

Towards Green Game Software Engineering: A Comparative Analysis of Energy Consumption Between the Widespread Unity and Unreal Video Game Engines

Carlos Pérez^a, Javier Verón^a, Francisca Pérez^b, M^aÁngeles Moraga^c, Coral Calero^c, Carlos Cetina^b

^aSVIT Research Group, Universidad San Jorge, Zaragoza, Spain

^bUniversitat Politècnica de València, Valencia, Spain

^cArcos Research Group, Universidad de Castilla La Mancha, Ciudad Real, Spain

Abstract

Context: The total energy cost of computing activities is steadily increasing, and projections indicate that it will be one of the dominant global energy consumers in the coming decades. However, the video game sector has not yet developed the same level of environmental awareness as other computing technologies despite the estimated three billion regular video game players in the world.

Objective: This work evaluates the energy consumption of the most widely used industry-scale video game engines: Unity and Unreal Engine.

Method: Specifically, our work uses three scenarios representing relevant aspects of video games (Physics, Static Meshes, and Dynamic Meshes) to compare the energy consumption of the engines. The aim is to determine the influence of using each engine on energy consumption.

Results: Our research has confirmed notable differences in energy consumption: 351% in Physics in favor of Unity, 17% in Static Meshes in favor of Unity, and 26% in Dynamic Meshes in favor of Unreal Engine.

Conclusion: Considering the estimated three billion regular video game players worldwide and the high computational requirements of the sector, the magnitude of potential savings is a relevant issue for the research community. This might encourage a new branch of research on energy efficient video game engines.

Keywords: Energy consumption, Video Games, Green software, Green Video Games, Software sustainability, Game Engines, Game Software Engineering

1. Introduction

An increasing number of human activities, even those traditionally associated with the physical world, rely to a large extent on software for their development. The widespread adoption of software across industries is accompanied by a sharp increase in the energy costs required to run it. The total energy cost of computing activities is steadily increasing, and projections indicate that it will be one of the dominant global energy consumers in the coming decades [1]. Therefore, there is growing interest in understanding the environmental impact of software in the various activities in which it is relevant and how this impact can be evaluated and decreased.

One of the sectors where the growth has been most evident in recent years is video games. The development of many recent video games is characterized by, among other things, greater graphical realism and an increase in the number of interactions and players, which requires more powerful equipment capable of managing this complexity without degrading the user experience. All of these factors suggest that the energy consumption of video games and their environmental impact are becoming increasingly important. For instance [2] estimate that gaming PCs consumed 75 TWh/year of electricity globally in 2012. This amount underscores the importance of energy-

efficient game development.

To put this into perspective, the average annual amount of electricity purchased by a EU member residential electricity customer was 3900 kWh[3]. Therefore, 75 TWh is equivalent to the annual energy consumption of approximately 19 million households in the European Union. This does not take into account the consumption of the additional infrastructure beyond the player's computer that games like *Baldur's Gate III* require; e.g., servers for multiplayer gameplay. This also does not count the new trend of cloud gaming (e.g., GeForce Now), where the game is run on remote servers and then played on the local device, which can increase the overall energy consumption [4].

However, perhaps due to its relative youth the video game sector has not yet developed the same level of environmental awareness as other computing technology sectors. In the case of computing technologies in general, there are research efforts in the area of green cloud computing [5], green mobile computing [6], green software [7], and green data centers [8] among others. Nevertheless, in the case of video games, efforts are specifically concentrated on what is called Green-by computing. There are two perspectives for analyzing the sustainability of software engineering in general and its energy consumption in particular: Green-in and Green-by [9]. The first one deals

with improving the energy consumption of a field per se, e.g., video games, whereas the second one is focused on the application of a field (video games) to improve sustainability in any context.

Modern video games are highly complex products of software that rely on interrelated technologies to function. It is common to use a video game engine to build video games. The video game engine enables developers to create the different games in a much more streamlined way, without having to repeat or code low-level elements whose design from scratch would be very costly and incompatible with the pace of development of these products. The most well-known and widespread video game engines are Unity and Unreal Engine [10, 11]. Comparable video games in terms of visuals and physics can be achieved with both Unity and Unreal engine; however, the developers do not know the impact of the engines in terms of energy consumption because it has not been explored so far.

This work constitutes a first approach to the evaluation of energy consumption of a video game using the two most widely used industry-scale video game engines: Unity and Unreal Engine. Specifically, our work uses three scenarios representing relevant aspects of video game development (Physics, Static Meshes, and Dynamic Meshes) to compare the energy consumption of the engines. The aim is to determine the influence of using each of the two engines on energy consumption. The results show that there are clear differences between the versions coded with Unity and Unreal Engine, depending on the scenario. These results can be revulsive for the industry, triggering a race in which manufacturers will make their engines better in terms of efficiency, approaching the best values identified. Furthermore, these results might encourage a new branch of research on energy-efficient video game engines.

The paper is structured as follows: After this introductory section, section 2 reviews relevant existing literature for this study. Section 3 provides a concise summary of video game engines: what they are and how they are used within a video game. Section 4 discusses the research methodology used in the study, including the experiment description and the detail of the experimental setup. Section 5 analyses and presents the results of the study and answers the research questions. The threats to the validity of the experiment are explained in Section 6 and, lastly, conclusions are summarized and future work is outlined in Section 7.

2. Related work

The broad field of green computing acknowledges software energy consumption as a growing concern for manufacturers, engineers, programmers, and users [12][13]. This concern has motivated research into "Green Software," which is developed to limit energy consumption. This is an intense area of research where various techniques are being developed to analyze and optimize the energy consumption of software systems. For example, [7] conducted a systematic comparison of 27 programming languages, evaluating their efficiency in energy, time, and memory usage across ten different problems.

Moving beyond software in general, specific hardware components such as Graphics Processing Units (GPUs), originally designed for rendering graphics in video games, are significant energy consumers in modern computing, and its use has significantly expanded beyond video games. For example, in scientific computing, [14] characterized the performance, power, and energy characteristics of GPUs demonstrated that a hybrid CPU+GPU environment can deliver an energy-delay product multiple orders of magnitude better than traditional CPU-only setups for data-parallel scientific applications. Similarly, in the automotive industry, [15] measured the power consumption of General Purpose GPU (GPGPU) applications, and their findings indicated that existing GPU power prediction models were too simplistic for automotive purposes.

On the other hand, concern about video game energy consumption is growing due to the large number of players and the high computational requirements of modern video games, leading to a rapidly increasing overall electricity consumption. Some studies have addressed the broader energy footprint of gaming platforms.[2] identified gaming as the most energy-intensive use of personal computers, with high-performance gaming PCs being the fastest-growing platform. [16] focused on the electricity consumption of video game consoles in the United States, estimating total consumption at 11 TWh in 2007 and 16 TWh in 2010, which constituted approximately 1% of US residential electricity consumption.

However, only a limited number of studies in the literature focus specifically on the energy efficiency of video game software itself. In contrast, most research applies video games as tools to promote sustainability and environmental awareness through gamification. This latter approach aligns with what is known as the Green-by perspective in software sustainability. [9] For instance, [17] presents a systematic review evaluating the effectiveness of gamification and serious games in influencing domestic energy consumption. The study highlights their relevance in shaping user behavior and encouraging energy-efficient practices. Similarly, [18] develops a serious game aimed at raising awareness of energy use and reducing carbon emissions in social housing.

Within the scope of the Green-in perspective, recent research in the scientific community has focused on mobile video games, emphasizing battery optimization as a means to extend gameplay duration and enhance user satisfaction and engagement. Excessive battery consumption negatively impacts the user experience and can lead to lower game ratings. For example, [19] aims to extend mobile device battery life to improve user satisfaction, while [20] proposes two energy-aware adaptation strategies for 3D graphics—one that limits lighting and another that transforms textures to reduce GPU and bandwidth usage—achieving energy savings with minimal compromise to visual fidelity and user experience.

Finally, [21] compares the energy consumption of three key video game components across two implementation strategies: Blueprint models—a model-driven development technique that substitutes textual code with a visual language of interconnected nodes—and traditional C++ coding. The findings reveal that C++ implementations consume up to 48% less energy

per frame than their Blueprint-based counterparts.

