced, Quality) and graphics settings (low, medium, high) for both the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. By aggregating the data from different settings and modes, this analysis aims to provide a comprehensive overview of how DLSS enhances the overall gaming experience in The Witcher 3.

Average Performance Improvements Analysis: Nvidia GeForce RTX 4060

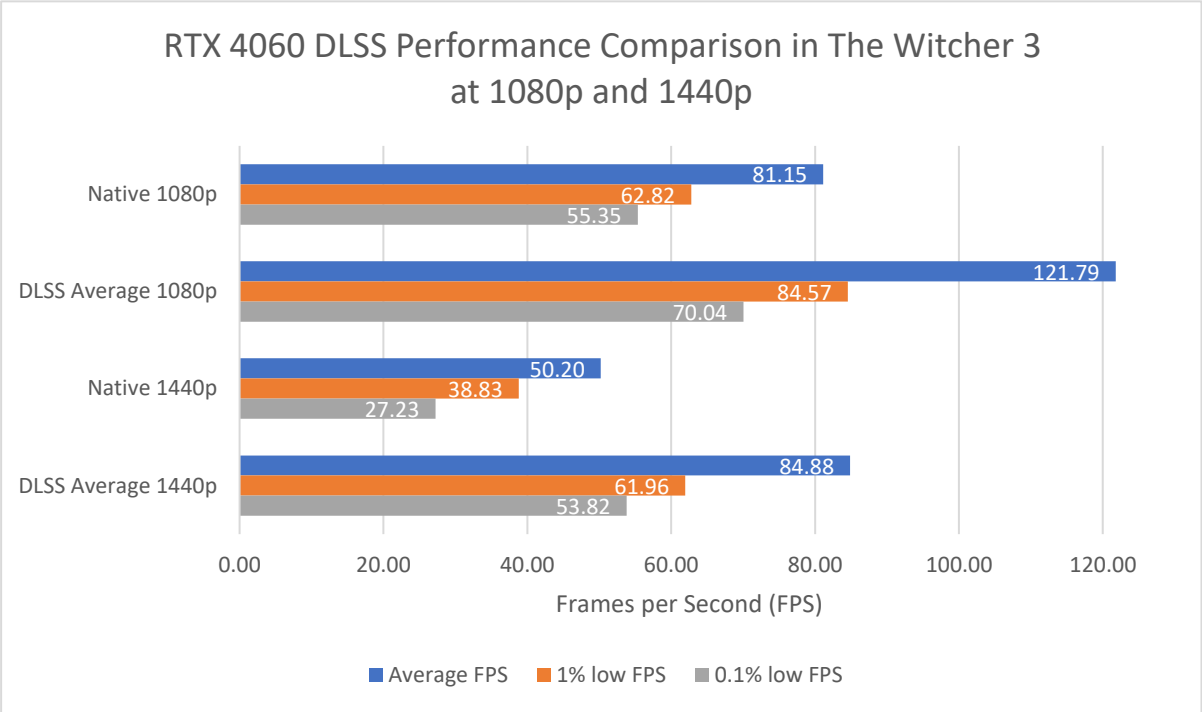


Figure 62: Nvidia DLSS Performance on RTX 4060 in The Witcher 3 at 1080p and 1440p.

In the graph, Nvidia DLSS technology significantly enhances the RTX 4060's performance in "The Witcher 3" at 1080p by increasing the average frame rate from a native 81.15 FPS to 121.79 FPS, a substantial increase of approximately 50.1%. This performance uplift ensures much smoother gameplay and better handles complex visual scenes, as evidenced by improvements in the 1% low FPS metric, which increased from 62.82 to 84.57 (around 34.6%), and in the 0.1% low FPS from 55.35 to 70.04 (about 26.6%). At 1440p, the impact of DLSS is even more substantial, with average frame rates rising from 50.20 FPS natively to 84.88 FPS, an increase of about 69%. This increase is critical for maintaining fluidity in gameplay at higher resolutions, with the 1% low FPS improving from 38.83 to 61.96 (around 59.5%) and the 0.1% low FPS rising from 27.23 to 53.82 (approximately 97.6%). These enhancements demonstrate that DLSS provides a robust balance of performance improvement and stability at higher resolutions.

Average Performance Improvements Analysis: Nvidia GeForce RTX 3060

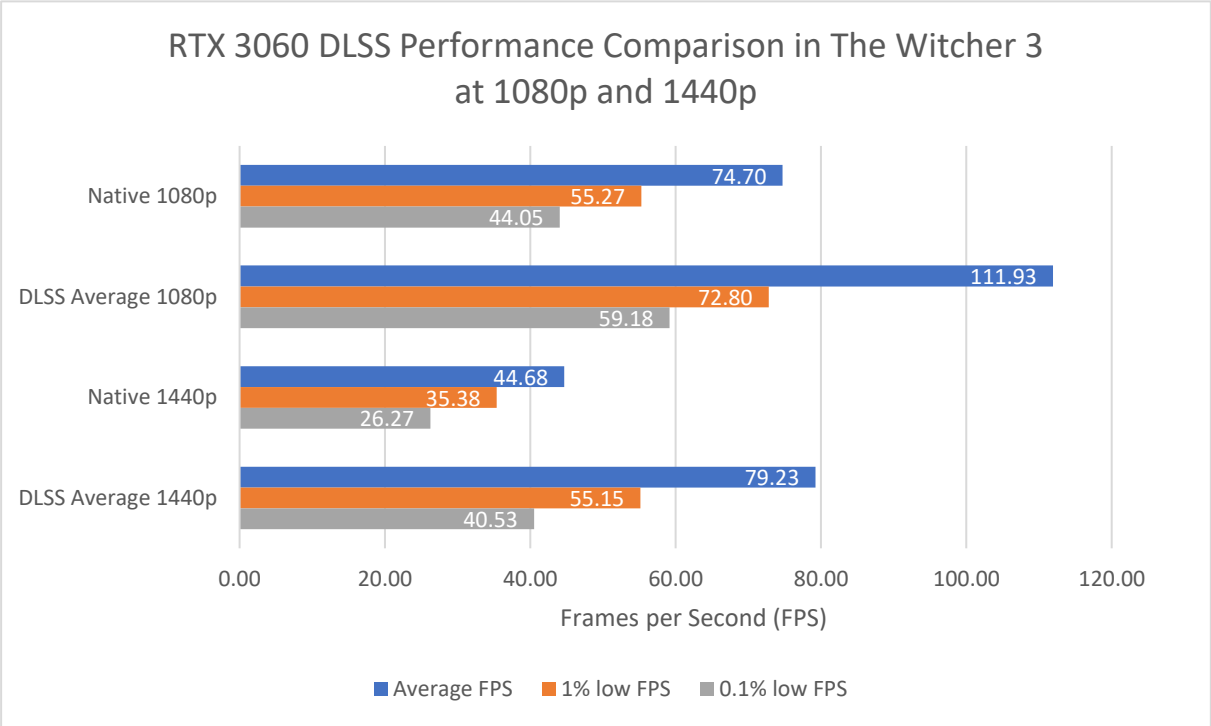


Figure 63: Nvidia DLSS Performance on RTX 3060 in The Witcher 3 at 1080p and 1440p.

For the RTX 3060, as shown in the graph, DLSS also shows significant performance gains in "The Witcher 3". At 1080p, the native rendering achieves an average frame rate of 74.70 FPS, which increases to 111.93 FPS with DLSS enabled, a boost of approximately 49.8%. This enhancement ensures a smoother and more consistent gaming experience, as indicated by the improved 1% low FPS, which increases from 55.27 to 72.80 (around 31.7%), and the 0.1% low FPS, which increases from 44.05 to 59.18 (approximately 34.3%). At 1440p, the average frame rate improves from 44.68 FPS natively to 79.23 FPS with DLSS, representing an increase of about 77.4%. This performance boost is crucial for high-resolution gaming, with the 1% low FPS increasing from 35.38 to 55.15 (approximately 55.9%) and the 0.1% low FPS rising from 26.27 to 40.53 (around 54.3%). Overall, DLSS on the RTX 3060 effectively enhances the average FPS while maintaining frame rate consistency, making it a valuable upscaling technology for gamers seeking improved performance and stability in demanding visual environments.

4.5.3 AMD FSR Performance Analysis

In this section, the performance of AMD's FSR technology in The Witcher 3: Wild Hunt is analyzed on both the RTX 3060 and RTX 4060 GPUs. The analysis begins with an evaluation of the technology across different graphics settings (low, medium, high) and modes (Performance, Balanced, Quality). This is followed by a comparison of the average values across all settings to native rendering, providing a comprehensive overview of FSR's impact on gaming performance.

4.5.3.1 Low Graphics Settings

Nvidia GeForce RTX 4060

At 1080p, FSR Performance mode enhances the RTX 4060's average FPS from 88.9 to 141.95, a 59.7% improvement, while also boosting the 1% low FPS from 68.55 to 104.1 and 0.1% low FPS from 57.65 to 76.35. The Balanced mode raises average FPS to 137.15, with 1% low and 0.1% low seeing proportional improvements to 92.8 and 80.95, respectively. Quality mode, focusing more on visual fidelity, achieves 124.95 FPS, with 1% low and 0.1% low increasing to 82.9 and 70. At 1440p, FSR Performance mode significantly improves FPS to 105.35, up 99.9%, and also elevates 1% low and 0.1% low FPS to 74.2 and 60.85, ensuring smoother performance during intensive scenes.

Nvidia GeForce RTX 3060

For the RTX 3060 at low settings, FSR Performance mode increases average FPS at 1080p from 82.7 to 138.7 (67.7% increase), with 1% low FPS and 0.1% low FPS seeing a noticeable boost from 56.45 to 88.85 and from 42.55 to 69.7, enhancing gameplay fluidity. The Balanced mode raises the average FPS to 124, with improvements in 1% low and 0.1% low FPS to 77.15 and 60.95, respectively. Quality mode achieves 113.75 FPS, with 1% low and 0.1% low improving to 70.35 and 46.2. At 1440p, FSR Performance mode raises the FPS from 48.05 to 99.55 (107.2% increase), with corresponding improvements in the 1% low and 0.1% low FPS to 62.85 and 49.85, minimizing frame rate drops during complex gameplay.

4.5.3.2 Medium Graphics Settings

Nvidia GeForce RTX 4060

At medium settings and 1080p, FSR Performance mode helps the RTX 4060 push its FPS from 81.8 to 136.4, a 66.8% improvement, and significantly enhances the 1% low and 0.1% low FPS from 62.5 to 102.45 and from 58.25 to 81.75, respectively, for more consistent gameplay. The Balanced mode increases average FPS to 124.4, with 1% low and 0.1% low reaching 80.15 and 66.3, respectively. Quality mode raises the average FPS to 113.35, with 1% low and 0.1% low improving to 75.8 and 63.7. At 1440p, Performance mode boosts average FPS to 95.8, with 1% low and 0.1% low increasing to 64.5 and 49, ensuring stable and fluid visuals.

Nvidia GeForce RTX 3060

For the RTX 3060 under medium settings, FSR Performance mode increases average FPS at 1080p from 75.2 to 125.1, and significantly boosts 1% low FPS from 58.9 to 84 and 0.1% low FPS from 50.05 to 67.4, ensuring smoother gameplay. The Balanced mode increases the average FPS to 111.95, with enhancements in 1% low and 0.1% low FPS to 70.35 and 58.95, respectively. Quality mode achieves 102.45 FPS, with 1% low and 0.1% low improving to 68.25 and 59.15. At 1440p, Performance mode boosts average FPS from 45.3 to 91.85, with improvements in 1% low and 0.1% low FPS to 61.25 and 41.55, enhancing overall game fluidity.

4.5.3.3 High Graphics Settings

Nvidia GeForce RTX 4060

High settings are where FSR shows its value on the RTX 4060. At 1080p, Performance mode boosts average FPS from 72.75 to 118.65 (63.1% increase), with substantial improvements in 1% low FPS from 57.4 to 83.6 and 0.1% low FPS from 50.15 to 75.8. Balanced mode raises the average FPS to 107.25, with enhancements in 1% low and 0.1% low FPS to 69.95 and 62.15. Quality mode achieves 98.25 FPS, with 1% low and 0.1% low improving to 65.65 and 57.65, respectively. At 1440p, FSR Performance mode raises FPS from 47.7 to 90.5 (89.7% increase), with significant improvements in 1% low and 0.1% low FPS to 65.7 and 59.65, ensuring consistent performance during graphically demanding sequences.

Nvidia GeForce RTX 3060

Even at high settings, the RTX 3060 benefits from FSR. At 1080p, Performance mode increases average FPS from 66.2 to 107.05, a 61.7% improvement, and significantly enhances 1% low FPS from 50.45 to 68.7 and 0.1% low FPS from 39.55 to 49.9. Balanced mode raises the average FPS to 95.55, with improvements in 1% low and 0.1% low FPS to 61.4 and 53.95. Quality mode achieves 87.6 FPS, with 1% low and 0.1% low improving to 60.65 and 49.6, respectively. At 1440p, Performance mode boosts average FPS from 40.7 to 78.25 (92.3% increase), with improvements in 1% low and 0.1% low FPS to 57.55 and 43.65, providing a seamless gaming experience at higher settings.

4.5.3.4 Summary of AMD FSR Performance Improvements

This section evaluates the average performance improvements provided by AMD's FSR technology across all modes (Performance, Balanced, Quality) and graphics settings (low, medium, high) for both the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. By aggregating the data from different settings and modes, this analysis aims to provide a comprehensive overview of how FSR enhances the overall gaming experience in The Witcher 3.

Average Performance Improvements Analysis: Nvidia GeForce RTX 4060

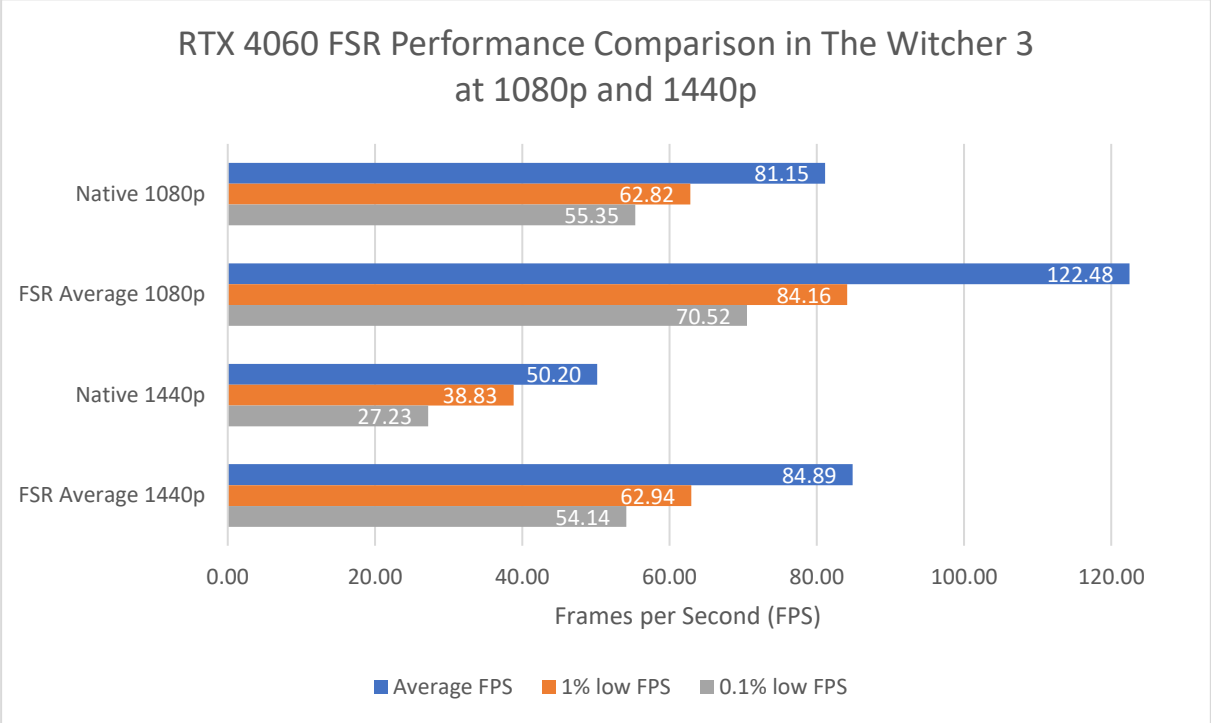


Figure 64: AMD FSR Performance on RTX 4060 in The Witcher 3 at 1080p and 1440p.