This study also adopts the Green-in perspective by assessing the energy consumption of a specific video game implemented using the two most widely adopted game engines in the industry: Unity and Unreal Engine. As in previous research, it examines the impact of varying software implementations on energy usage. However, unlike [21], which restricts its analysis to a single engine (Unreal), the present work offers a direct comparative evaluation of both engines from the standpoint of energy efficiency.

3. A brief overview on video game engines

Video game engines, often simply referred to as "game engines", are software products designed to ease the development of video games. A game engine provides game developers with essential tools and functionalities, enabling them to focus on the creative and unique aspects of the game rather than having to program all of the basic functionalities from scratch. The functionalities that a game engine usually implements are the following:

- **Rendering engine:** This engine is responsible for the graphical display and renders game elements on the screen. It employs advanced computer graphics techniques, including 2D and 3D rendering, lighting, and shading.
- **Physics engine:** This engine simulates the laws of Physics within the game world, adding realism to the movement and interactions of objects. This includes the simulation of gravity, collisions, and other forces.
- **Sound system:** This component manages all aspects of audio in the game, which is essential for including music, sound effects, and voice acting. It aids in creating an immersive experience for the player and in providing feedback for the player's actions.
- **Input system:** This component handles how the game is going to receive the user input from the different external devices supported by the system (e.g., mouse, keyboard, or controllers).
- **Game logic:** This component handles how the game is going to work and be played, including scripting systems.

Game engines usually include level editors, graphical user interface (GUI) editors, animation systems, and profiling tools; allowing developers to design, test, and polish their games faster. A game engine also usually offers other functionalities that greatly shorten the development time, such as cross-platform support, which enables the game to run on multiple devices and platforms just by building it for different target devices.

Most game developers use game engines, (60% as of 2022 [22]). There are multiple industry-scale engines, but Unity has the largest share of the game engine market: 38%

of game developers who use game engines use Unity as their primary engine [22]. The next most popular game engine, Unreal Engine, has 15% usage as a primary engine [22].

Unreal Engine is the preferred choice for high budget developments, such as *Persona 3 Reload*, *Mortal Kombat 1*, *Fortnite Wilds*, *Final fantasy VII Rebirth*, or *Payday 3* [23] (e.g., *Payday 3* had a budget of at least 59 million USD [24]).

On the one hand, Unity is very flexible in performance depending on the target platform, allowing the creation of mobile games [25]

On the other hand Unreal Engine is recognized for its advanced graphics and high-fidelity rendering capabilities [26]. Although Unreal Engine 5 is typically used for games with more demanding visual requirements than Unity, the scenarios implemented in this study were designed to be comparable across both engines, allowing for a fair assessment of their energy consumption.

It should be noted that some of the previous references used to describe current trends in video-game development and engine usage ([22] to [26]) come from industry or online sources that have not been peer-reviewed. These sources are included because peer-reviewed publications on this topic are still scarce. Consequently, the supporting evidence from these references should be considered anecdotal or indicative rather than validated through scientific review.

Unreal Engine offers C++ as scripting language, and it also offers Blueprint Visual Scripting. This visual scripting system allows developers to create game logic and behaviors using a node-based interface without traditional programming to prototype or create game logic and interactions without deep programming knowledge. However, even with the visual scripting, Unreal Engine is considered to have a steeper learning curve than other alternatives such as Unity.

On an industry scale, both Unity and Unreal Engine have been used to develop indie and AAA games. "Indie" is short for "independent". An indie game is typically developed by solo developers or small teams without the financial support for a large development. Indie games are known for their innovative and creative design. For example, *A Short Hike* is an indie game developed with Unity and *RiME* is an indie game developed with Unreal Engine. Both games are shown in Fig. 1. AAA (also called "triple-A") games are high-budget, high-profile games that are typically produced and distributed by large, well-established gaming companies [27]. AAA games are known for their impressive visuals and high production values. For example, *Escape from Tarkov* is a AAA game developed with Unity and *The Calisto Protocol* is a AAA game developed with Unreal Engine. Both games are also shown in Fig. 1.

Rendering and physics are key functionalities of video game engines that are widely present in almost all video games. Both Unity and Unreal Engine can be used to make games with simple or very complex physics. *Kerbal Space Program* and *Rocket League* are two examples of well-known games with complex physics made with Unity and Unreal Engine, respectively. *Kerbal Space Program* simulates real-world orbital mechanics and space travel physics. It includes elements like gravitational



Figure 1: Indie and AAA games made in Unity and Unreal Engine: *A Short Hike* (indie, Unity), *RiME* (indie, Unreal Engine), *Escape from Tarkov* (AAA, Unity), and *The Calisto Protocol* (AAA, Unreal Engine).

forces from planets and moons, orbital trajectories, the physics of thrust and propulsion in a vacuum, atmospheric drag, and re-entry heat. *Rocket League* combines the physics of driving with the physics of a bouncing, spinning soccer ball. The game realistically simulates the momentum and inertia of both the cars and the ball and accurately simulates the interactions between the cars and the ball, including how the ball bounces and reacts to hits. All in all, comparable results of the key elements of visuals and physics can be achieved with both Unity and Unreal engine; however, the developers do not know the impact of the engines in terms of energy consumption because it has not been explored so far.

4. Research methodology

4.1. Measuring the energy consumption of software

There are two different methodologies for this purpose: The first one resorts to specialized software tools that can estimate the energy consumed by the hardware when a given software is being used, such as Perf [28] or IntelPCM [29]. These tools do not directly measure the energy consumed but rather estimate it from a model that is fed with parameters that the software collects while the object of study is being executed. These methods have the advantage that they are generally effortless, easy to apply, and produce valuable results at different levels of granularity. However, since they only estimate the energy consumed, the accuracy of the results depends on the fit of the model to the situation being analyzed.

The other methodologies available are those that use measuring equipment connected to a suitably instrumented computer to measure the energy consumed by the computer as a whole or by the different components to be studied while the software under study is running. This approach has the advantage over

the previous one of producing real energy consumption results, whose accuracy depends only on the quality of the equipment and the measurement procedure. However, it requires instrumentation of the computer on which the test is to be performed and can be more costly and complicated to implement.

Having a physical device that allows us to measure the energy consumption of a computer running a certain software is not enough to guarantee that the results are sufficient to draw conclusions about it. It is necessary to define a complete process that guarantees the rigor and consistency of the studies so that the conclusions obtained are scientifically relevant. In this work, we use the process defined by Mancebo et al. [30], the stages of which are described in Section 4.3.

4.2. Scenario design

The goal of this study is to assess the influence of the use of different video game engines on the energy consumption of a commercial video game. There are no public video games that have two identical versions programmed with Unity in one of them and Unreal Engine in the other for comparison. In practice, studios decide on the engine at the beginning of development and rarely change engines during development because it is a very costly decision. Furthermore, if we were to take a complete video game, it would not be possible to isolate engine performance for key aspects such as visuals and physics. Video game scenes simultaneously combine multiple aspects such as physics simulations or mesh rendering, among others. For example, in the video games shown in Fig. 1, many of the video game engine's functionalities are working simultaneously with all of the needed calculations derived from: physics simulations (e.g., when the character moves, jumps, or shoots physics simulations have to be performed); mesh rendering (e.g., every 3D visual element needs the rendering of its mesh with its textures);

animation system operations (e.g., when the character moves, it needs to look like it is walking); and others.

Consequently, to compare video game engines, we have developed the same scenarios representing key aspects of the video games for both engines. Video games might differ one from another in interaction and mechanical aspects, but they require common aspects that include 2D and 3D rendering, physics, sound, and Artificial Intelligence [31, 32, 33]. Currently, the most developed type of games are 3D games (47% vs 36% for 2D games [22]). Three of the most common systems in 3D video games are physics, 3D rendering, and animation systems[34, pp. 36, 41, 42, 304]. That is why we decided to create three scenarios that focus on these systems in order to carry out the consumption comparison between Unity and Unreal Engine.

The first scenario (Physics scenario) was built to evaluate the physics aspects of the engine. The scenario instantiates 1000 cubes. Each cube has a mass of 50 kilograms, a size of 1 meter on each axis (X, Y, Z), and physics simulation and collision detection enabled. A random force of between 1 and 80 Newtons is applied to each cube on each frame, pushing them continuously toward the origin position. That will make the cubes collide with each other while they keep receiving the force toward the origin. Collisions of this nature are common in video games such as the popular Doom or the Battlefield series, where there are shots and explosions affecting players, non-player characters (NPCs), and other scene elements. The second and third scenarios were built to evaluate the visual aspects of the engine: Static Meshes rendering and animated Dynamic Meshes rendering. Static meshes are 3D models that do not change shape or move during gameplay. They are often used for environment and background elements, such as buildings and furniture. Dynamic meshes are 3D models that can change shape and move in real time. They are often used for characters and interactive elements, such as NPCs and vehicles.