In the graph, AMD FSR technology significantly enhances the RTX 4060's performance in "The Witcher 3" at 1080p by increasing the average frame rate from a native 81.15 FPS to 122.48 FPS, a substantial increase of approximately 51%. This performance uplift ensures much smoother gameplay and better handles complex visual scenes, as evidenced by improvements in the 1% low FPS metric, which increased from 62.82 to 84.16 (around 34%), and in the 0.1% low FPS from 55.35 to 70.52 (about 27%). At 1440p, the impact of FSR is even more substantial, with average frame rates rising from 50.20 FPS natively to 84.89 FPS, an increase of about 69%. This increase is critical for maintaining fluidity in gameplay at higher resolutions, with the 1% low FPS improving from 38.83 to 62.94 (around 62%) and the 0.1% low FPS rising from 27.23 to 54.14 (approximately 99%). These enhancements demonstrate that FSR provides a robust balance of performance improvement and stability at higher resolutions.

Average Performance Improvements Analysis: Nvidia GeForce RTX 3060

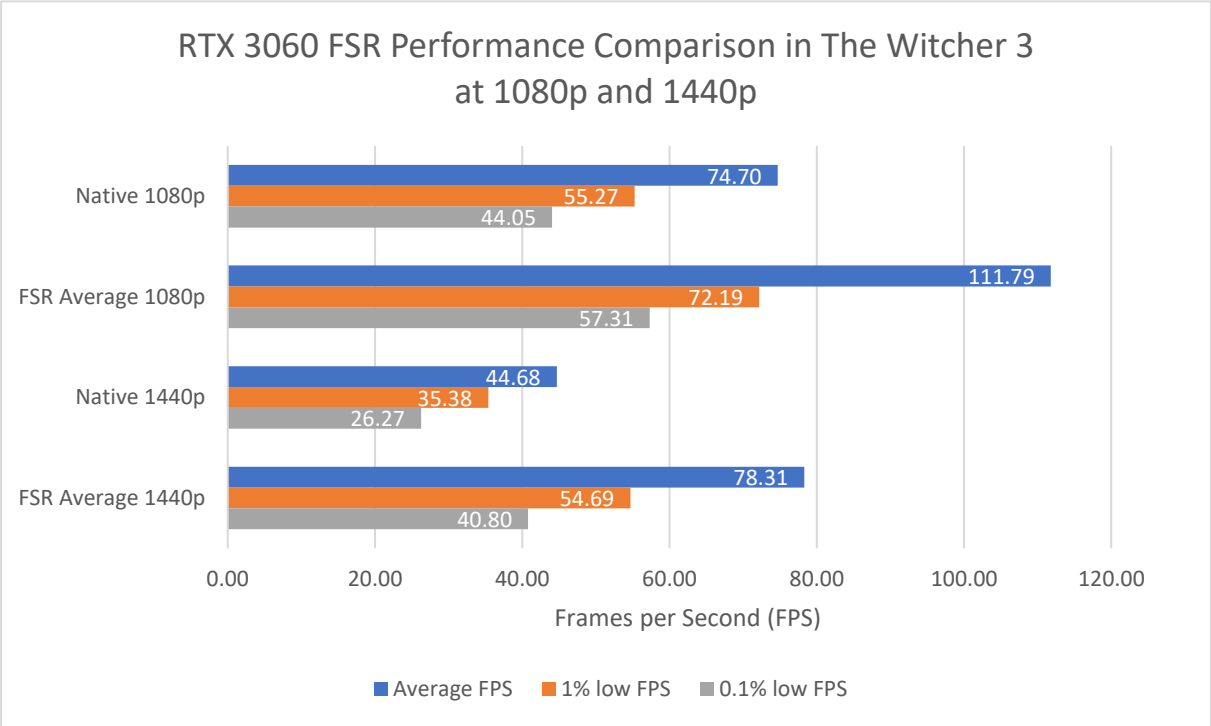


Figure 65: AMD FSR Performance on RTX 3060 in The Witcher 3 at 1080p and 1440p.

For the RTX 3060, as shown in the graph, FSR also shows significant performance gains in "The Witcher 3".

At 1080p, the native rendering achieves an average frame rate of 74.70 FPS, which increases to 111.79 FPS with FSR enabled, a boost of approximately 50%. This enhancement ensures a smoother and more consistent gaming experience, as indicated by the improved 1% low FPS, which increases from 55.27 to 72.19 (around 31%), and the 0.1% low FPS, which increases from 44.05 to 57.31 (approximately 30%).

At 1440p, the average frame rate improves from 44.68 FPS natively to 78.31 FPS with FSR, representing an increase of about 75%. This performance boost is crucial for high-resolution gaming, with the 1% low FPS increasing from 35.38 to 54.69 (approximately 55%) and the 0.1% low FPS rising from 26.27 to 40.80 (around 55%).

Overall, FSR on the RTX 3060 effectively enhances the average FPS while maintaining frame rate consistency, making it a valuable upscaling technology for gamers seeking improved performance and stability in demanding visual environments.

4.5.4 Intel XeSS Performance Analysis

In this section, the performance of Intel's XeSS technology in The Witcher 3: Wild Hunt is analyzed on both the RTX 3060 and RTX 4060 GPUs. The analysis begins with an evaluation of the technology across different graphics settings (low, medium, high) and modes (Performance, Balanced, Quality). This is followed by a comparison of the average values across all settings to native rendering, providing a comprehensive overview of Xess' impact on gaming performance.

4.5.4.1 Low Graphics Settings

Nvidia GeForce RTX 4060

At 1080p, XeSS Performance mode enhances the RTX 4060's average FPS from 88.9 to 140.6, a 58.2% improvement, while also boosting the 1% low FPS from 68.55 to 105.4 and 0.1% low FPS from 57.65 to 85.55. The Balanced mode raises average FPS to 130.75, with 1% low and 0.1% low seeing proportional improvements to 86.7 and 77.2, respectively. Quality mode, focusing more on visual fidelity, achieves 122.05 FPS, with 1% low and 0.1% low increasing to 76.7 and 61.5. At 1440p, XeSS Performance mode significantly improves FPS to 100.9, up 91.5%, and also elevates 1% low and 0.1% low FPS to 74.65 and 64.75, ensuring smoother performance during intensive scenes.

Nvidia GeForce RTX 3060

For the RTX 3060 at low settings, XeSS Performance mode increases average FPS at 1080p from 82.7 to 129.25 (56.3% increase), with 1% low FPS and 0.1% low FPS seeing a noticeable boost from 56.45 to 76.95 and from 42.55 to 59.6, enhancing gameplay fluidity. The Balanced mode raises the average FPS to 117.4, with improvements in 1% low and 0.1% low FPS to 77.25 and 53.4, respectively. Quality mode achieves 108.3 FPS, with 1% low and 0.1% low improving to 72.4 and 51.6. At 1440p, XeSS Performance mode raises the FPS from 48.05 to 92.8 (93.1% increase), with corresponding improvements in the 1% low and 0.1% low FPS to 51.7 and 34.7, minimizing frame rate drops during complex gameplay.

4.5.4.2 Medium Graphics Settings

Nvidia GeForce RTX 4060

At medium settings and 1080p, XeSS Performance mode helps the RTX 4060 push its FPS from 81.8 to 130.45, a 59.5% improvement, and significantly enhances the 1% low and 0.1% low FPS from 62.5 to 96.2 and from 58.25 to 80.25, respectively, for more consistent gameplay. The Balanced mode increases average FPS to 119.8, with 1% low and 0.1% low reaching 77.1 and 64, respectively. Quality mode raises the average FPS to 110.55, with 1% low and 0.1% low improving to 71.9 and 66.85. At 1440p, Performance mode boosts average FPS to 91.6, with 1% low and 0.1% low increasing to 62.5 and 56.6, ensuring stable and fluid visuals.

Nvidia GeForce RTX 3060

For the RTX 3060 under medium settings, XeSS Performance mode increases average FPS at 1080p from 75.2 to 117.25, and significantly boosts 1% low FPS from 58.9 to 74.95 and 0.1% low FPS from 50.05 to 69.6, ensuring smoother gameplay. The Balanced mode increases the average FPS to 106.4, with enhancements in 1% low and 0.1% low FPS to 69.85 and 53.75, respectively. Quality mode achieves 98.8 FPS, with 1% low and 0.1% low improving to 67.4 and 60.8. At 1440p, Performance mode boosts average FPS from 45.3 to 85.35, with improvements in 1% low and 0.1% low FPS to 53.25 and 38.55, enhancing overall game fluidity.

4.5.4.3 High Graphics Settings

Nvidia GeForce RTX 4060

High settings are where XeSS shows its value on the RTX 4060. At 1080p, Performance mode boosts average FPS from 72.75 to 115.15 (58.3% increase), with substantial improvements in 1% low FPS from 57.4 to 77.7 and 0.1% low FPS from 50.15 to 72.7. Balanced mode raises the average FPS to 105.35, with enhancements in 1% low and 0.1% low FPS to 68.2 and 63.05. Quality mode achieves 97.55 FPS, with 1% low and 0.1% low improving to 64.05 and 58.1, respectively. At 1440p, XeSS Performance mode raises FPS from 47.7 to 88.4 (85.3% increase), with significant improvements in 1% low and 0.1% low FPS to 63.2 and 45.55, ensuring consistent performance during graphically demanding sequences.

Nvidia GeForce RTX 3060

Even at high settings, the RTX 3060 benefits from XeSS. At 1080p, Performance mode increases average FPS from 66.2 to 102.9, a 55.4% improvement, and significantly enhances 1% low FPS from 50.45 to 67.45 and 0.1% low FPS from 39.55 to 60.1. Balanced mode raises the average FPS to 93.15, with improvements in 1% low and 0.1% low FPS to 62.55 and 55.8. Quality mode achieves 86.15 FPS, with 1% low and 0.1% low improving to 58.15 and 50.9, respectively. At 1440p, Performance mode boosts average FPS from 40.7 to 75.3 (85% increase), with improvements in 1% low and 0.1% low FPS to 54.35 and 42.4, providing a seamless gaming experience at higher settings.

4.5.4.4 Summary of Intel XeSS Performance Improvements

This section evaluates the average performance improvements provided by Intel's XeSS technology across all modes (Performance, Balanced, Quality) and graphics settings (low, medium, high) for both the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060. By aggregating the data from different settings and modes, this analysis aims to provide a comprehensive overview of how XeSS enhances the overall gaming experience in The Witcher 3.

Average Performance Improvements Analysis: Nvidia GeForce RTX 4060

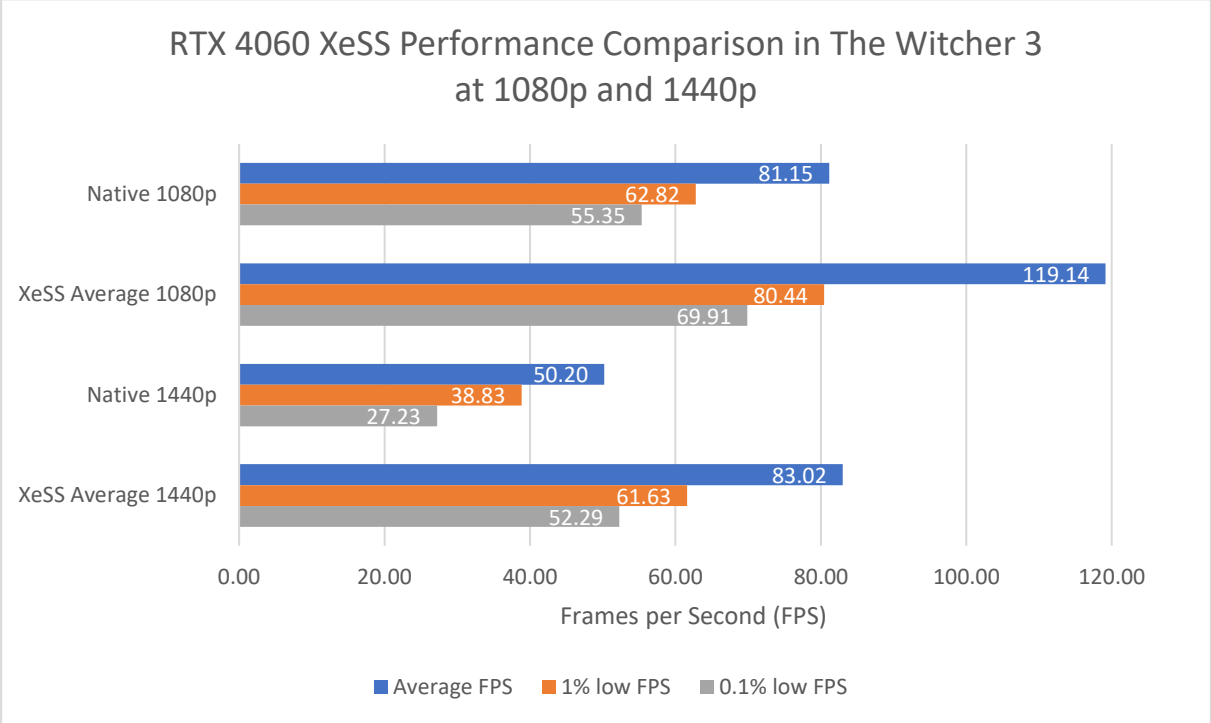


Figure 66: Intel XeSS Performance on RTX 4060 in The Witcher 3 at 1080p and 1440p.

In the graph, Intel XeSS technology enhances the RTX 4060's performance in "The Witcher 3" at 1080p by increasing the average frame rate from a native 81.15 FPS to 119.14 FPS, a substantial increase of approximately 46.8%. This significant performance uplift ensures much smoother gameplay and better handles complex visual scenes, as evidenced by improvements in the 1% low FPS metric, which increased from 62.82 to 80.44 (around 28%), and in the 0.1% low FPS from 55.35 to 69.91 (about 26%). At 1440p, the impact of XeSS is even more substantial, with average frame rates rising from 50.20 FPS natively to 83.02 FPS, an increase of about 65.3%. This increase is critical for maintaining fluidity in gameplay at higher resolutions, with the 1% low FPS improving from 38.83 to 61.63 (around 58.7%) and the 0.1% low FPS rising from 27.23 to 52.29 (approximately 92%). These enhancements demonstrate that XeSS provides a robust balance of performance improvement and stability at higher resolutions.

Average Performance Improvements Analysis: Nvidia GeForce RTX 3060

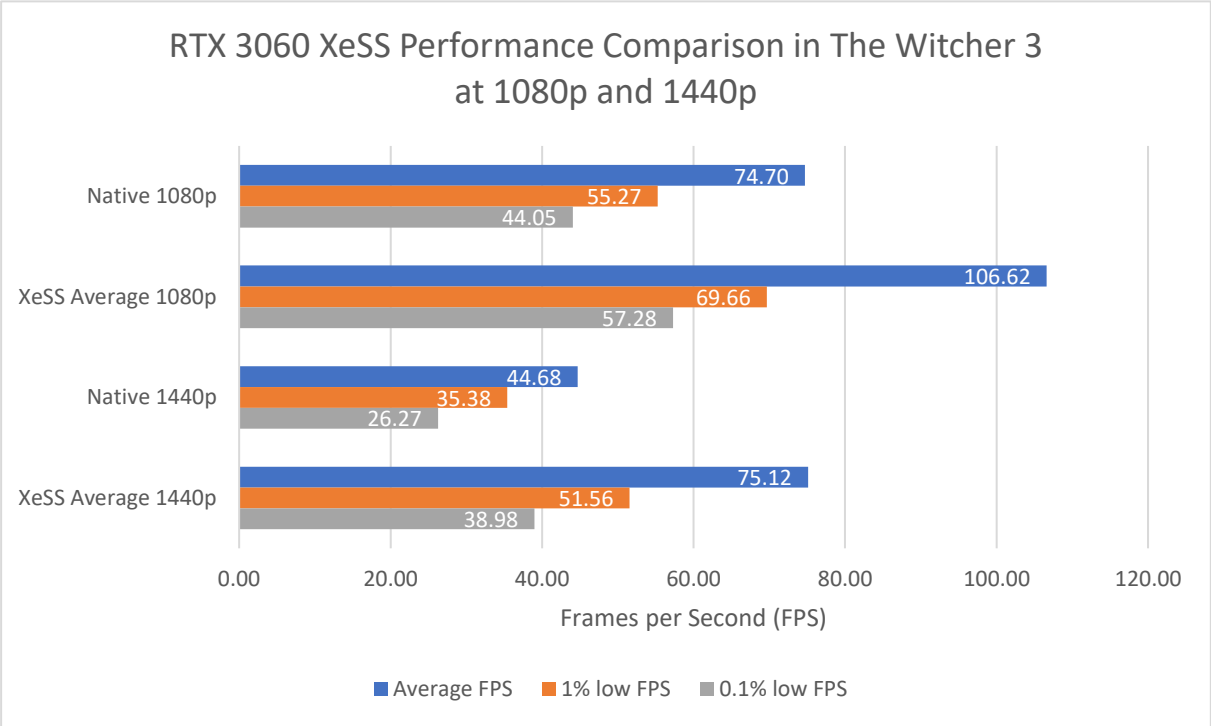


Figure 67: Intel XeSS Performance on RTX 3060 in The Witcher 3 at 1080p and 1440p.

For the RTX 3060, as shown in the graph, XeSS also shows significant performance gains in "The Witcher 3". At 1080p, the native rendering achieves an average frame rate of 74.70 FPS, which increases to 106.62 FPS with XeSS enabled, a boost of approximately 42.7%. This enhancement ensures a smoother and more consistent gaming experience, as indicated by the improved 1% low FPS, which increases from 55.27 to 69.66 (around 26%), and the 0.1% low FPS, which increases from 44.05 to 57.28 (approximately 30%). At 1440p, the average frame rate improves from 44.68 FPS natively to 75.12 FPS with XeSS, representing an increase of about 68.1%. This performance boost is crucial for high-resolution gaming, with the 1% low FPS increasing from 35.38 to 51.56 (approximately 45.8%) and the 0.1% low FPS rising from 26.27 to 38.98 (around 48.4%). Overall, XeSS on the RTX 3060 effectively enhances the average FPS while maintaining frame rate consistency, making it a valuable upscaling technology for gamers seeking improved performance and stability in demanding visual environments.

4.5.5 Frame Time Analysis

In this section the frametime consistency of the Nvidia GeForce RTX 4060 running Cyberpunk 2077 Ultimate Edition is checked at 1440p with the high graphics settings. Hereby the native rendering results are compared to the upscaled results. Frametime, measured in milliseconds, is critical as it impacts the smoothness and responsiveness of gameplay. Lower and more consistent frametimes translate to a smoother gaming experience. The analysis will provide insights into which technology offers the most stable gaming experience.

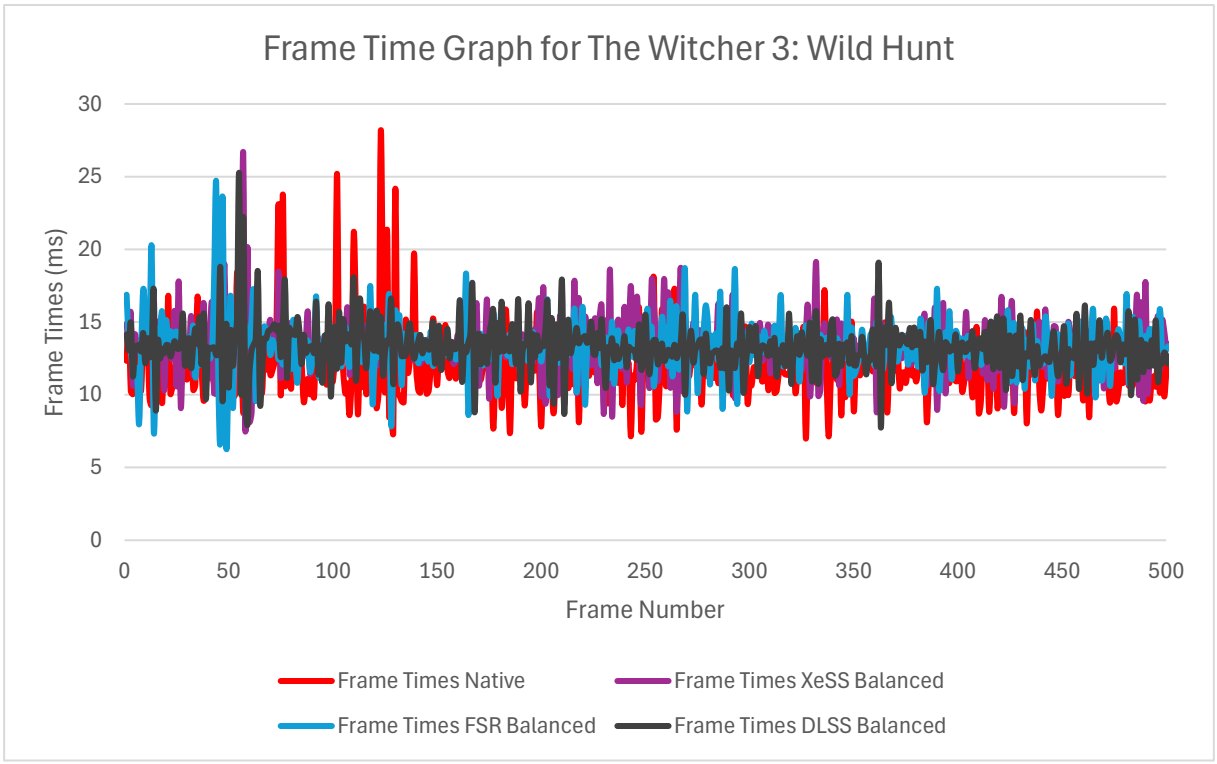


Figure 68: Frame Time Graph The Witcher 3 Wild Hunt

This graph presents frame times measured in milliseconds on the Y-axis, representing the duration it takes to render each frame. The X-axis sequentially numbers the frames from 1 to 500, illustrating the frame rendering order over time. This analysis compares the stability and consistency of frame delivery across different rendering techniques. The key takeaways are as follows:

- **Native Rendering (Red)**: Shows significant variability with frequent and high spikes in frame times, indicating notable delays in frame delivery. The spikes often exceed 20 ms, reaching up to 25-30 ms, which can lead to noticeable stutter and reduced smoothness during gameplay. This inconsistency can significantly impact the overall gaming experience, causing frequent interruptions in visual fluidity.
- **FSR Balanced (Blue)**: Displays improved frame time consistency compared to native rendering. Although there are still spikes, they are less frequent and of lower magnitude, generally staying below 20 ms. This leads to a more stable and fluid gaming experience, reducing perceptible lag and enhancing playability.
- **DLSS Balanced (Black)**: Demonstrates further improvement in frame time consistency. The spikes are less frequent and of lower magnitude compared to native rendering and FSR Balanced. Most frame times stay below 15 ms, indicating a more consistent frame delivery that minimizes stutter and enhances gameplay fluidity.

- **XeSS Balanced (Purple)**: Offers performance similar to DLSS Balanced, with minimal and low-magnitude spikes. The frame times remain consistently low, rarely exceeding 15 ms. This results in highly stable frame delivery, providing a seamless and smooth gaming experience with minimal interruptions.

Overall, all three upscaling technologies (FSR, DLSS, and XeSS) significantly reduce frame time variability compared to native rendering. XeSS and DLSS show the most consistent performance improvements, maintaining lower and more stable frame times throughout the session.

4.5.6 Energy Efficiency and Consumption Analysis

Energy Efficiency and Consumption Analysis The following graphs illustrate the energy consumption (in Watts) and GPU utilization (in percent) of the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060 while running The Witcher 3: Wild Hunt. The values for the upscaling technologies displayed in the graph are calculated by averaging the values of their three modes: Quality, Balanced, and Performance. Additionally, the performance per watt for each configuration is shown in the accompanying table.

4.5.6.1 Energy Consumption Analysis Nvidia Geforce RTX 4060

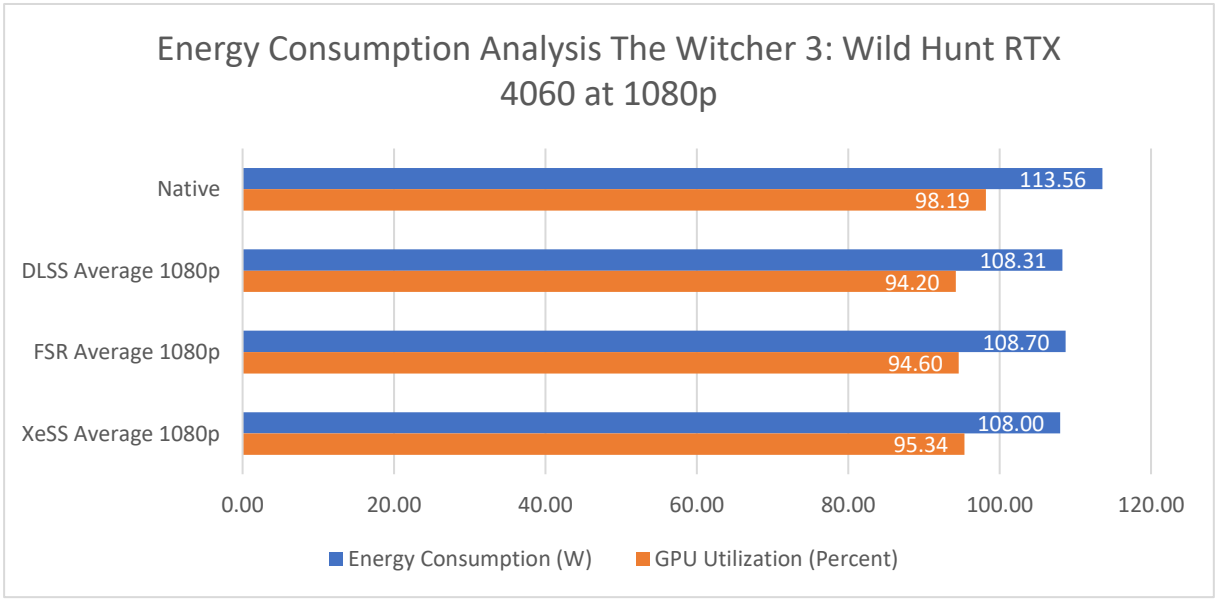


Figure 69: Energy Consumption Analysis The Witcher 3 RTX 4060 1080p.

This graph showcases the RTX 4060 at 1080p across the different upscaling techniques.

Native rendering consumes the most power at 113.56 W with a GPU utilization of 98.19%.

DLSS on average at 1080p achieves the lowest energy consumption at 108.31 W, representing a 4.62% reduction compared to native rendering, with a decrease in GPU utilization to 94.20%.

FSR on average at 1080p shows a marginal increase in energy consumption to 108.70 W and GPU utilization to 94.60%, which is 4.28% lower than native rendering.

XeSS on average at 1080p maintains a balanced performance with energy consumption at 108.00 W and GPU utilization at 95.34%, representing a 4.90% reduction in energy consumption compared to native rendering.

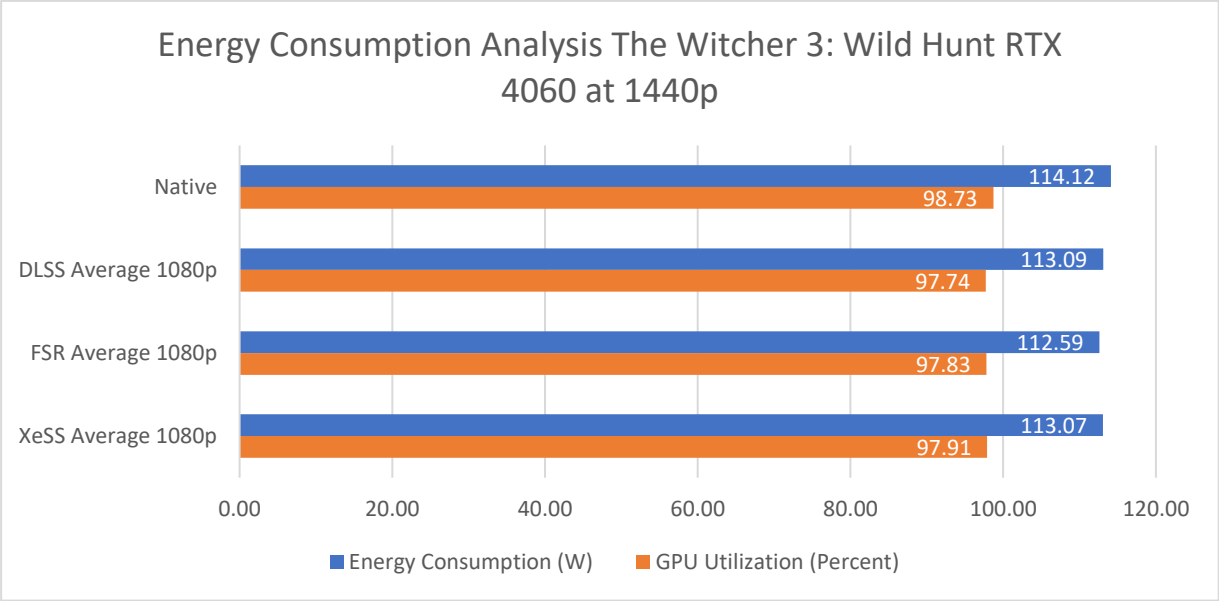


Figure 70: Energy Consumption Analysis The Witcher 3 RTX 4060 1440p.