In the second scenario (implementing Static Meshes), 1000 static meshes are instantiated and stay in place, making the engine render them for the duration of the scenario. In the third scenario (implementing Dynamic Meshes), 1000 dynamic meshes with a simple animation are instantiated and stay in place. The animation consists of the character stabbing with both hands, which is a common action in many fantasy video games, such as the popular video game *Baldur's Gate III*.

The mesh and textures for both the second and third scenarios and the animation for only the third scenario have all been downloaded from *Mixamo* (<https://www.mixamo.com/>). *Mixamo*, which is owned by Adobe Inc., allows the downloading of ready-to-use professional 3D character meshes and animations for personal, commercial, and non-profit projects, including video games.

Images of the implementation of all three scenarios are shown in Fig. 2. Each row of the figure shows a different scenario. The first row contains two images from the execution of the Physics scenario, where 1000 cubes start scattered and then receive forces towards the center. The second row contains an image from the execution of the Static Meshes scenario, followed by a zoomed-in image of it so that the static mesh and

its textures can be seen better. Lastly, the third row contains an image from the execution of the animated Dynamic Mesh scenario, followed by nine zoomed-in captures at different times of the execution which show the animation of the dynamic mesh.

The implementations of the scenarios in both engines have the same number of elements and complexity between the engines. The scenarios in both engines are built from an empty level where any skybox or atmosphere of any type has been removed, along with other elements that might have been in the default scene or level. The only elements in the scenarios are:

1. One directional light with default configuration values except for the intensity, which has been modified to have the light in both engines with a similar intensity.
2. The scenario element (i.e., an empty GameObject placed in the Scene in Unity or a Pawn instantiated in the PlayerStart on play in Unreal Engine) with default values and containing both the camera and a script that generates all of the objects (i.e., Prefab instances in Unity or Blueprint Actors instances in Unreal Engine) needed for each scenario (i.e., the cubes for the Physics scenario and the static and dynamic meshes for the other two scenarios). This script in Unity is programmed in C# with a *MonoBehaviour* class of Unity inheritor, as is expected to be done in this engine. In Unreal Engine, it is programmed with a combination of Blueprints visual scripting and C++ with an *APawn* class of Unreal Engine inheritor, as is expected to be done in this engine.

We used the latest available versions of both engines at the time when the different scenarios were implemented: 2022.3.6f1 for Unity and 5.2.1 for Unreal Engine. The scenarios were implemented by the second author, who happens to be a professional game developer himself, and have been validated as equivalent between the two engines by two different professionals in the industry (not involved in this paper).

All six applications, i.e., the versions of the three scenarios in the two engines, are available at the following URL for replication purposes: <https://doi.org/10.5281/zenodo.16313729>

Since our aim is to compare the energy consumption of these two commercial game engines, the Research Questions for this work are built around this goal:

- RQ1 – Is there a relationship between the energy consumption needed by a physics-related task at run time and the engine used during the development?
- RQ2 – Is there a relationship between the energy consumption needed by a static mesh rendering-related task at run time and the engine used during the development?
- RQ3 – Is there a relationship between the energy consumption needed by an animated dynamic mesh rendering-related task at run time and the engine used during the development?

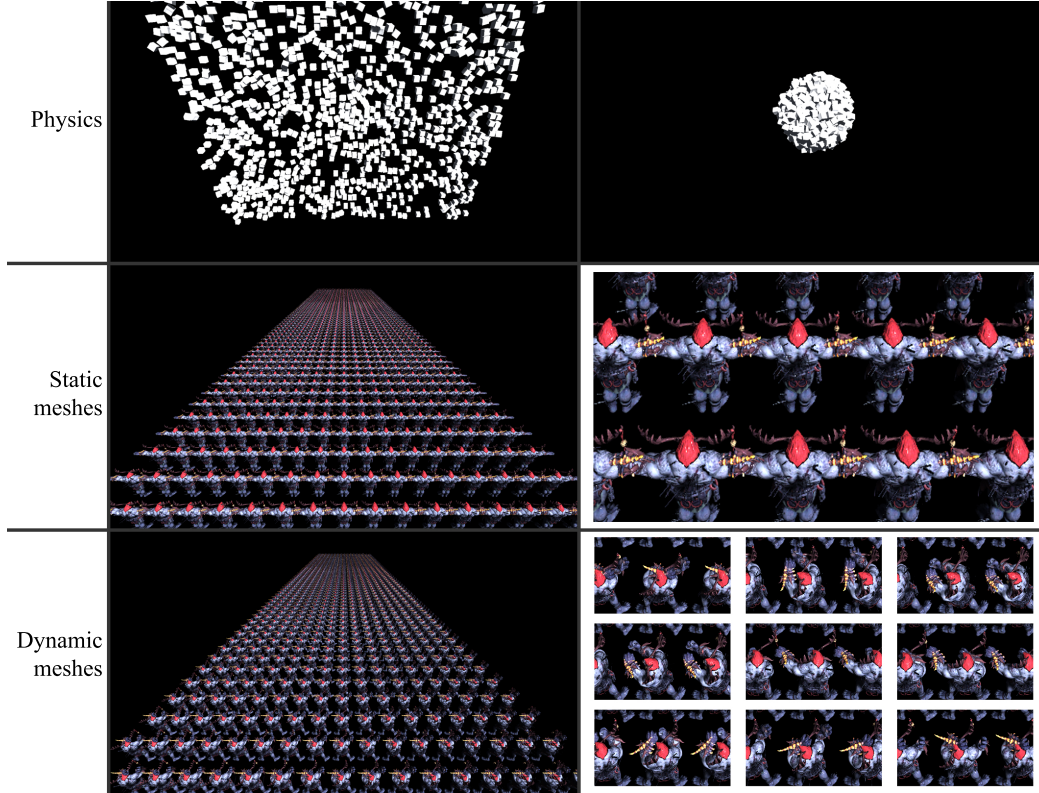


Figure 2: The three scenarios implementing Physics, Static Mesh rendering, and Dynamic Mesh rendering.

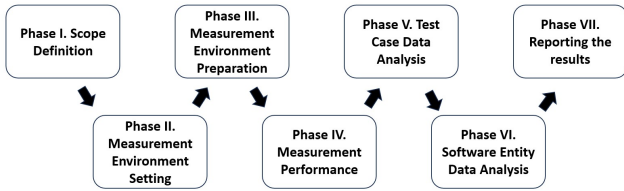


Figure 3: Process for evaluating the energy efficiency of software

4.3. Experimental setup

The process we follow in the execution of our experiment is defined by [30]. Based on a review of good practices in measuring software energy consumption, the process defined in [30] improves the reliability and consistency of the measurements, so that reproducibility and comparison of different studies is facilitated.

We followed the Green Software Measurement Process (GSMP), as proposed by Mancebo et al. [35]. This process consists of a series of phases outlined in Fig. 3, encompassing all the necessary steps for conducting a thorough analysis of software energy consumption during execution.

4.3.1. Phase I. Scope Definition

During this stage, a complete set of requirements is obtained for evaluating energy efficiency. Furthermore, clear definitions of the software under study and the test cases to be analyzed are established.

Our study aims to compare the energy consumption during the execution of three representative scenarios of real video games, programmed with two different game engines. It is worth emphasizing that our objective is to find out if there is any noticeable difference in energy consumption between scenarios implemented with different engines. The goal is not to discover what this difference is exactly because this will always depend on the environment in which the applications are run.

Special care has to be taken to actively ensure that there are no background processes beyond those required by the operating system. The consumption of the processes required by Windows needs to be measured separately and discounted from the results as a baseline.

4.3.2. Phase II. Measurement Environment Settings

The purpose of this phase is the definition of the measurement environment that will be used in the software energy consumption assessment.

The measurement environment of the Framework for Energy Efficiency Testing to Improve Environmental Goals of the Software (FEETINGS) [35] (to which GSMP also belongs) is used to evaluate the energy efficiency of the software. It is based on actual measurements using a device connected to a computer. Specifically, there are two elements for consumption measurement in FEETINGS:

1. The Efficient Energy Tester (EET), which is a device designed to measure the power requirement of a group of hardware components and the execution time of the

Table 1: DUT specifications

Monitor	Falkon Q2702S 27" 2K
Motherboard	Asus Prime B460-Plus
Processor	i7 10700
RAM	4 modules of 32GB DDR4 Kingston 2666MHz CL16
Graphics card	Zotac Gaming GForce RTX 3060 12 GB GDDR6
Hard Disk	Hard Disk & Kingston SSD A400 – 480GB SATA
Power supply	Energy PS901SX 900W
O.S.	Windows 11 Pro

Software Entity when running on the Device Under Test (DUT).

2. The ELLIOT, which is the software application that processes and analyzes the data collected by the EET.

The DUT is a desktop computer utilized for executing the test cases and conducting time and power measurements. In our experiment, the DUT had the specifications outlined in Table 1.

The energy consumption of the processor, the HDD, and the overall energy consumption of the device are accepted measurements in green software studies [36]. However, in the case of video games, it is also necessary to measure the energy consumption of the graphics card as video games use it intensively.

The final power measurements are computed by subtracting the baseline power required (background processes before launching the scenarios) from the real measurements recorded during the experiment (after launching the scenarios).

4.3.3. Phase III. Measurement Environment Preparation

The primary objective of this phase is to prepare for the power measurements and configure the measurement environment accordingly.

EET has a power supply that must be connected to the device under test where the software is executed, replacing the power supply of the DUT.

The power of the computer cooling system may influence the power required by the whole system if, in one of the scenarios, the computational demand causes the processor to overheat. To verify that this effect does not occur, two runs of the three scenarios with the two engines in different order have been performed to check if the order in which the different cases are run alters the results. The order of the two runs, labeled V1 and V2, is as follows:

- V1: Unreal Engine-Dynamic Mesh, Unreal Engine-Static Mesh, Unreal Engine-Physics, Unity-Dynamic Mesh, Unity-Static Mesh, Unity-Physics
- V2: Unity-Physics, Unity-Static Mesh, Unity-Dynamic Mesh, Unreal Engine-Physics, Unreal Engine-Static Mesh, Unreal Engine-Dynamic Mesh

The power required for each scenario and the execution time are measured and recorded. Energy consumption can then be calculated by multiplying the average power by the execution time. All of the scenarios were executed during the same time (60 seconds) for the different scenarios to be comparable in terms of energy consumption.

The executable files of the six scenarios for the engines are copied to the DUT. After checking that no other software is running in the background, the runs are then executed through a .BAT file. Both the sequence of executions and the number of repetitions have been detailed in the .BAT file.

To ensure the reliability of the analysis and the statistical results, both runs (V1 and V2) were executed and recorded 30 times. This repetition helps mitigate undesirable effects and allows for the detection of anomalies, such as background software activity or unexpected cooling fan activation, that could temporarily increase the power consumption of the Device Under Test (DUT). Such anomalies would manifest as inconsistencies across the recorded measurements.

All of the power measurements that have been collected by the EET are saved onto a file for further processing.

4.3.4. Phase IV. Perform the Measurements

During this phase, power measurements are carried out and the raw power data taken from the measuring instrument is collected. A sample plot of the raw data as collected by the EET is shown in Fig. 4. Approximately 6000 individual measurements are recorded, which corresponds to 60 seconds of recording at a sampling frequency of 100 Hz.

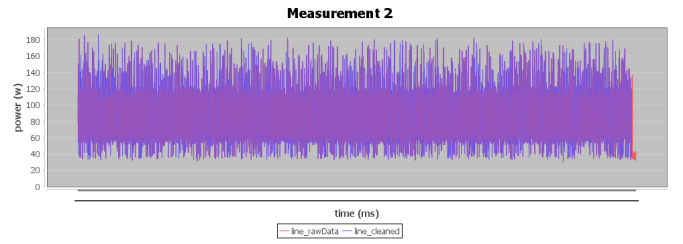


Figure 4: Plot of the power measurements of one scenario as collected by the EET.

4.3.5. Phase V. Test Case Data Analysis

In this phase, the raw data of power obtained by the measuring instrument is processed using ELLIOT. As we mentioned previously, all of the measurements are repeated 30 times. Then, this raw dataset is cleaned by removing invalid measurements. A measurement is considered invalid if it corresponds to a wrong execution detected because all of the values obtained are not consistent with the rest of the results for the other executions, or it corresponds to an outlier, in which one or more values are either too high or too low compared to the rest of the results for the other executions. The number of executions removed from the exercise is shown in Table 2. Once the data has been processed and prepared with ELLIOT, it also calculates the descriptive statistics of the values obtained.

4.3.6. Phase VI. Software Entity Data Analysis

In this phase, the power required by the DUT during the executions of the different scenarios is presented, comparing the values of the scenarios executed with Unity and those executed with the Unreal Engine.

Table 2: Number of valid and invalid executions per scenario in Unity and UE (Unreal Engine)

	Dynamic Mesh		Static Mesh		Physics	
	Unity	UE	Unity	UE	Unity	UE
Invalid measurements	4	7	5	9	4	9
Valid executions	26	23	25	21	26	21

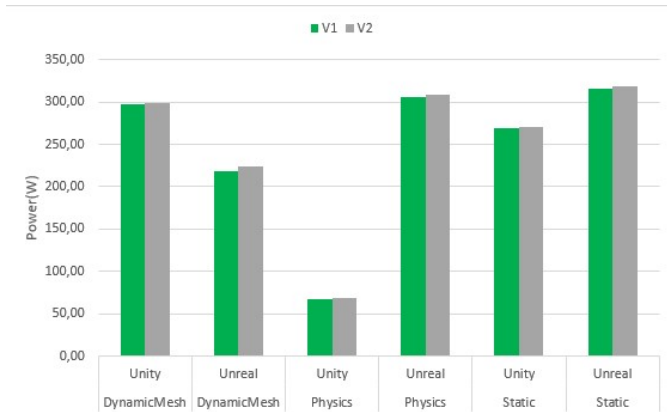


Figure 5: DUT power required for sequences v1 and v2

5. Results and analysis

5.1. Execution order validation

Fig. 5 shows the comparison between the power in each of the three scenarios for both engines of the exercise run according to the sequences described in Section 4.3.3. In other words, sequences V1 and V2 run the same cases but in reverse order. This exercise aims to determine whether the order of execution of the different cases has any effect on the power required by the device for each of the scenarios. To determine the statistical significance of the possible differences, we performed the Mann–Whitney U test for independent samples, comparing the total consumption data for each execution order in each engine. For Unity, no statistically significant differences were detected in any of the scenarios, with p-values above 0.05 (0.869 in Static Mesh, 0.091 in Dynamic Mesh, and 0.109 in Physics). For Unreal Engine, the differences between orders were statistically significant, with p-values below 0.001 for all scenarios. However, as shown in fig. 5, the differences are very small (between 1% for Unity and 3% for Unreal Engine), so we consider that the order in which the cases are executed does not alter the representativeness of the comparison between the Unity and Unreal Engine versions of the three scenarios.

5.2. Variability of the test data

The descriptive statistics of the test data are shown in Table 3, Table 4, and Table 5.

Boxplots enable the examination of dataset distribution. In our case, the raw dataset is made up of 30 measurements, before deleting the invalid measurements. Energy consumption is calculated for each measurement by multiplying the average power by the execution time. The boxplots of the consumption data for our study are shown in Fig. 6, Fig. 7, and Fig. 8.

Uneven sizes among the four sections of a boxplot indicate variability in measurements across different parts of the scale, with some sections showing similar values while others demonstrate greater variability. In our case, if we look at the boxplots of each of the three scenarios comparing those run with Unity and Unreal Engine, we can see that there are no outstanding asymmetries. Boxplots are skewed left for the Dynamic Mesh scenario in Unity (Graphics Card), for the Static Mesh scenario (Graphics Card), and for the Physics scenario with Unity (HDD) and Unreal Engine (DUT). Boxplots are skewed right for the Dynamic Mesh scenario (HDD), for the Dynamic Mesh scenario with Unreal Engine (HDD), and for the Physics scenario with Unity (Graphics Card and Processor). The rest of the scenarios show relatively symmetrical distributions.