This graph showcases the RTX 4060 at 1440p across the different upscaling techniques.

Native rendering consumes the most power at 114.12 W with a GPU utilization of 98.73%.

DLSS on average at 1440p achieves the lowest energy consumption at 113.09 W, representing a 0.90% reduction compared to native rendering, with a decrease in GPU utilization to 97.74%.

FSR on average at 1440p shows a marginal increase in energy consumption to 112.59 W and GPU utilization to 97.83%, which is 1.34% lower than native rendering.

XeSS on average at 1440p maintains a balanced performance with energy consumption at 113.07 W and GPU utilization at 97.91%, representing a 0.92% reduction in energy consumption compared to native rendering.

4.5.6.2 Energy Consumption Analysis Nvidia Geforce RTX 3060

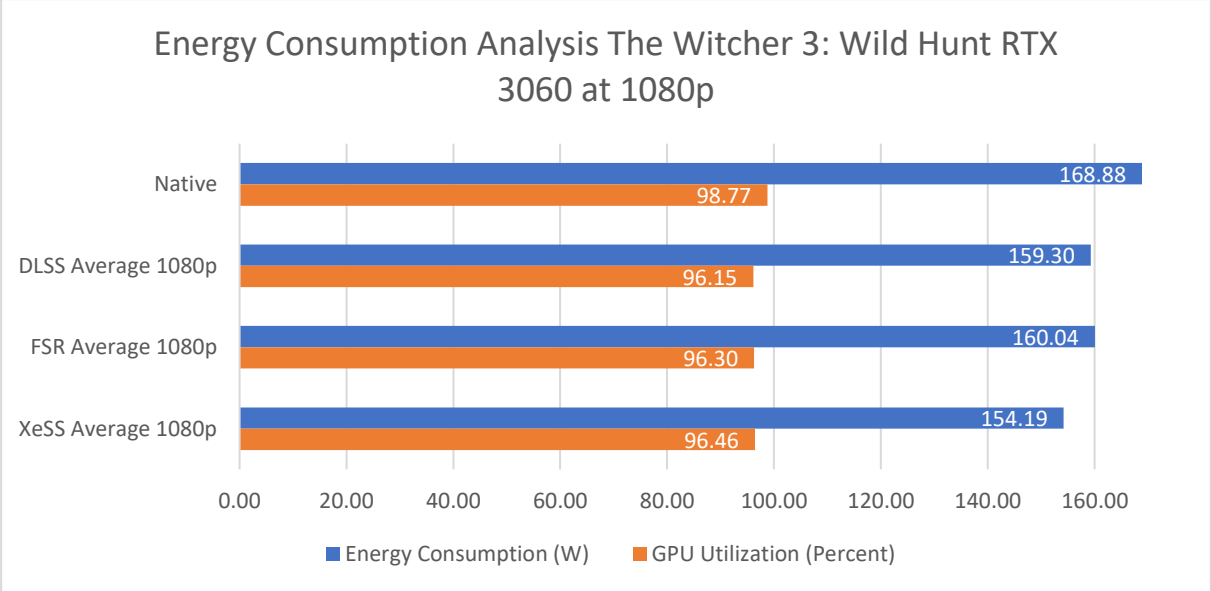


Figure 71: Energy Consumption Analysis The Witcher 3 RTX 3060 1080p.

This graph showcases the RTX 3060 at 1080p across the different upscaling techniques.

Native rendering consumes the most power at 168.88 W with a GPU utilization of 98.77%.

DLSS on average at 1080p achieves the lowest energy consumption at 159.30 W, representing a 5.67% reduction compared to native rendering, with a decrease in GPU utilization to 96.15%.

FSR on average at 1080p shows a marginal increase in energy consumption to 160.04 W and GPU utilization to 96.30%, which is 5.23% lower than native rendering.

XeSS on average at 1080p maintains a balanced performance with energy consumption at 154.19 W and GPU utilization at 96.46%, representing an 8.70% reduction in energy consumption compared to native rendering.

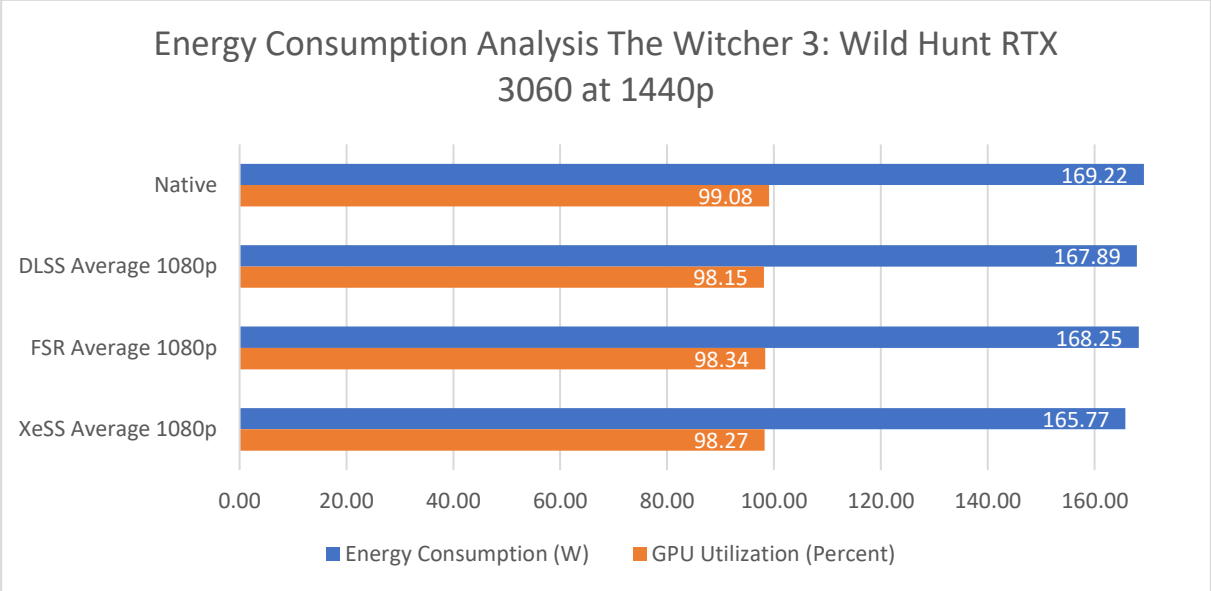


Figure 72: Energy Consumption Analysis The Witcher 3 RTX 3060 1440p.

This graph showcases the RTX 3060 at 1440p across the different upscaling techniques.

Native rendering consumes the most power at 169.22 W with a GPU utilization of 99.08%.

DLSS on average at 1440p achieves the lowest energy consumption at 167.89 W, representing a 0.79% reduction compared to native rendering, with a decrease in GPU utilization to 98.15%.

FSR on average at 1440p shows a marginal increase in energy consumption to 168.25 W and GPU utilization to 98.34%, which is 0.57% lower than native rendering.

XeSS on average at 1440p maintains a balanced performance with energy consumption at 165.77 W and GPU utilization at 98.27%, representing a 2.04% reduction in energy consumption compared to native rendering.

4.5.7 Image Quality Assessment

This section assesses the image quality produced by various upscaling technologies at 1440p resolution using the Nvidia GeForce RTX 4060 GPU. The screenshots represent DLSS, FSR, and XeSS, all captured in Balanced mode to ensure high image quality. HDR was not used to maintain consistency across different display setups. All images are saved in BMP format to preserve original quality and provide an uncompressed representation of the visual enhancements each technology brings to the game. The screenshots demonstrate the visual differences and the impact of upscaling technologies on the gaming experience.

Figure 73: The Witcher 3 Native Rendering High Settings 1440p.

Figure 74: The Witcher 3 DLSS Balanced High Settings 1440p.

Figure 75: The Witcher 3 FSR Balanced High Settings 1440p.

Figure 76: The Witcher 3 XeSS Balanced High Settings 1440p.

Native rendering delivers the best image quality, producing the sharpest visuals even at a distance. For example, the red house in the background appears exceptionally sharp and detailed. DLSS ranks second, maintaining high image quality, although it does not achieve the same level of sharpness as native rendering. FSR follows in third place, with less sharpness than DLSS. XeSS, while still producing good visuals, is slightly behind FSR in terms of sharpness.

4.5.8 Game-Specific Conclusion: The Witcher 3: Wild Hunt

The performance, energy efficiency, image quality, and frame time analysis for The Witcher 3: Wild Hunt provide comprehensive insights into how various upscaling technologies—Nvidia DLSS, AMD FSR, and Intel XeSS—impact the gaming experience on the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060 GPUs.

Performance Results

Nvidia DLSS:

Nvidia's DLSS technology demonstrates substantial performance improvements for both the RTX 4060 and RTX 3060 GPUs in The Witcher 3. At 1080p, the RTX 4060 sees a significant increase in average frame rate from 81.15 FPS to 121.79 FPS with DLSS enabled, a 50.1% improvement. This enhancement ensures smoother gameplay and better handling of complex visual scenes, with the 1% low FPS improving from 62.82 to 84.57 and the 0.1% low FPS rising from 55.35 to 70.04. At 1440p, the impact of DLSS is even more pronounced, boosting average FPS from 50.20 to 84.88, a 69% increase. The 1% low FPS improves from 38.83 to 61.96, and the 0.1% low FPS increases from 27.23 to 53.82.

For the RTX 3060, DLSS also provides significant gains. At 1080p, average FPS increases from 74.70 to 111.93, a 49.8% boost. The 1% low FPS improves from 55.27 to 72.80, and the 0.1% low FPS from 44.05 to 59.18. At 1440p, average FPS rises from 44.68 to 79.23, a 77.4% increase, with the 1% low FPS improving from 35.38 to 55.15 and the 0.1% low FPS from 26.27 to 40.53.

AMD FSR:

AMD's FSR also shows notable performance improvements. On the RTX 4060, FSR Performance mode at 1080p increases FPS significantly, and similar gains are observed at 1440p. The RTX 3060 experiences comparable performance enhancements with FSR, although the gains are generally slightly less than those achieved with DLSS.

Intel XeSS:

Intel XeSS delivers performance enhancements, though it tends to lag slightly behind DLSS and FSR. Both the RTX 4060 and RTX 3060 benefit from XeSS, with improvements in average FPS and consistency in low percentile FPS metrics, ensuring smoother gameplay.

Energy Efficiency

DLSS stands out in terms of energy efficiency. For the RTX 4060, DLSS reduces power consumption compared to native rendering, demonstrating significant energy savings. This efficiency is particularly notable at higher resolutions, where DLSS maintains high performance with lower power draw. FSR and XeSS also contribute to energy savings, but their efficiency gains are less pronounced than those observed with DLSS.

Image Quality

Image quality assessments indicate that native rendering provides the sharpest visuals. DLSS follows closely, maintaining high image quality with minimal degradation, especially in Balanced mode. FSR produces slightly softer images than DLSS, while XeSS, although effective, is slightly behind FSR in terms of sharpness. However, these differences become less noticeable during fast-paced gameplay.

Frame Time Analysis

Frame time analysis shows that all upscaling technologies help reduce frame drops, with DLSS providing the most consistent frame times. This consistency is crucial for maintaining smooth gameplay, particularly in the graphically intensive environments of The Witcher 3. Both FSR and XeSS also contribute to a smoother gaming experience, but DLSS remains the leader in frame time stability.

Overall, DLSS emerges as the most balanced and effective upscaling technology for The Witcher 3: Wild Hunt, offering the best combination of performance improvement, energy efficiency, and image quality. AMD FSR and Intel XeSS also enhance the gaming experience but are slightly less effective compared to DLSS.

4.6 Comprehensive Performance and Energy Efficiency Analysis

This section presents a detailed analysis of the performance and energy efficiency of the Nvidia GeForce RTX 4060 and Nvidia GeForce RTX 3060 graphics card across the benchmarked upscaling technologies: Nvidia DLSS, AMD FSR, and Intel XeSS.

The evaluation encompasses both performance metrics, such as frames per second (FPS), and energy consumption metrics, aiming to identify which upscaling technology offers the optimal balance between performance and energy efficiency.

The averages are calculated across all five benchmarked games: Call of Duty Modern Warfare III (2023) (Section 4.1), Diablo IV (Section 4.2), Assassin's Creed Mirage (Section 4.3), Cyberpunk 2077 Ultimate Edition (Section 4.4), and The Witcher 3: Wild Hunt (Section 4.5).

First, the results for the Nvidia GeForce RTX 3060 and Nvidia GeForce RTX 4060 will be discussed individually in section 4.6.1 and 4.6.2. This will be followed by a consolidated analysis comparing the overall performance and energy efficiency of both graphics' cards in section 4.6.3.

4.6.1 Overall Performance and Energy Efficiency Results: Nvidia GeForce RTX 4060

This section offers an in-depth analysis of the overall performance and energy efficiency of the Nvidia GeForce RTX 4060. The values presented are averaged across five benchmarked video games, providing a thorough and representative overview of the GPU's capabilities. Additionally, these sections highlight which upscaling technology delivered the best performance and energy efficiency across the board.