If we compare the boxplots for each of the video game engines for the same component and scenario, it can be observed that the median line lies outside the box of the comparison boxplot for all of the simulations except for the comparison between HDD consumption with Unity versus Unreal Engine in the Static Mesh scenario. This means that there are consistent differences between the consumption of the scenarios executed with between Unity and Unreal Engine in almost all of the situations.

Lastly, we can explore the interquartile range to assess the dispersion of the data. As depicted in Figures 6, 7, and 8, overall, the length of the box is small, indicating limited data dispersion.

5.3. Scenario Comparisons

We now move on to analyze the power required of the computer running each of the three scenarios with the two engines that constitute the main goal of the work. Table 6, Table 7, and Table 8 show the mean power values obtained in each of the three scenarios of both engines. The columns show the power required by the hard disk, the graphics card, and the processor, and the last column reflects the power of the DUT as a whole.

Table 6 shows the results of the comparison for the Static Mesh scenario. In this case, Unreal Engine is approximately 17% less efficient in terms of the power required by the DUT than Unity. If we look at the power required by the different components, the difference is more than 18% in processor power and more than 12% in the case of the graphics card. There are no appreciable differences in hard disk data.

Unreal Engine is known for its high-fidelity graphics and advanced rendering features. These results might be because these features can be more power-intensive and might favor higher visual quality at the cost of increased energy consumption. It is important to point out that the Static Mesh scenario in Unreal Engine and the one in Unity have the same visuals, that is, the very same mesh. Therefore, the rendering of Unreal Engine comes at an energy cost even though there is no visual benefit.

Table 7 shows the comparison between Unity and Unreal Engine for the Dynamic Mesh scenario. In this scenario, the results of the previous scenario are reversed and Unreal Engine is more energy efficient than Unity, with a difference of more than 26% in the power required by the DUT. If we look at the power

Table 3: Comparison between Unity and UE (Unreal Engine). Static Mesh scenario

Average without baseline (W)	HDD		Graphics Card		Processor		DUT	
Video Game Engine	UE	Unity	UE	Unity	UE	Unity	UE	Unity
Mean	1,95	1,98	104,53	93,20	22,75	19,26	422,51	377,18
Mean StandardDeviation (W) (Time in s)	1,27	1,09	38,21	37,11	15,80	18,42	33,55	20,74
Mean Median (W) (Time in s)	1,65	1,84	102,71	71,08	17,61	11,92	426,31	378,55
Min Record (W)	0,03	0,03	30,94	30,68	0,3	0,3	166,277	235,15
Max Record (W)	8,16	7,47	194,44	193,5	147,22	144,25	490,963	457,789

Table 4: Comparison between Unity and UE (Unreal Engine). Dynamic Mesh scenario

Average without baseline (W)	HDD		Graphics Card		Processor		DUT	
Video Game Engine	UE	Unity	UE	Unity	UE	Unity	UE	Unity
Mean	1,87	1,87	67,46	86,45	24,80	29,53	218,74	296,59
Mean StandardDeviation (W) (Time in s)	1,28	1,16	22,88	38,33	33,50	30,17	21,26	24,14
Mean Median (W) (Time in s)	1,54	1,71	64,53	65,60	11,26	16,98	327,57	404,98
Min Record (W)	0,03	0,03	28,90	28,15	0,30	0,30	168,24	252,97
Max Record (W)	7,22	7,22	188,37	190,72	157,32	154,35	397,96	499,35

Table 5: Comparison between Unity and UE (Unreal Engine). Physics scenario

Average without baseline (W)	HDD		Graphics Card		Processor		DUT	
Video Game Engine	UE	Unity	UE	Unity	UE	Unity	UE	Unity
Mean	1,91	1,37	62,39	21,28	63,49	18,80	413,58	175,32
Mean StandardDeviation (W) (Time in s)	1,23	0,81	28,78	4,63	29,38	22,78	30,65	9,39
Mean Median (W) (Time in s)	1,65	1,26	48,08	21,07	58,17	9,22	417,15	174,97
Min Record (W)	0,03	0,03	27,52	2,87	0,41	0,30	165,70	125,15
Max Record (W)	7,03	6,88	179,11	63,99	178,15	142,46	469,77	244,23

Table 6: Power required (W) for Unity and UE (Unreal Engine). Static Mesh

Test case	Engine	HDD	GraphicsCard	Processor	DUT
StaticMesh (W)	Unity	1,95	90,74	18,96	269,78
StaticMesh (W)	UE	1,92	102,07	22,45	315,11
Power diff (Unity-UE)		1,36%	-12,49%	-18,41%	-16,80%

required by the different components, the difference is 16% in processor power and almost 22% in the case of the graphics card. There is also no appreciable difference in hard disk data for this scenario.

These results denote that the animation of Unity might be less optimized for handling complex animations compared to the one used by Unreal Engine. In addition, Unreal Engine might have rendering optimizations that specifically benefit dynamic meshes, since the consumption in the Static Mesh scenario is also greater than in the Dynamic Mesh scenario for this engine.

The Physics scenario comparison, shown in Table 8, is the one that shows the greatest percentage differences in power between the Unity and Unreal Engine executions. In this case, there are clear differences in hard disk power, which in the previous cases had not shown any discrepancy. The version developed with Unity requires 41% less power than the version developed with Unreal Engine. This difference is amplified when the consumption of the graphics card and processor is analyzed, where the power requirement of the Unreal Engine version is more than three times bigger than the power requirement of the Unity version (218% and 241%, respectively), and 4.5 times bigger (351%) when considering the power required by the complete DUT.

The origin of this difference in consumption might be in the physics engine employed by default in each of the game engines: Unity uses *NVIDIA PhysX*, while Unreal Engine uses *Chaos*. To date, there has been no study on the energy efficiency of these physics engines.

5.4. Energy consumption of the different components

Finally, we compare the power required by each of the different elements of the computer in the different scenarios. The power required by the hard disk is almost two orders of magnitude lower than that of the other elements included in the study (graphics card and processor) with small differences between the two engines. The power of the graphics card, (shown in Fig. 9); and the processor, (shown in Fig. 10), are comparable (same order of magnitude). The graphics card requires more power in the two rendering cases (Static and Dynamic) while the processor should be dominant in the case of Physics. This is so in the case of Unreal Engine, but in the case of Unity, the power required by the processor for the three cases is quite similar. The power required by the complete DUT for the three scenarios in both engines is also shown in Fig. 11.

5.5. Answering the Research Questions

To determine the statistical significance of the power differences between the different engines across the various scenarios, we performed the Mann–Whitney U test for independent

Table 7: Power required (W) for Unity and UE (Unreal Engine). Dynamic Mesh

Test case	Engine	HDD	GraphicsCard	Processor	DUT
DynamicMesh (W)	Unity	1,87	86,45	29,53	296,59
DynamicMesh (W)	UE	1,87	67,46	24,80	218,74
Power diff (Unity-UE)		0,01%	21,97%	16,02%	26,25%

Table 8: Power required (W) for Unity and UE (Unreal Engine). Physics

Test case	Engine	HDD	GraphicsCard	Processor	DUT
Physics (W)	Unity	1,34	18,82	18,50	67,92
Physics (W)	UE	1,88	59,93	63,19	306,17
Power diff (Unity-UE)		-40,92%	-218,45%	-241,49%	-350,78%

samples, comparing the total consumption data of each engine in each scenario. In all scenarios, p-values below 0.001 were obtained, indicating that the differences in consumption are due to the change of engine rather than random variation. We can now answer the research questions that were posed at the beginning of the article. Although all of the graphs are presented in power, we can draw conclusions about energy consumption since the run time was the same in all of the scenarios (60 seconds).

5.5.1. Answering RQ1 - Physics

When asked whether there is a relationship between the energy consumption of the physics-related scenario between the versions coded in the two engines (RQ1), it is observed that there is a clear difference in consumption, with the DUT consumption of the Unreal Engine version being almost 4,5 times higher than that of the Unity version (351 %). This difference in the overall consumption of the device also appears in the consumption of the different components, (218 % for the graphics card and 241 % for the processor). For the hard disk consumption, the difference between the two engines is smaller (about 41%), but relevant.