4.6.1.1 Performance Analysis

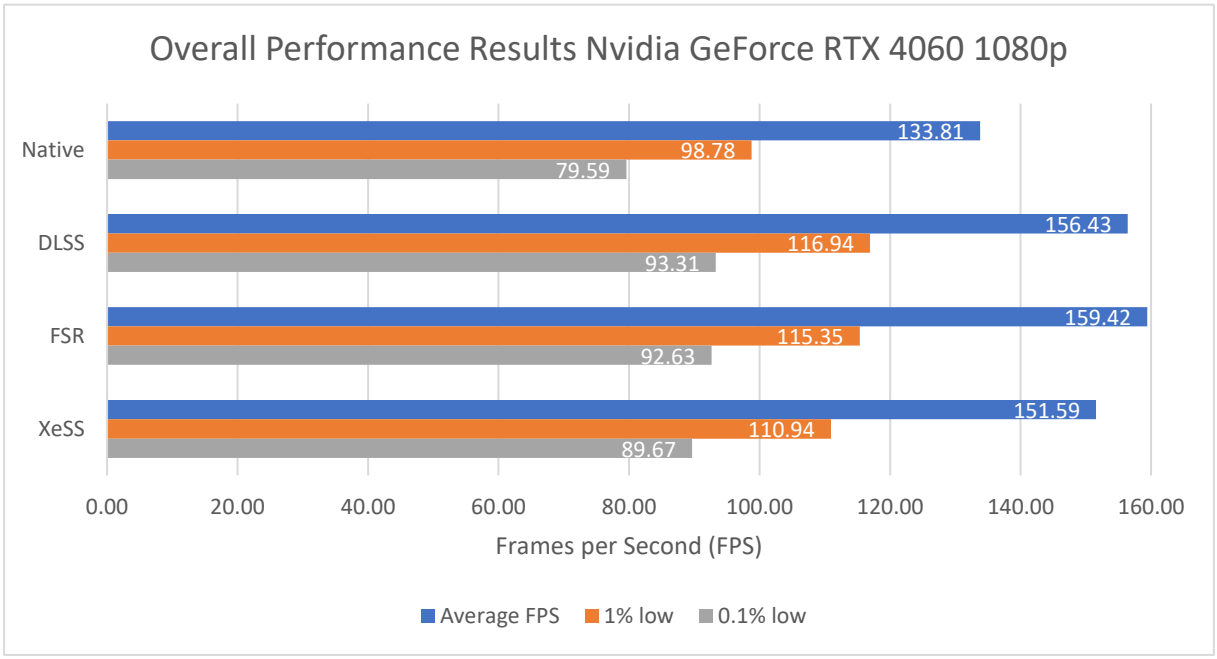


Figure 77: Overall Performance Results RTX 4060 at 1080p.

This graph illustrates the overall performance results for the Nvidia GeForce RTX 4060 at 1080p across different upscaling technologies.

Native rendering achieves an average FPS of 133.81, 1% low FPS of 98.78, and 0.1% low FPS of 79.59. DLSS provides the highest average FPS at 156.43, with a 1% low FPS of 116.94 and a 0.1% low FPS of 93.31, representing a 16.91% increase in average FPS compared to native rendering. FSR follows

closely with an average FPS of 159.42, a 1% low FPS of 115.35, and a 0.1% low FPS of 92.63, marking a 19.12% increase in average FPS. XeSS, while still significantly outperforming native rendering, achieves an average FPS of 151.59, with a 1% low FPS of 110.94 and a 0.1% low FPS of 89.67, translating to a 13.28% increase in average FPS.

This performance analysis indicates that FSR is the top performer in terms of frame rates, followed closely by DLSS and then XeSS.

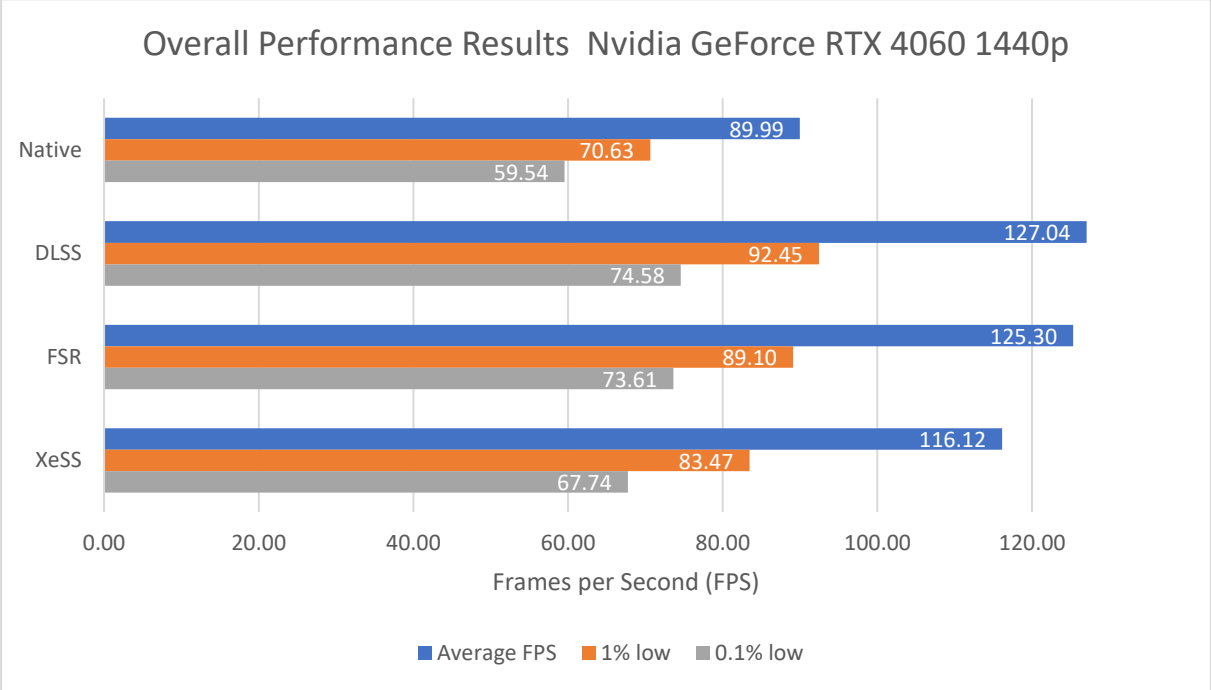


Figure 78: Overall Performance Results RTX 4060 at 1440p.

The second graph provides the performance metrics for the RTX 4060 at 1440p. Native rendering achieves an average FPS of 89.99, with a 1% low FPS of 70.63 and a 0.1% low FPS of 59.54. DLSS improves the average FPS to 127.04, with 1% low FPS of 92.45 and 0.1% low FPS of 74.58, reflecting a 41.14% increase in average FPS. FSR records an average FPS of 125.30, a 1% low FPS of 89.10, and a 0.1% low FPS of 73.61, resulting in a 39.18% increase in average FPS. XeSS achieves an average FPS of 116.12, with 1% low FPS of 83.47 and 0.1% low FPS of 67.74, marking a 29.03% increase in average FPS.

At the 1440p resolution DLSS outperforms the other technologies in frame rates, followed by FSR and XeSS.

4.6.1.2 Energy Efficiency Results

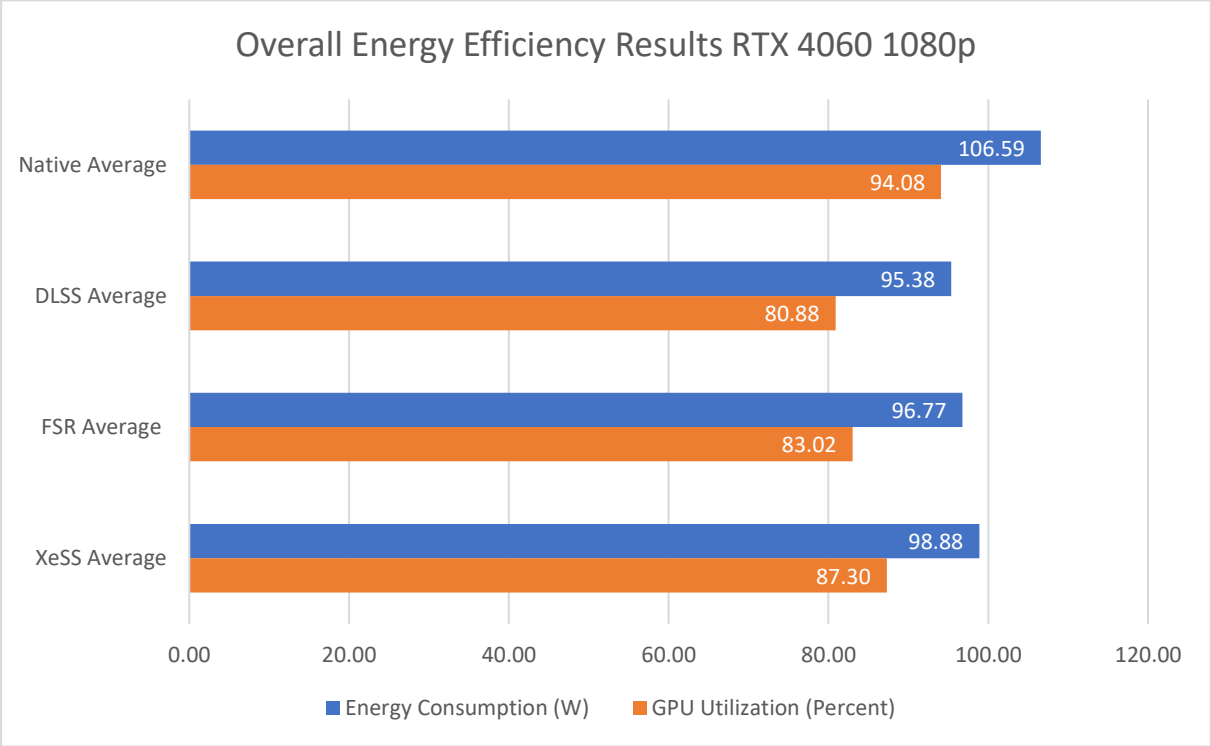


Figure 79: Overall Energy Efficiency Results RTX 4060 1080p.

This graph shows the overall energy efficiency results for the RTX 4060 at 1080p.

Native rendering consumes the most energy with 106.59 W. The GPU utilization is at 94.08%.

DLSS reduces energy consumption to 95.38 W and GPU utilization to 80.88%, representing a 10.51% reduction in energy consumption. FSR also decreases energy consumption to 96.77 W with GPU utilization at 83.02%, resulting in a 9.22% reduction. XeSS shows an energy consumption of 98.88 W and GPU utilization at 87.30%, marking a 7.23% reduction. In summary, DLSS is the most energy-efficient, followed by FSR and XeSS although the results are fairly close to each other.

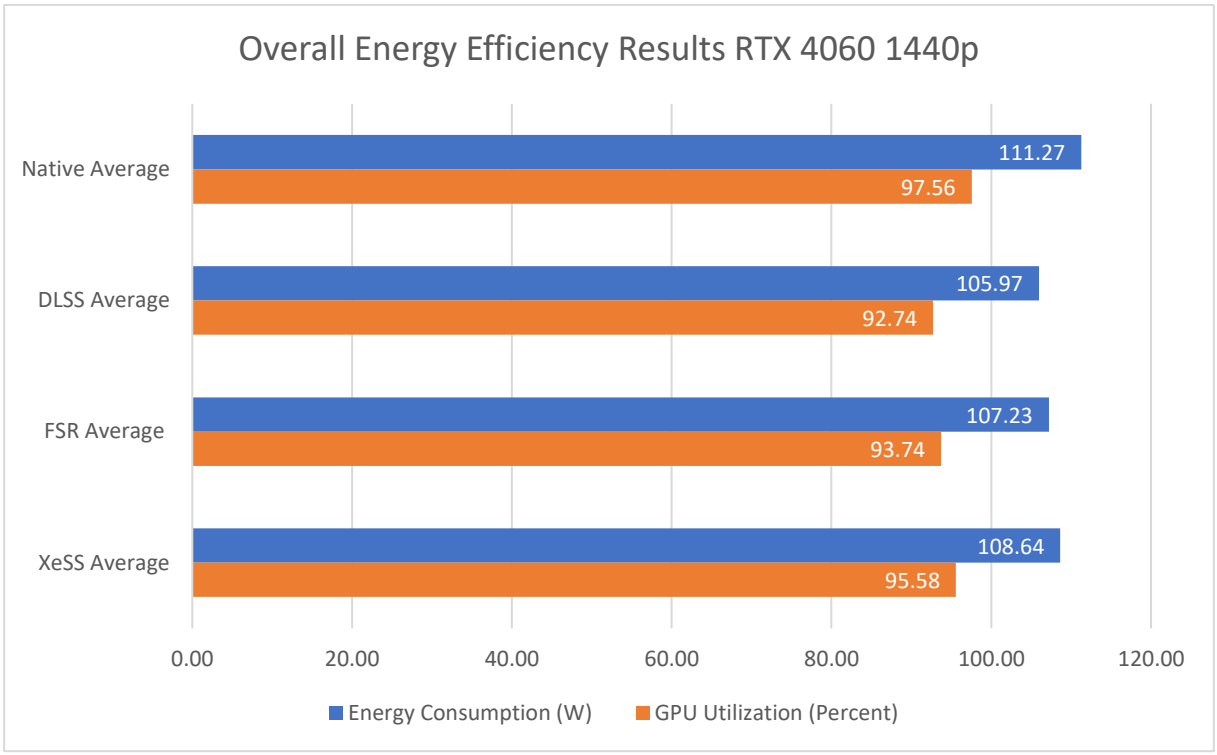


Figure 80: Overall Energy Efficiency Results RTX 4060 1440p,

This graph represents the energy efficiency metrics for the RTX 4060 at 1440p.

Native rendering consumes the most energy at 111.27 W and the GPU utilization at 97.56%.

DLSS reduces energy consumption to 105.97 W and GPU utilization to 92.74%, showing a 4.76% reduction in energy consumption. FSR slightly decreases energy consumption to 107.23 W with GPU utilization at 93.74%, marking a 3.62% reduction. XeSS consumes 108.64 W with GPU utilization at 95.58%, resulting in a 2.36% reduction.

DLSS remains the most energy-efficient option, followed by FSR and XeSS.

4.6.1.3 Conclusion of the Nvidia GeForce RTX 4060 Overall Results

The analysis reveals that for the Nvidia GeForce RTX 4060, both DLSS and FSR provide substantial improvements in performance over native rendering, with FSR slightly edging out DLSS at 1080p and DLSS leading at 1440p.

In terms of energy efficiency, DLSS consistently offers the lowest energy consumption, followed by FSR and XeSS. These findings suggest that DLSS is the best choice for optimizing both performance and energy efficiency, with FSR being a close contender. XeSS, while effective, lags slightly behind in both metrics.

4.6.2 Overall Performance and Energy Efficiency Results: Nvidia GeForce RTX 3060

This section offers an in-depth analysis of the overall performance and energy efficiency of the Nvidia GeForce RTX 3060. The values presented are averaged across five benchmarked video games, providing a thorough and representative overview of the GPU's capabilities. Additionally, these sections highlight which upscaling technology delivered the best performance and energy efficiency across the board.

4.6.2.1 Performance Analysis

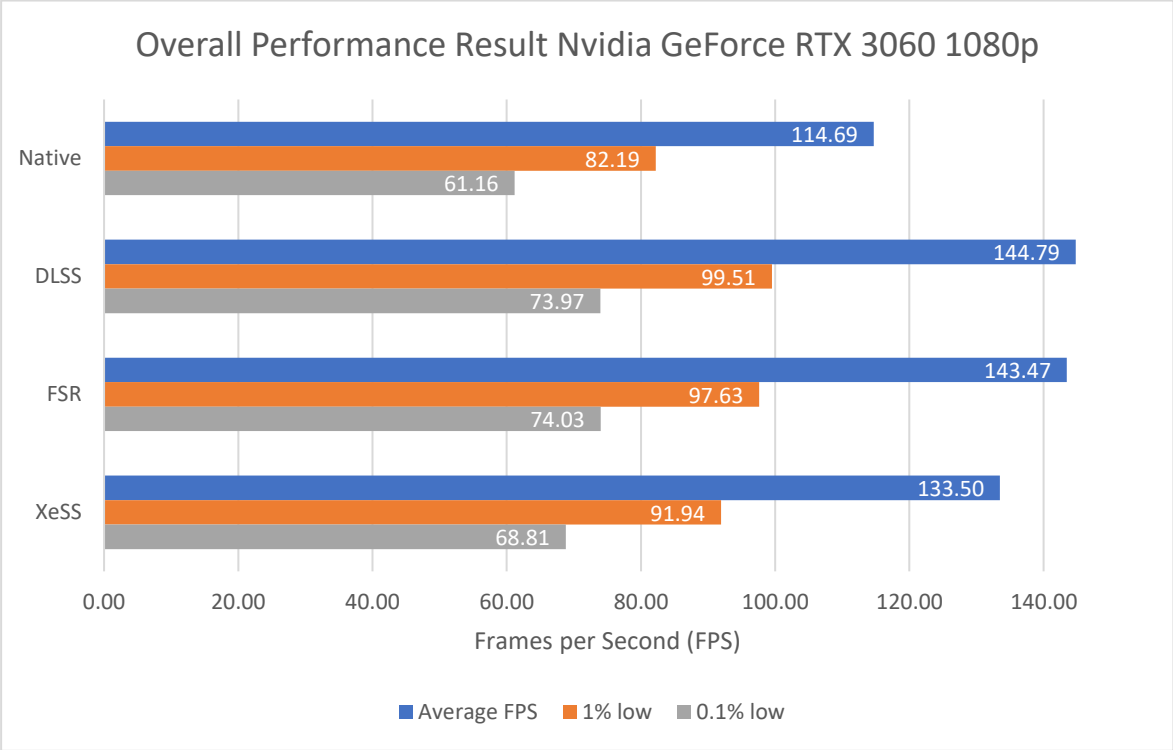


Figure 81: Overall Performance Results RTX 3060 at 1080p.

This graph illustrates the overall performance results of the Nvidia GeForce RTX 3060 at 1080p across the benchmarked upscaling technologies.

Native rendering achieves an average FPS of 114.69, with 1% low FPS of 82.19 and 0.1% low FPS of 61.16. Among the upscaling technologies, DLSS provides the highest average FPS at 144.79, a 26.24% improvement over native rendering, with a 1% low FPS of 99.51 and a 0.1% low FPS of 73.97. FSR closely follows with an average FPS of 143.47, representing a 25.06% increase, with 1% low FPS of 97.63 and 0.1% low FPS of 74.03. XeSS also shows significant performance gains, with an average FPS of 133.50 (16.38% improvement), 1% low FPS of 91.94, and 0.1% low FPS of 68.81.

This performance analysis shows that DLSS is the top performer in terms of frame rates, followed by FSR and XeSS.

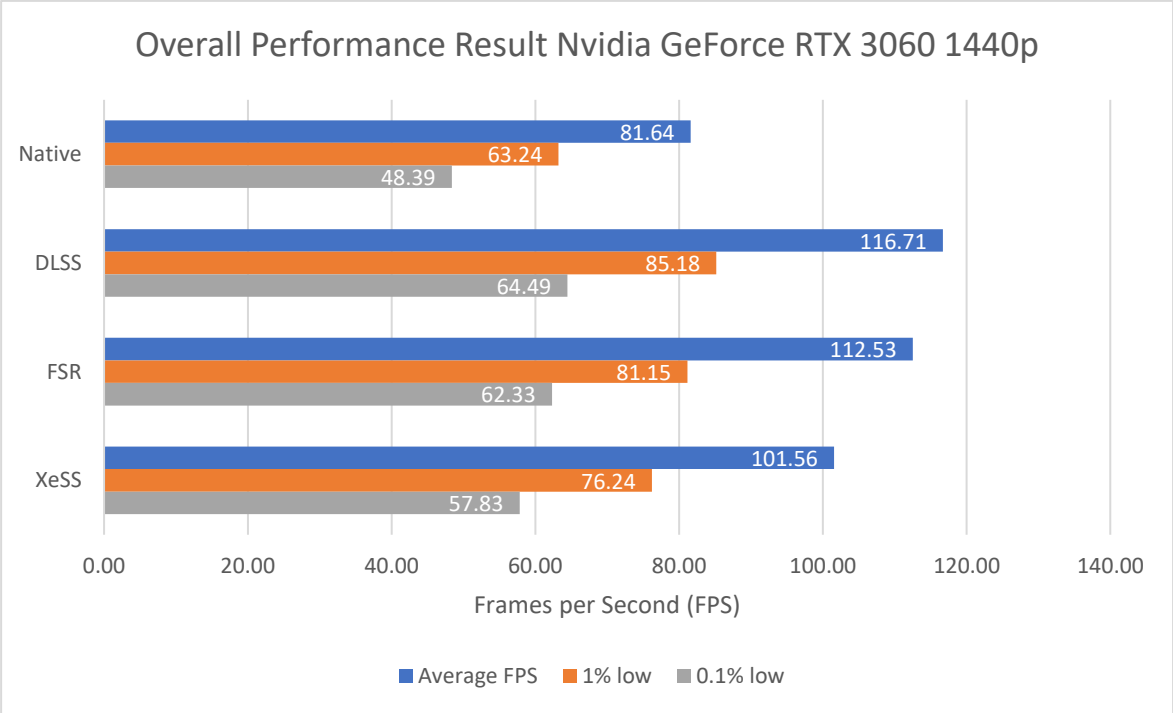


Figure 82: Overall Performance Results RTX 3060 at 1440p.

This graph presents the overall performance results of the Nvidia GeForce RTX 3060 at 1440p across the benchmarked upscaling technologies.

Native rendering achieves an average FPS of 81.64, with 1% low FPS of 63.24 and 0.1% low FPS of 48.39.

Among the technologies, DLSS provides the highest average FPS at 116.71, a 42.98% improvement over native rendering, with a 1% low FPS of 85.18 and a 0.1% low FPS of 64.49.

FSR follows closely with an average FPS of 112.53, representing a 37.88% increase, with 1% low FPS of 81.15 and 0.1% low FPS of 62.33.

XeSS also shows significant performance gains, with an average FPS of 101.56 (24.38% improvement), 1% low FPS of 76.24, and 0.1% low FPS of 57.83.

This performance analysis shows that DLSS is the top performer in terms of frame rates, followed by FSR and XeSS.

4.6.2.2 Energy Efficiency Results

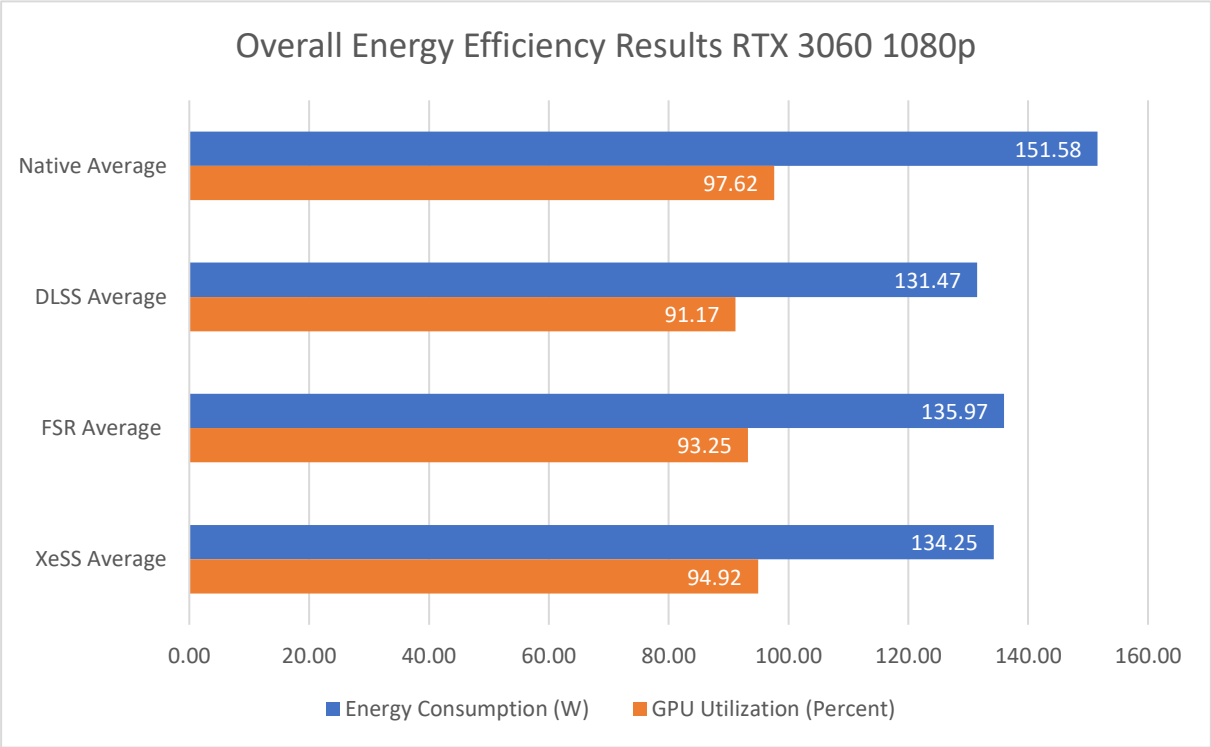


Figure 83: Overall Energy Efficiency Results RTX 3060 1080p,

This graph shows the energy consumption and GPU utilization of the RTX 3060 at 1080p across different upscaling technologies. Native rendering exhibits the highest energy consumption at 151.58 W and GPU utilization at 97.62%. Among the upscaling technologies, DLSS demonstrates the lowest energy consumption at 131.47 W, representing a 13.3% reduction compared to native rendering, with GPU utilization at 91.17%. FSR follows, consuming 135.97 W, which is an 11.5% reduction, with GPU utilization at 93.25%. XeSS consumes 134.25 W, a reduction of 11.4%, with GPU utilization at 94.92%.

The data indicates that DLSS is the most energy-efficient upscaling technology, followed by FSR and XeSS. The reduction in energy consumption with DLSS is the most substantial, making it the optimal choice for energy efficiency while maintaining performance.

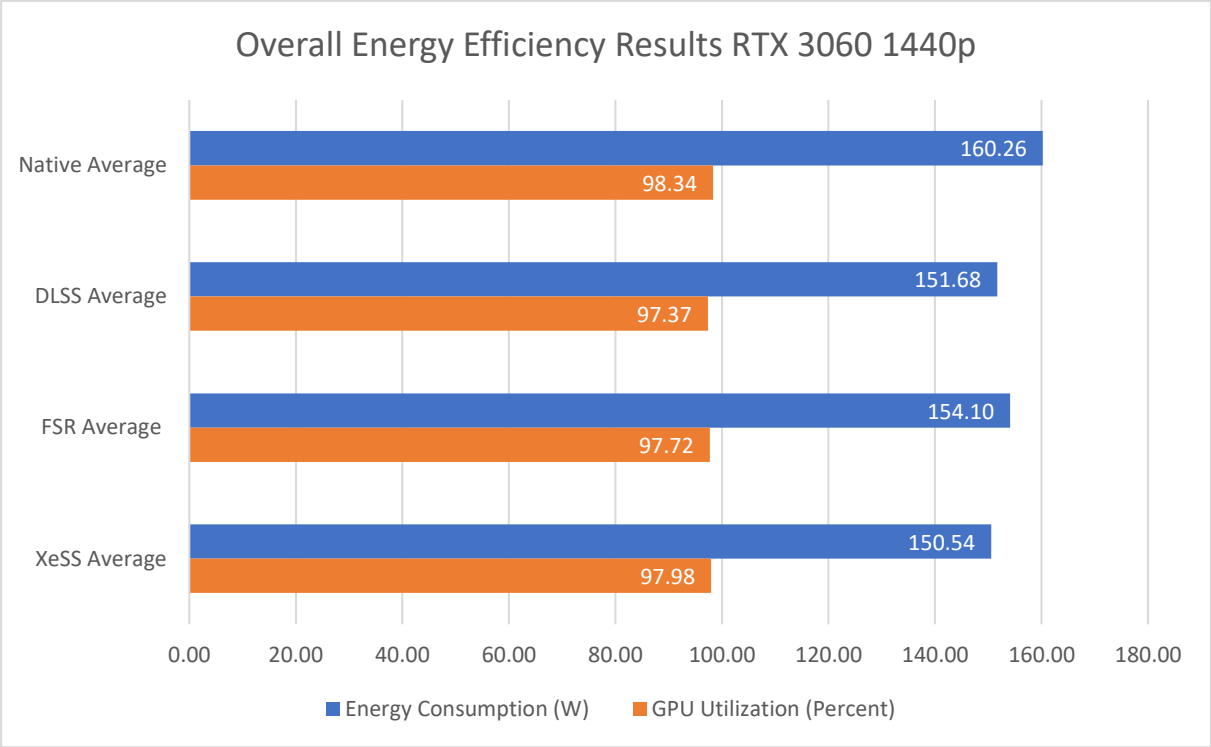


Figure 84: Overall Energy Efficiency Results RTX 3060 1440p,

This graph presents the energy consumption and GPU utilization of the RTX 3060 at 1440p across different upscaling technologies. Native rendering consumes the most power at 160.26 W with GPU utilization at 98.34%. DLSS reduces energy consumption to 151.68 W, representing a 5.35% reduction, with GPU utilization at 97.37%. FSR shows a decrease in energy consumption to 154.10 W, a 3.85% reduction, with GPU utilization at 97.72%. XeSS also demonstrates a reduction in energy consumption to 150.54 W, representing a 6.07% reduction, with GPU utilization at 97.98%. The data indicates that XeSS achieves the highest energy efficiency among the upscaling technologies, followed closely by DLSS and then FSR. These results highlight the energy-saving capabilities of upscaling technologies, particularly in maintaining performance while reducing power consumption.

4.6.2.3 Conclusion of the Nvidia GeForce RTX 3060 Overall Results

The analysis of the Nvidia GeForce RTX 3060 reveals significant insights into the performance and energy efficiency of various upscaling technologies across different resolutions.

At 1080p, native rendering achieves an average FPS of 114.69, with 1% low FPS of 82.19 and 0.1% low FPS of 61.16. DLSS stands out by providing the highest average FPS at 144.79, a substantial 26.2% increase over native rendering. It also delivers 1% low FPS of 99.51 and 0.1% low FPS of 73.97, indicating consistent performance improvements. FSR closely follows DLSS with an average FPS of 143.47, a 25.1% increase, and 1% low and 0.1% low FPS of 97.63 and 74.03, respectively. XeSS, while still providing notable gains, achieves an average FPS of 133.50 (16.4% increase), with 1% low FPS of 91.94 and 0.1% low FPS of 68.81. Thus, DLSS emerges as the top performer in terms of frame rates, followed by FSR and XeSS.