5.5.2. Answering RQ2 - Static Mesh rendering

When asked if there is a relationship between the energy consumption of the DUT in a static mesh rendering task and the game engine used (RQ2), the answer is affirmative. There is a difference of 17% in favour of the Unity version in the overall consumption of the device in this type of task. Once again, the differences in hard disk consumption are very small (less than 2%), while the differences in this case for both the consumption of the graphics card and the processor show differences ranging from 12% to 18%.

5.5.3. Answering RQ3 - Animated Dynamic Mesh rendering

Finally, for the third research question about whether there are differences in consumption between the versions coded in Unity and Unreal engine in the rendering of dynamic meshes, the results indicate that, in this case, it is the Unreal Engine that has 26% lower energy consumption than the Unity engine. This difference in consumption is evident in the consumption of the graphics card, (22% lower in the case of Unreal Engine

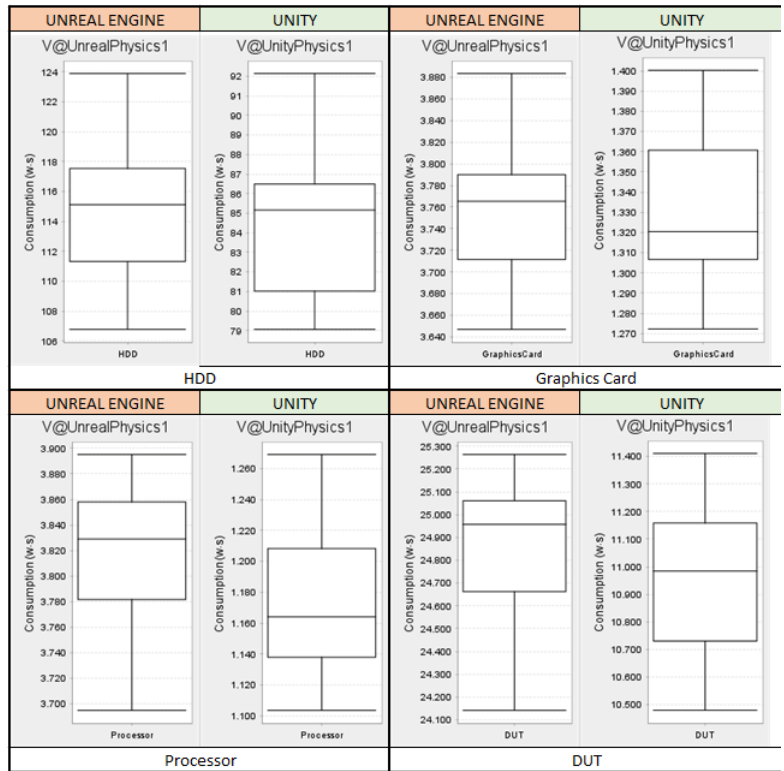


Figure 6: Energy consumption boxplots for Dynamic Mesh scenario

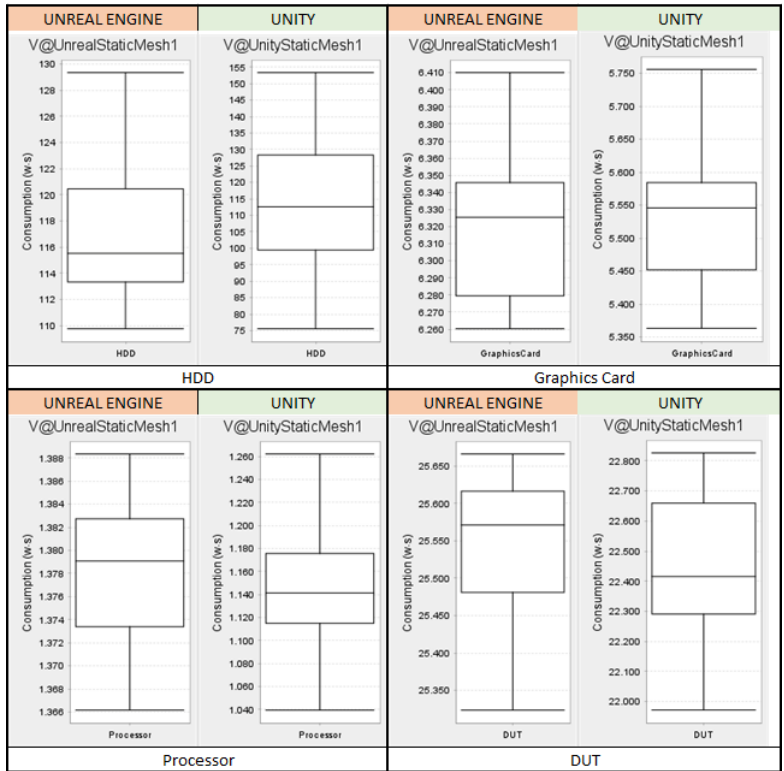


Figure 7: Energy consumption boxplots for Static Mesh scenario

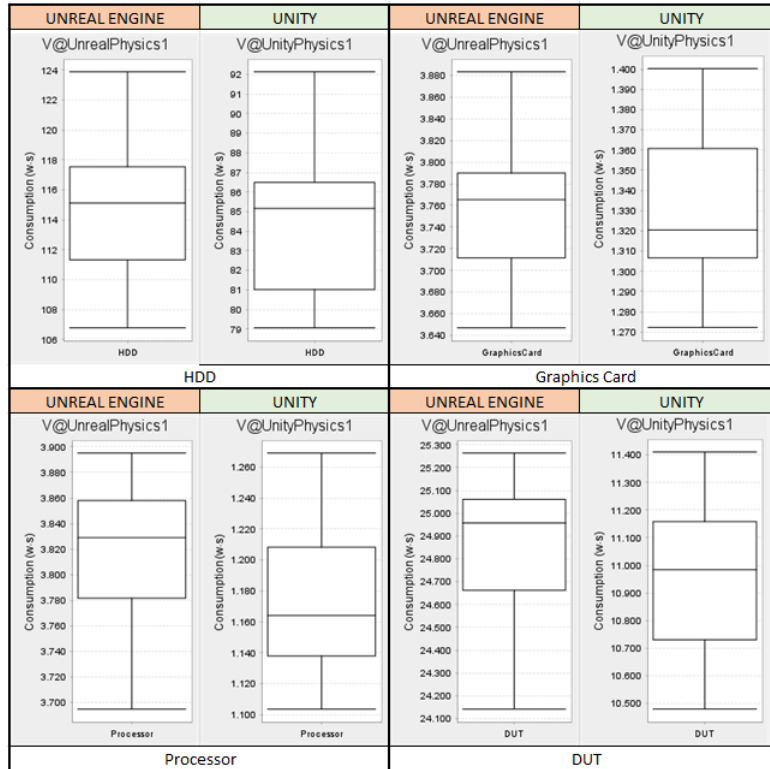


Figure 8: Energy consumption boxplots for Physics scenario

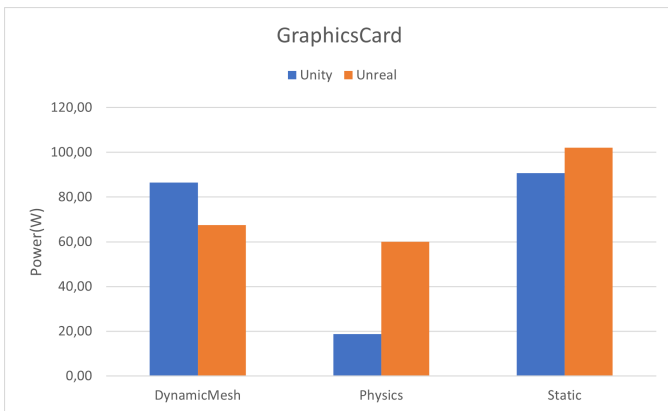


Figure 9: Graphic card power required for the three scenarios

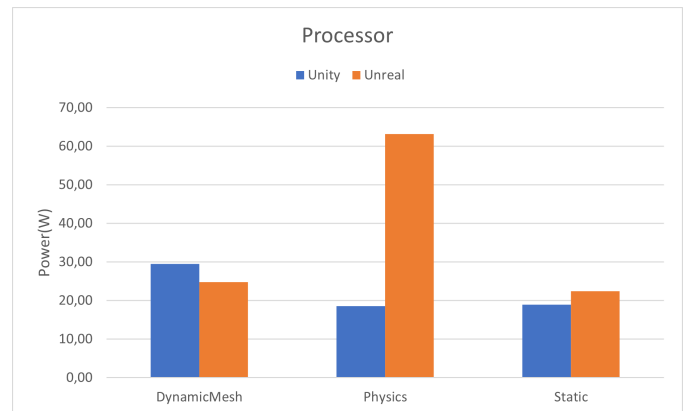


Figure 10: Processor power required for the three scenarios

and 16% lower in the processor), while the consumption of the hard disk is virtually identical between the two versions.

5.6. Putting the results in context

We can state that, in light of the results obtained, there are clear differences between the versions using one or the other video game engine in the case of the scenarios analyzed. Our research has confirmed marked differences in the energy consumption of video game engines: 351% in Physics in favor of Unity, 17% in Static Mesh in favor of Unity, and 26% in Dynamic Mesh in favor of Unreal Engine.

By combining both engines and theoretically choosing the most efficient engine technology for each scenario (assuming

the simplification that the three components have a similar weight in the context of a video game), it would be possible to outperform any of the two engines, as presented in Table 9. When comparing this data with a weighted average accounting for the market share of the video game engines, a global power saving (from the current situation) of 22% can be estimated as shown in Table 10. According to the estimate to the worldwide consumption figures presented in Section 1 22% represents a potential saving of 16,5 TWh which is equivalent to the annual consumption of more than 4 millions of European households. There is so much opportunity for improvement because of the huge popularity of video games. More than 40% of the world's population plays games, and, in recent years, this has grown at

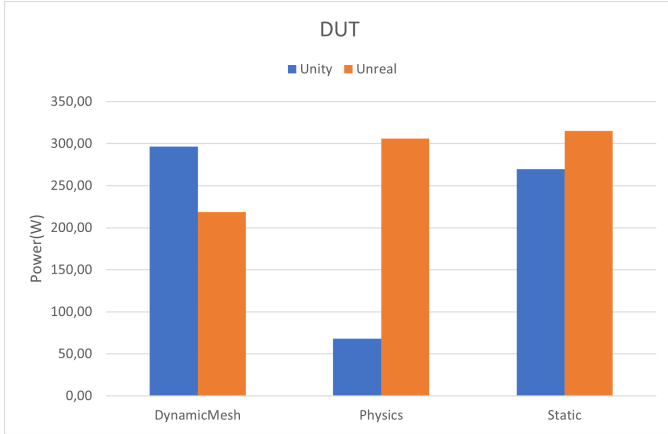


Figure 11: DUT power required for the three scenarios

Table 9: Power estimation. Average of scenarios. The optimum per scenario is highlighted

Power measurements DUT (W)				
	Static Mesh	Dynamic Mesh	Physics	Average power
Unity	269,8	296,6	67,9	211,4
Unreal Engine	315,1	218,7	306,2	280,0
Best case	269,8	218,7	67,9	185,5

a rate of 15% per year. Moreover, if in the future teleworking leads to virtual environments made with video game engines, these numbers will grow even more. We expect these results to raise awareness regarding the energy consumption of video game engines and to motivate a new branch of research in that direction.

6. Threats to validity

In this section, we use the classification of threats to validity of Wohlin et al. [37].

Construct validity: This aspect of validity reflects "the degree to which the independent and the dependent variables are accurately measured by the measurement instruments used in the experiment".

- **Dependent variables.** In this experiment, the dependent variables are the consumption of energy required for executing the different test scenarios. These consumptions were objectively measured using the Efficient Energy Tester, which has been validated as a dependable device for assessing the energy efficiency of software execution [36]. Additionally, each execution was repeated 30

Table 10: Global estimated power savings (The average of the measured power of Unity and Unreal Engine is used as an estimation for the "Others" category).

Engine	Market share	Average power (W)	Optimum power (W)
Unity	0,38	211,4	185,5
Unreal Engine	0,15	280,0	185,5
Others	0,47	245,7	185,5
Average per user(W)		237,8	185,5
		Potential savings	-22,0%

times, and all scenarios were executed on the same physical machine, operating system, and configuration.

- **Independent variables.** The independent variables are the use of Unity or Unreal Engine as the video game engine of the application and the selection of the three scenarios to represent the consumption behavior of a typical video game.

Internal Validity: This aspect of validity becomes crucial when exploring causal relationships. There is a potential risk that the factor under investigation might be influenced by other unaccounted variables.

Due to the nature of both experiments, all of the variables were controlled, thereby minimizing potential threats to internal validity. Specifically, the test cases are the same and run the same scenarios in both video game engines (Unity and Unreal Engine). It is worth noting again that the repetition of the experiments 30 times during the same time also helped to minimize any possible bias. In addition, subtracting the baseline power in the measurements and removing invalid measurements (wrong executions or outliers) also helped to ensure that the dataset was valid for analyzing and answering the Research Questions.

External Validity: This aspect of validity focuses on the extent to which findings can be generalized and are relevant to other cases. Enhanced external validity indicates a greater ability to apply the results of an empirical study to real-world software engineering practices.

To minimize the risk of the Unity and Unreal Engine implementations not being comparable, the scenarios have been validated as being equivalent between the two engines by two different professionals in the industry. Furthermore, the scenarios are representative of key aspects of video games (visual and physical) that are present in the vast majority of video games being marketed today.

Another threat to the external validity is the fact that the measurements are obtained for a specific computer (the DUT being used). However, we believe that using an already validated process and measurement device makes the results more reliable because, although the actual consumption data may be different on another computer, the relative differences between those values would be similar to those obtained in this case. The study was carried out with a computer that can be considered "standard" for gaming, although there could be more significant changes if a particularly powerful computer were chosen in some aspect.

7. Conclusions

The video games sector has experienced strong growth in recent years, both in terms of the number of users and the complexity of the games. This necessarily implies a significant increase in the energy consumed by this activity. However, the environmental awareness of this sector, particularly the efforts to reduce the energy consumption of the billions of gamers, is still far from maturity, and the magnitude of the energy consumed makes this a relevant issue for the research community.

Within the set of tools available to developers, game engines provide game developers with essential tools and functionalities, enabling them to focus on the creative and unique aspects of the game rather than having to program all of the basic functionalities from scratch.

The influence of the game engine on the energy consumption of the application has been studied in this work. We selected the most popular video game engines (Unity and Unreal Engine) and three representative scenarios of common tasks that are relevant to the majority of video games (Static Mesh rendering, Animated Dynamic Mesh rendering, and Physics simulations). The power required for the different implementations has been carefully measured in a controlled environment. Since the execution time was the same for all of the scenarios, the power measurements and energy consumption are strictly proportional.

The results obtained show that there are clear differences in energy consumption in the different scenarios for the two engines. These differences can be summarized as follows:

Unreal Engine has a lower consumption than Unity in the Dynamic Mesh rendering scenario (17%).

Unity has a lower consumption than Unreal Engine in the Static Mesh scenario (26%).

Unity has a lower consumption than Unreal Engine in the Physics simulation scenario (351%).

The differences are notable, both in the consumption of individual components such as the graphics card or the processor and in the overall power of the computer. Therefore the selection of an energy-efficient engine for the tasks included in the game could have a direct impact on the overall consumption.

The fact that Unity and Unreal Engine outperform each other in energy efficiency based on the selected scenario, indicates that there is potential interest in finding the most energy-efficient video game engines, identifying best practices, and implementing them in a more refined, energy-efficient video game engine technology.

There are still relevant functionalities implemented in both engines that are common in many different video games that should be analyzed, such as the sound system and the navigation system for AI path-finding. Also, one of the reasons for choosing the usage of commercial engines such as Unity or Unreal Engine is that they allow the development and building of a video game for multiple target devices (PC, mobile, consoles, etc.). By targeting multiple platforms, developers can reach a broader user base. New differences between the builds for different devices in both engines may emerge, thus making the analysis of the same game on different platforms a goal for our future work.

Declaration of Competing Interest

The authors do not have any conflict of interest.