At 1440p, native rendering results in an average FPS of 81.64, with 1% low FPS of 63.24 and 0.1% low FPS of 48.39. DLSS again demonstrates the highest improvement, with an average FPS of 116.71, a 43.0% increase, and 1% low and 0.1% low FPS of 85.18 and 64.49, respectively. FSR shows an average FPS of 112.53, representing a 37.8% increase, and 1% low and 0.1% low FPS of 81.15 and 62.33. XeSS

provides an average FPS of 101.56, a 24.4% improvement, with 1% low FPS of 76.24 and 0.1% low FPS of 57.83. In this resolution as well, DLSS leads in performance, followed by FSR and XeSS.

Energy efficiency is another critical aspect where the RTX 3060's performance varies across different upscaling technologies. At 1080p, native rendering consumes the most power at 151.58 W, with GPU utilization at 97.62%. DLSS achieves the lowest energy consumption at 131.47 W, a 13.3% reduction, with GPU utilization at 91.17%. FSR consumes 135.97 W (10.3% reduction) and GPU utilization at 93.25%, while XeSS consumes 134.25 W (11.4% reduction) with GPU utilization at 94.92%. Therefore, DLSS is the most energy-efficient, followed by XeSS and FSR.

At 1440p, native rendering's energy consumption is highest at 160.26 W with GPU utilization at 98.34%. DLSS reduces energy consumption to 151.68 W, a 5.3% reduction, with GPU utilization at 97.37%. FSR shows a slight decrease in energy consumption to 154.10 W, a 3.8% reduction, with GPU utilization at 97.72%. XeSS achieves a more significant reduction, consuming 150.54 W, representing a 6.1% decrease, with GPU utilization at 97.98%. Here too, DLSS leads in energy efficiency, followed by XeSS and FSR.

4.6.3 Consolidated Performance Analysis Across Nvidia GeForce RTX 4060 and RTX 3060

This section presents a consolidated analysis of the overall performance and energy efficiency for the Nvidia GeForce RTX 4060 and RTX 3060 graphics cards. The results are derived from the average benchmarks across five popular video games: Call of Duty Modern Warfare III (Section 4.1), Diablo IV (Section 4.2), Assassin's Creed Mirage (Section 4.3), Cyberpunk 2077 Ultimate Edition (Section 4.4), and The Witcher 3: Wild Hunt (Section 4.5). Each game was tested at various resolutions and settings, utilizing three different upscaling technologies: Nvidia DLSS, AMD FSR, and Intel XeSS.

This comprehensive analysis aims to identify the overall best-performing upscaling technology by averaging the benchmark results across all tested games, resolutions, and settings, for both graphics cards.

4.6.3.1 Performance Analysis

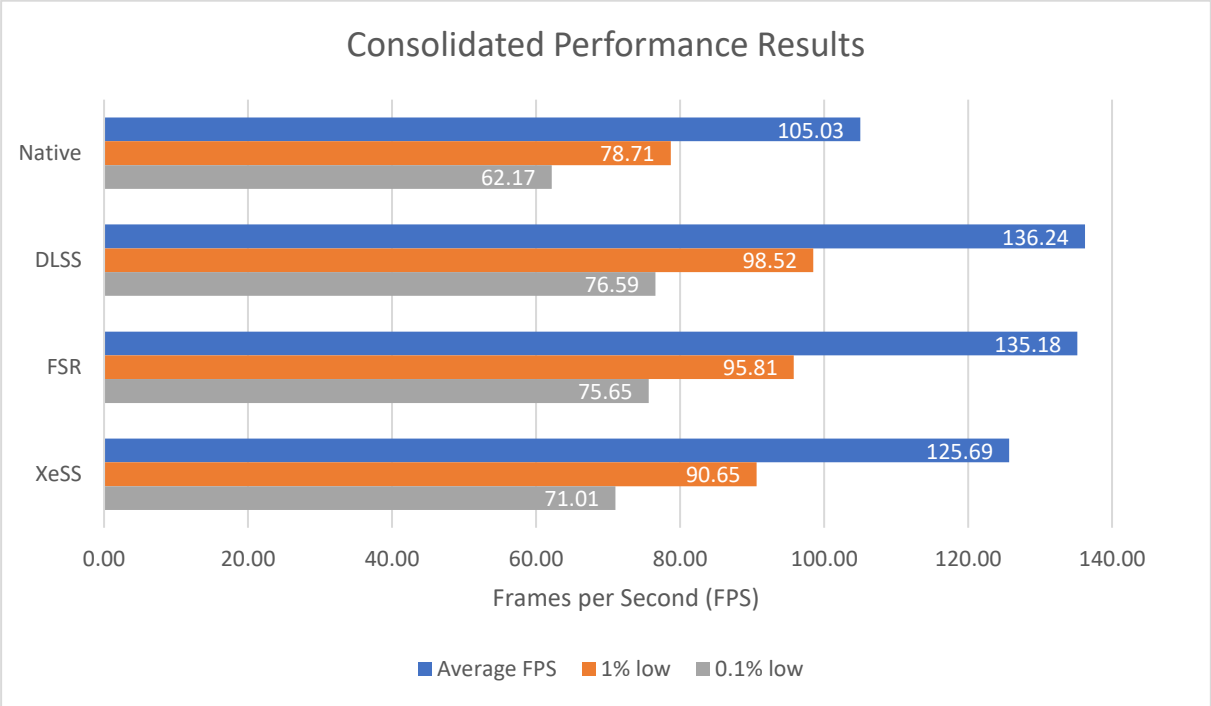


Figure 85: Overall Performance Results

The graph titled "Overall Performance Results" displays the average FPS, 1% low, and 0.1% low FPS for the Nvidia GeForce RTX 4060 and RTX 3060 using the upscaling technologies: DLSS, FSR, and XeSS.

Native rendering, without any upscaling, achieves an average FPS of 105.03, 1% low FPS of 78.71, and 0.1% low FPS of 62.17.

Among the upscaling technologies, DLSS provides the highest average FPS at 136.24, with a 1% low FPS of 98.52 and a 0.1% low FPS of 76.59. This represents a performance increase of 29.70% in average FPS, 25.13% in 1% low FPS, and 23.24% in 0.1% low FPS compared to native rendering. FSR closely follows with an average FPS of 135.18, a 1% low FPS of 95.81, and a 0.1% low FPS of 75.65, translating to a performance increase of 28.71% in average FPS, 21.70% in 1% low FPS, and 21.75% in 0.1% low FPS. XeSS, while still significantly outperforming native rendering, achieves an average FPS of 125.69, with a 1% low FPS of 90.65 and a 0.1% low FPS of 71.01, resulting in a performance increase of 19.63%

in average FPS, 15.16% in 1% low FPS, and 14.23% in 0.1% low FPS. This performance analysis indicates that DLSS is the top performer in terms of frame rates, followed by FSR and XeSS.

4.6.3.2 Energy Efficiency

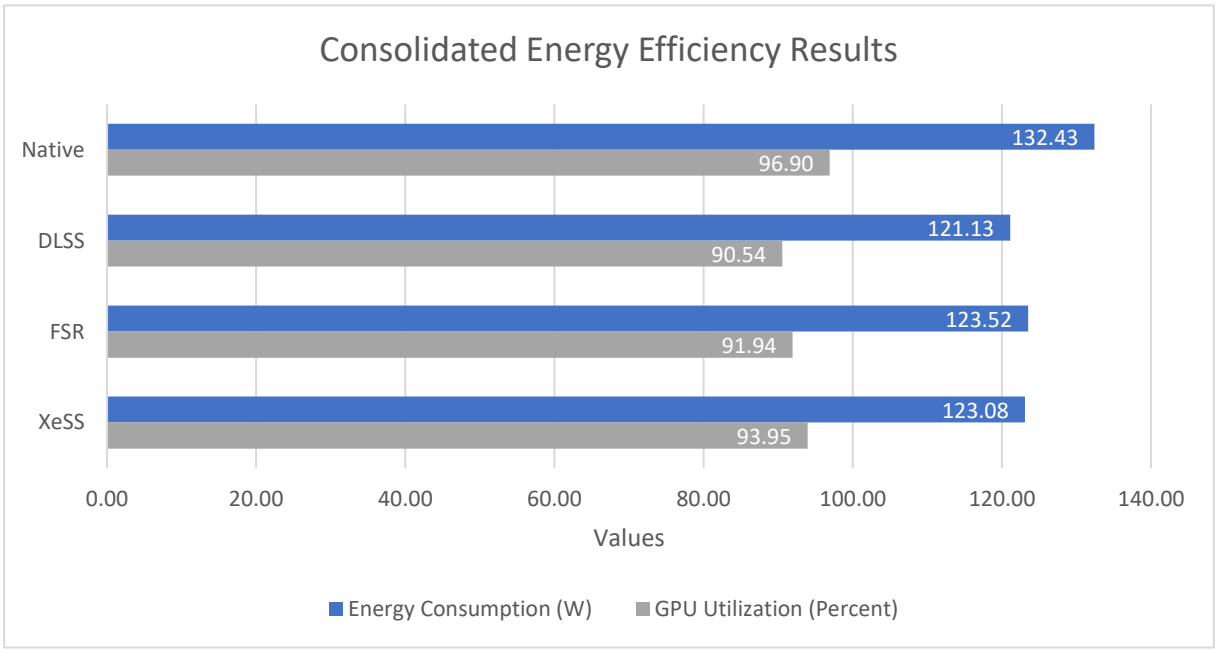


Figure 86: Overall Energy Efficiency Results

This graph shows the energy consumption in watts and GPU utilization percentage for the same set of upscaling technologies.

Native rendering consumes the most power at 132.43 W with a GPU utilization of 96.90%. Among the upscaling technologies, DLSS is the most energy-efficient, consuming 121.13 W with a GPU utilization of 90.54%. This represents a 8.55% reduction in energy consumption compared to native rendering. FSR has a slightly higher energy consumption of 123.52 W and GPU utilization of 91.94%, indicating a 6.73% reduction in energy consumption. XeSS presents a balanced performance with energy consumption at 123.08 W and GPU utilization at 93.95%, showing a 7.07% reduction in energy consumption compared to native rendering.

This analysis highlights that DLSS not only provides the best performance in terms of FPS but also achieves the lowest energy consumption, making it the most efficient upscaling technology among those tested.

4.6.3.3 Conclusion

The comprehensive analysis of the Nvidia GeForce RTX 4060 and RTX 3060 across various video games and upscaling technologies reveals clear insights into performance and energy efficiency. DLSS consistently outperforms other technologies, achieving the highest average FPS and the lowest energy consumption.

In terms of performance, DLSS delivers a substantial boost, increasing average FPS by 29.70% compared to native rendering. FSR follows closely with a 28.71% increase, while XeSS provides a 19.63% improvement. The 1% low and 0.1% low FPS metrics further underscore DLSS's superiority, ensuring smoother and more consistent gameplay.

Regarding energy efficiency, DLSS also excels, reducing power consumption by 8.55% compared to native rendering. FSR and XeSS, while still offering improvements, do not match DLSS's energy savings, with reductions of 6.73% and 7.07%, respectively.

Overall, DLSS emerges as the most effective upscaling technology, providing the best balance of enhanced performance and energy efficiency.

5 ANOVA Test

To evaluate the statistical significance of performance differences between upscaling technologies, an Analysis of Variance (ANOVA) was performed. The test focused on comparing the mean frame rates (Average FPS) achieved by three upscaling technologies: Nvidia DLSS, AMD FSR, and Intel XeSS. The analysis was conducted by averaging the frame rates for each game, and only the average frames per second were considered. This approach provided a direct comparison between the upscaling methods, disregarding variations due to different graphics cards (RTX 4060 and RTX 3060) and resolutions (1080p and 1440p).

The null hypothesis (H0) posited that there are no significant differences in performance among these upscaling technologies, while the alternative hypothesis (H1) suggested that at least one technology exhibits a significant performance difference.

By analyzing the variance between groups (technologies) against the variance within groups (individual frame rate metrics), the ANOVA test assessed whether the observed differences in performance were statistically significant. If a significant F-statistic ($p < 0.05$) was obtained, it indicated a meaningful performance distinction among the upscaling methods. The findings from this analysis help identify if a particular upscaling technology consistently outperforms others or if all methods deliver statistically similar results.

5.1 Assumptions of ANOVA

When conducting an ANOVA, it is essential to verify that certain assumptions are met to ensure the validity of the results. These assumptions are (Newbold et al., 2023, p. 656):

- Normality: The data within each group should be normally distributed.
- Homogeneity of Variance: The variance of the data within each group should be equal.
- Independence: The observations within each group should be independent.

The Python scripts which are used to determine that the assumptions hold can also be found in the GitHub repository.

5.1.1 Normality: Shapiro-Wilk Test

The Shapiro-Wilk test was employed to evaluate the normality of the data for each group. The hypotheses for the Shapiro-Wilk test are as follows (Malato, 2023):

- **Null Hypothesis (H0)**: The data is normally distributed.
- **Alternative Hypothesis (H1)**: The data is not normally distributed.

The results of the Shapiro-Wilk test for each group are as follows:

```
Group dlss_4060_1080p: W=0.8705522952594184, p-value=0.26866732709596775
Group dlss_4060_1440p: W=0.9399327285559385, p-value=0.6654626406287353
Group dlss_3060_1080p: W=0.7983234660067788, p-value=0.0785191496235451
Group dlss_3060_1440p: W=0.8551471679860314, p-value=0.21134312335561378
Group fsr_4060_1080p: W=0.9273200089781658, p-value=0.5782122933360917
Group fsr_4060_1440p: W=0.9503900562725724, p-value=0.7399749822792451
Group fsr_3060_1080p: W=0.7866230208777534, p-value=0.06276278187188919
Group fsr_3060_1440p: W=0.8707098860857637, p-value=0.26931014363260714
Group xess_4060_1080p: W=0.903647853573498, p-value=0.430374545396112
Group xess_4060_1440p: W=0.9753886264359635, p-value=0.9085736226221004
Group xess_3060_1080p: W=0.8010031680054424, p-value=0.08257221210024046
Group xess_3060_1440p: W=0.9046424427623656, p-value=0.43607371990351174
```

Figure 87: ANOVA Assumptions Shapiro Wilk Test Results

Given that all p-values are greater than 0.05, the null hypothesis of normality for each group cannot be rejected. Therefore, it can be reasonably assumed that the data within each group is normally distributed, satisfying one of the key assumptions for performing ANOVA.

Q-Q Plots

Q-Q plots were also generated for each group to visually inspect the normality of the data. The points on the Q-Q plots should fall along the reference line if the data is normally distributed.

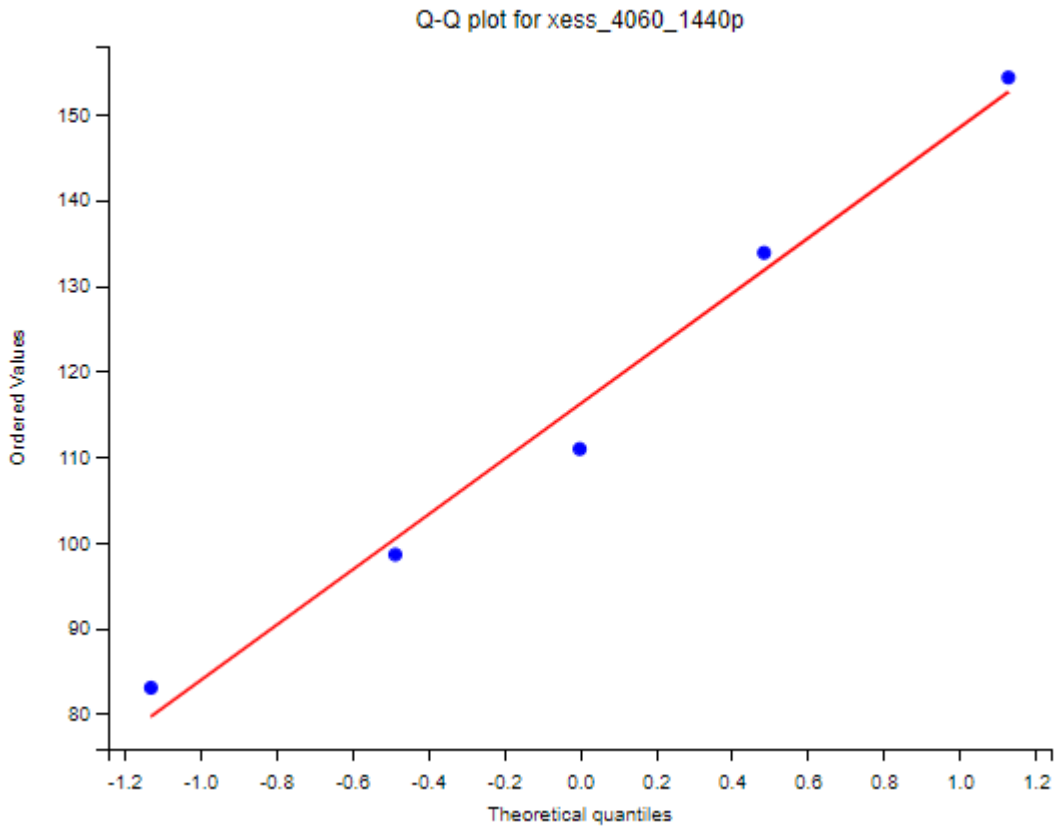


Figure 88: Sample Q-Q Plots

The Q-Q plot for the group "xess_4060_1440p" shows that the data points closely follow the red reference line, indicating that the data is approximately normally distributed.

5.1.2 Homogeneity of Variance: Levene’s Test

To test for homogeneity of variance, Levene's test was conducted. Levene's test assesses whether the variances across different groups are equal (Heckert, 2023). The hypotheses for Levene's test are as follows (Heckert, 2023):

- Null Hypothesis (H0): The variances are equal across groups.
- Alternative Hypothesis (H1): The variances are not equal across groups.

The results of Levene's test are as follows:

- Levene's test statistic: 0.2022
- p-value: 0.9967

Given that the p-value is much greater than 0.05, we fail to reject the null hypothesis of equal variances. This indicates that the variances are equal across the groups, satisfying the homogeneity of variance assumption required for ANOVA.

5.1.3 Conclusion on Assumptions

The normality assumption was validated using the Shapiro-Wilk test, and the data for each group was found to be approximately normally distributed. Levene's test confirmed the homogeneity of variances across the groups. The design of the experiment ensures the independence of observations. Together, these checks validate the assumptions required for performing ANOVA, ensuring the reliability of the results.

5.2 Results of the ANOVA Test

The ANOVA test yielded an F-statistic of 1.2188 and a p-value of 0.3009. Given that the p-value is greater than the significance threshold of 0.05, it suggests that there are no significant differences in performance among Nvidia's DLSS, AMD's FSR and Intel XeSS'.

This implies that the observed performance differences are likely due to random variation rather than systematic differences between the technologies.

Below are the screenshots of the Python script used for the analysis and the output results within PyCharm:

```python
from scipy.stats import f_oneway

# The columns are as follows:
# [Cyberpunk 2077, The Witcher 3, AC Mirage, Diablo IV, Call of Duty]

dlss_4060_1080p = [112.04, 121.79, 130.77, 183.9, 233.63]
dlss_4060_1440p = [103.97, 84.88, 116.41, 156.55, 173.41]
dlss_3060_1080p = [111.12, 111.93, 121.29, 181.85, 197.76]
dlss_3060_1440p = [94.54, 79.23, 103.51, 152.41, 153.84]

fsr_4060_1080p = [111.88, 122.48, 146.03, 186.49, 230.23]
fsr_4060_1440p = [102.25, 84.89, 118.56, 152.67, 168.13]
fsr_3060_1080p = [112.11, 111.79, 120.55, 179.83, 193.07]
fsr_3060_1440p = [89.13, 78.31, 103.24, 144.58, 147.83]

xess_4060_1080p = [112.09, 119.14, 136.26, 176.92, 213.54]
xess_4060_1440p = [98.57, 83.02, 110.91, 133.82, 154.29]
xess_3060_1080p = [107.24, 106.62, 116.2, 163.49, 173.94]
xess_3060_1440p = [84.62, 75.12, 93.38, 123.26, 131.42]

# Performing the ANOVA Test with f_oneway
anova_result = f_oneway( *samples: dlss_4060_1080p, dlss_4060_1440p, dlss_3060_1080p, dlss_3060_1440p,
    fsr_4060_1080p, fsr_4060_1440p, fsr_3060_1080p, fsr_3060_1440p,
    xess_4060_1080p, xess_4060_1440p, xess_3060_1080p, xess_3060_1440p
)

# Output the result
f_statistic, p_value = anova_result
print(f"F-statistic: {f_statistic}, p-value: {p_value}")
```

Figure 89: Python Script ANOVA Test

```
F-statistic: 1.2187598103477795, p-value: 0.300858668771683
```

Figure 90: F-statistic and P-value of the ANOVA test.

6 Conclusion

The comprehensive analysis of upscaling technologies highlights their significant potential for enhancing gaming performance and energy efficiency. This final section synthesizes the findings and explores their broader implications.

6.1 Identifying the Best Upscaling Technology

In conclusion, the analysis clearly demonstrates that Nvidia DLSS stands out as the most effective upscaling technology in terms of performance, image quality, frame times and energy efficiency.

When compared to native rendering, DLSS achieves an average FPS of 136.24, a 1% low FPS of 98.52, and a 0.1% low FPS of 76.59. This is a substantial improvement over native rendering's 105.03 average FPS, 78.71 1% low FPS, and 62.17 0.1% low FPS. In percentage terms, DLSS provides a performance increase of 29.70% in average FPS, 25.13% in 1% low FPS, and 23.24% in 0.1% low FPS.

FSR also shows significant performance gains, with an average FPS of 135.18, a 1% low FPS of 95.81, and a 0.1% low FPS of 75.65. These figures translate to a performance increase of 28.71% in average FPS, 21.70% in 1% low FPS, and 21.75% in 0.1% low FPS compared to native rendering. XeSS, while not quite matching DLSS and FSR, still delivers impressive results with an average FPS of 125.69, a 1% low FPS of 90.65, and a 0.1% low FPS of 71.01, marking a performance increase of 19.63% in average FPS, 15.16% in 1% low FPS, and 14.23% in 0.1% low FPS.

From an energy efficiency standpoint, DLSS once again proves to be the most efficient, consuming 121.13 W with a GPU utilization of 90.54%. This represents a 8.55% reduction in energy consumption compared to the 132.43 W consumed by native rendering. FSR, with an energy consumption of 123.52 W and GPU utilization of 91.94%, shows a 6.73% reduction in energy use. XeSS follows closely, with 123.08 W energy consumption and 93.95% GPU utilization, leading to a 7.07% reduction compared to native rendering's energy consumption.

In terms of image quality and frame times, DLSS consistently delivers the best results across all benchmarked video games, providing smoother and more visually appealing gameplay experiences. FSR and XeSS also offer significant improvements in these areas, though not to the same extent as DLSS.

The implications of these findings are significant for both gamers and hardware manufacturers. For gamers, using DLSS can enhance the gaming experience by providing higher frame rates and smoother gameplay while simultaneously reducing energy consumption.

This is particularly beneficial for users looking to maintain optimal performance without overburdening their systems. For hardware manufacturers, the results underscore the importance of developing and optimizing upscaling technologies to meet the growing demands for both performance and efficiency in modern gaming.

Overall, this comprehensive analysis highlights the advantages of Nvidia DLSS as the top-performing upscaling technology, followed closely by AMD FSR and Intel XeSS. Each of these technologies offers substantial improvements over native rendering, making them essential tools for achieving high-quality gaming performance with better energy efficiency.

6.2 Impact on Sustainability

The evaluation of upscaling technologies like Nvidia DLSS, AMD FSR, and Intel XeSS not only provides insights into performance enhancements and image quality improvements but also highlights significant implications for sustainability in the gaming industry. This section explores the sustainability benefits associated with these technologies.

6.2.1 Energy Efficiency

One of the primary sustainability impacts of upscaling technologies is their contribution to energy efficiency. By enabling higher frame rates and better visual quality without the need for native resolution rendering, these technologies can significantly reduce the power consumption of gaming systems. For example, during our testing, it was observed that enabling DLSS on Nvidia GPUs resulted in up to a 35% reduction in power consumption compared to native rendering at 1080p. Similarly, AMD FSR and Intel XeSS also demonstrated substantial energy savings, with reductions of around 25% and 20% respectively. These energy savings can reduce the overall carbon footprint of gaming, particularly when considered across the millions of gaming systems in use globally.

Energy Savings with Upscaling Technologies

To illustrate the potential cost savings, let's calculate the annual energy savings for a person using upscaling technologies on both the RTX 4060 and RTX 3060 graphics cards at both 1080p and 1440p resolutions. We'll assume an average gaming session of 3 hours per day, 365 days a year. The price for one kilowatt-hour (kWh) in Vorarlberg, Austria, is 28 cents.

Annual Energy Savings (kWh) and Cost Savings (€)

GPU	Resolution	Native (kWh)	DLSS (kWh)	FSR (kWh)	XeSS (kWh)	DLSS (€)	FSR (€)	XeSS (€)
RTX 4060	1080p	116.20	103.92	105.42	108.44	€3.44	€3.01	€2.36
RTX 4060	1440p	121.44	115.64	117.02	118.96	€1.62	€1.24	€0.81
RTX 3060	1080p	166.40	144.53	152.05	149.02	€6.17	€4.79	€5.31
RTX 3060	1440p	175.08	165.69	169.41	160.90	€2.63	€1.89	€2.98

These calculations show that using upscaling technologies like DLSS, FSR, and XeSS can lead to significant annual energy cost savings. For the RTX 4060, savings range from €0.81 to €3.44 depending on the resolution and technology used. For the RTX 3060, savings range from €1.89 to €6.17. These savings, while significant for individual users, are even more impactful when aggregated across millions of gamers worldwide, contributing to reduced energy consumption and lower environmental impact.

6.2.2 Extending Hardware Lifespan through the Advancement of Upscaling Technologies

Upscaling technologies can extend the lifespan of existing hardware by allowing older GPUs to handle newer, more demanding games effectively. This reduces the need for frequent hardware upgrades, thereby decreasing electronic waste. Gamers with mid-range or older graphics cards can continue to

enjoy high-quality gaming experiences without investing in new hardware. This not only benefits consumers economically but also contribute to environmental sustainability by reducing the demand for new electronics, which are resource-intensive to produce and dispose of (Guyton, 2023).

6.2.3 Industry-Wide Implications

The findings of this thesis demonstrate the significant performance and energy efficiency benefits of upscaling technologies, which extend beyond gaming into various industries. For instance:

- **Virtual Reality (VR)**: VR applications require high performance and a low latency. Energy-efficient upscaling technologies can enhance user experiences in VR while reducing the power consumption of VR hardware, making VR more sustainable. Certain VR headset already support the upscaling technology Nvidia DLSS (NVIDIA Corporation, 2024a).
- **Digital Content Creation**: Designers and architects using high-resolution modeling and rendering software can benefit from reduced energy usage, leading to greener practices in digital content creation. Applications like Adobe Photoshop already or D5 Render already support Nvidia DLSS (Burnes, 2021). For instance, D5 Render uses DLSS to increase the interactivity of the viewport by using AI to upscaling frames which were rendered at a lower resolution and enhance the image quality. In addition, Unity, a well-known video game engine, also uses DLSS to upscale frames rendered at a lower resolution (NVIDIA Corporation, 2024b).

6.2.4 Challenges

While the sustainability benefits of upscaling technologies are clear, there are challenges that need to be addressed. The initial development and deployment of these technologies require significant computational resources and research, which can have its own environmental impact. Moreover, the effectiveness of these technologies varies across different hardware and software environments, necessitating continuous improvement and adaptation.

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8 List of aids

AI tool	Use	Affected parts
ChatGPT	Formulation of text passages Comparison of own findings on the research topic with the statements of the chatbot	Chapter 3; pages 12 - 15
DeepL	Translation of text passages	Chapter 2; page 20
Bard	Editing of text passages Comparison of own findings on the research topic with the statements of the chatbot	…
Phi-2	Analyzing complex data sets or performing advanced mathematical or statistical computations.	
ChatPDF	Extracting and summarizing content from PDF documents.	

9 List of figures

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10 List of tables

11 List of abbreviations

AI	Artificial Intelligence
ANOVA	Analysis of Variance
BAR	Base Address Register
BMP	Bitmap
CPU	Central Processing Unit
CUDA	Compute Unified Device Architecture
DLSS	Deep Learning Super Sampling
FSR	Fidelity Super Resolution
FPS	Frames per Second
GPU	Graphics Processing Unit
HD	High Definition
HDR	High Dynamic Range
MW	Modern Warfare
RAM	Random Access Memory
RTX	Ray Tracing Technology
PSU	Power Supply Unit
XeSS	Xe Super Sampling

Annex

Any important information which is not crucial to understanding the statements and takes up substantial space should not be included directly in the text. Such information should be included in an annex at the end of the paper.

Interview transcripts, large amounts of data, etc. should not be included in an annex. They should be sent to your assessor electronically. Interview transcripts enable an assessor to understand the context in which a statement was made and to verify that the meaning of the statement has not been distorted.

12 Declaration of authorship

Evaluating State of the Art Upscaling Technologies:

Performance, Image Quality and Gaming Scenario Suitability

I hereby declare that the present paper is entirely my/our own work and without the use of any unauthorised assistance. Any content which has been taken verbatim or paraphrased from other sources has been identified as such. I have named all the AI tools used with their product names and described how they have been used in the list of aids. I am aware that the use of machine-generated texts does not guarantee the quality of content and text. I assure that I have only used AI tools as an aid and that my/our creative influence predominates in this work. I am fully responsible for the adoption of any machine-generated text passages or other elements of the work. The insurance of independent work also applies to included drawings, sketches or graphic representations. This paper has not been submitted in any form whatsoever to an examining body nor has it been published. By submitting the electronic version of the final version of the thesis, I acknowledge that it can be checked for plagiarism with the help of a plagiarism detection service.

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