References

- [1] A. Andrae, T. Edler, On global electricity usage of communication technology: Trends to 2030, Challenges 6 (2015) 117–157. doi:10.3390/challe6010117.
- [2] N. Mills, E. Mills, Taming the energy use of gaming computers, Energy Efficiency 9 (2016) 321–338. doi:10.1007/s12053-015-9371-1. URL <https://doi.org/10.1007/s12053-015-9371-1>
- [3] Electricity consumption per dwelling, <https://www.odysseumure.eu/publications/efficiency-by-sector/households/electricity-consumption-dwelling.html>, [Online; accessed 16-January-2024] (2023).
- [4] N. I. B.V., Newzoo's global games market report 2023, <https://newzoo.com/resources/trend-reports/newzoo-global-games-market-report-2023-free-version#:~:text=Highlights%20of%20the%20free%202023%20Global%20Games%20Market%20Report%3A&text=The%20number%20of%20players%20worldwide,yar%20growth%20of%20%2B0.6%25.>, [Online; accessed 16-January-2024] (2023).
- [5] A. Atrey, N. Jain, N. C. S. N. Iyenger, A study on green cloud computing, International Journal of Grid and Distributed Computing 6 (2013) 93–102. doi:10.14257/ijgcd.2013.6.6.08.
- [6] C. Siebra, P. Costa, R. Marques, A. L. M. Santos, F. Q. B. Silva, Towards a green mobile development and certification, in: 2011 IEEE 7th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), 2011, pp. 288–294. doi:10.1109/WiMOB.2011.6085386.
- [7] R. Pereira, M. Couto, F. Ribeiro, R. Rua, J. Cunha, J. Fernandes, J. Saraiva, Ranking programming languages by energy efficiency, Science of Computer Programming 205 (2021). doi:10.1016/j.scico.2021.102609.
- [8] L. Wang, S. Khan, Review of performance metrics for green data centers: A taxonomy study, The Journal of Supercomputing 63 (2011) 1–18. doi:10.1007/s11227-011-0704-3.
- [9] M. Gutiérrez, M. Á. Moraga, F. García, C. Calero, Green-in machine learning at a glance, Computer 56 (6) (2023) 35–43.
- [10] Unity Technologies, Gaming poised to continue accelerated growth according to unity gaming report 2022, <https://unity.com/news/gaming-poised-continue-accelerated-growth-according-unity-gaming>, [Online; accessed 11-December-2023] (2022).
- [11] activeplayer.io Game Statistics Authority, Fortnite live player count and statistics, <https://activeplayer.io/fortnite/>, [Online; accessed 11-December-2023] (2023).
- [12] J. K. Jain, C. S. Dangi, A novel survey on green computing, International Journal of Communication and Information Technology (2020).
- [13] Q. Li, M. Zhou, The survey and future evolution of green computing, in: 2011 IEEE/ACM International Conference on Green Computing and Communications, IEEE, 2011, pp. 230–233.
- [14] S. Huang, S. Xiao, W. Feng, On the energy efficiency of graphics processing units for scientific computing, in: 2009 IEEE International Symposium on Parallel and Distributed Processing, IEEE, Rome, Italy, 2009, pp. 1–8. doi:10.1109/IPDPS.2009.5160980.
- [15] L. Stolz, H. Endt, M. Vaaranemi, D. Zehe, W. Stechele, Energy consumption of graphic processing units with respect to automotive use-cases, in: 2010 International Conference on Energy Aware Computing, IEEE, Cairo, Egypt, 2010, pp. 1–4. doi:10.1109/ICEAC.2010.5702293.
- [16] E. Hittinger, K. A. Mullins, I. L. Azevedo, Electricity consumption and energy savings potential of video game consoles in the united states, Energy Efficiency 5 (2012) 531–545. doi:10.1007/s12053-012-9152-z. URL <https://doi.org/10.1007/s12053-012-9152-z>
- [17] D. Johnson, E. Horton, R. Mulcahy, M. Foth, Gamification and serious games within the domain of domestic energy consumption: A systematic review, Renewable and Sustainable Energy Reviews 73 (2017) 249–264.
- [18] M. Casals, M. Gangolells, M. Macarulla, A. Fuertes, R. Jones, S. Pahl, M. Ruiz, Promoting energy users' behavioural change in social housing through a serious game, in: eWork and eBusiness in Architecture, Engineering and Construction: ECPPM 2016, CRC Press, 2017, pp. 573–577.
- [19] P. Muhuri, P. Gupta, J. Mendel, User-satisfaction-aware power management in mobile devices based on perceptual computing, IEEE Transactions on Fuzzy Systems 26 (4) (2018) 2311–2323, cited By 19. doi:10.1109/TFUZZ.2017.2773020.

- URL <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85034230318&doi=10.1109%2fTFUZZ.2017.2773020&partnerID=40&md5=708c712a35921df0e3bd5f8b698fd1cc>
- [20] M. Hosseini, A. Fedorova, J. Peters, S. Shirmohammadi, Energy-aware adaptations in mobile 3d graphics, in: Proceedings of the 20th ACM international conference on Multimedia, 2012, pp. 1017–1020.
- [21] J. Verón, C. Pérez, C. Calero, M. Moraga, F. Pérez, C. Cetina, A comparative analysis of energy consumption between visual scripting models and c++ in unreal engine: Raising awareness on the importance of green mdd, in: Proceedings of the ACM/IEEE 27th International Conference on Model Driven Engineering Languages and Systems, MODELS '24, Association for Computing Machinery, New York, NY, USA, 2024, p. 114–125. doi:10.1145/3640310.3674099.
URL <https://doi.org/10.1145/3640310.3674099>
- [22] E. Fanouraki, Did you know that 60% of game developers use game engines?, <https://www.slashdata.co/blog/did-you-know-that-60-of-game-developers-use-game-engines>, [Online; accessed 05-December-2023] (2022).
- [23] M. Williams, Over 40 unreal engine-powered games-highlighted-during recent summer events, <https://www.unrealengine.com/en-US/blog/over-40-unreal-engine-powered-games-highlighted-during-recent-summer-events>, [Online; accessed 10-September-2025] (2023).
- [24] M. Eddie, Payday 3 is coming in 2023, new image released, <https://www.gamespot.com/articles/payday-3-is-coming-in-2023-new-image-released/1100-6489060/>, [Online; accessed 10-September-2025] (2021).
- [25] Unity Technologies, Unity for mobile game development, <https://unity.com/solutions/mobile>, accessed: 2025-09-11 (2025).
- [26] Sensor Tower, The big game engines report of 2025, https://app.sensortower.com/vgi/assets/reports/The_Big_Game_Engines_Report_of_2025.pdf, accessed: 2025-09-11 (2025).
- [27] C. C. Mathews, N. Wearn, How are modern video games marketed?, *The computer games journal* 5 (1) (2016) 23–37.
- [28] P. Contributors, perf: Linux profiling with performance counters, <https://perfwiki.github.io/main/>, accedido el 22 de julio de 2025 (2025).
- [29] I. Corporation, Intel® performance counter monitor (intel® pcm), <https://github.com/opcm/pcm>, accedido el 22 de julio de 2025 (2025).
- [30] J. Mancebo, F. Garcia, C. Calero, A process for analysing the energy efficiency of software, *Information and Software Technology* 134 (2021) 106560.
- [31] J. Kasurinen, Games as software: Similarities and differences between the implementation projects, in: Proceedings of the 17th International Conference on Computer Systems and Technologies 2016, 2016, pp. 33–40.
- [32] J. Musil, A. Schweda, D. Winkler, S. Biffl, A survey on the state of the practice in video game software development, *Institute of Software Technology and Interactive Systems, Tech. Rep* (2010) 13.
- [33] S. Aleem, L. F. Capretz, F. Ahmed, Game development software engineering process life cycle: a systematic review, *Journal of Software Engineering Research and Development* 4 (1) (2016) 1–30.
- [34] J. Gregory, *Game Engine Architecture*, A K Peters/CRC Press, 6000 Broken Sound Parkway NW, Suite 300, Boca Raton, FL 33487-2742, USA, 2009.
- [35] J. Mancebo, C. Calero, F. García, M. Á. Moraga, I. G.-R. de Guzmán, Feetings: Framework for energy efficiency testing to improve environmental goal of the software, *Sustainable Computing: Informatics and Systems* 30 (2021) 100558.
- [36] C. Calero, M. Polo, M. Moraga, Investigating the impact on execution time and energy consumption of developing with spring, *Sustainable Computing: Informatics and Systems* 32 (2021) 100603. doi:10.1016/j.suscom.2021.100603.
- [37] C. Wohlin, P. Runeson, M. Höst, M. C. Ohlsson, B. Regnell, A. Wesslén, *Experimentation in Software Engineering*, Springer Science & Business Media, 2012.