DIPLOMA THESIS

Sustainability of Videogames Consoles

- Thermal/Energy Analysis and Evaluation

Submitted at the Faculty of Electrical Engineering and Information Technology,
TU Wien
in partial fulfillment of the requirements for the degree of
Diplom-Ingenieur (equals Master of Sciences)

under supervision of

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November 10, 2020

Abstract

This thesis deals with improvement potentials concerning energy efficiency and life expectancy of videogames consoles. Therefore, the aspects concerning improvement potentials for efficiency and lifetime concerning thermal stress are investigated. This thesis originates from a European Union review study for the voluntary agreement of the product group videogames consoles under the Sustainable Product Policy. The purpose was to determine whether producers' effort is reasonable concerning the reduction of energy and resource consumption. Some of the topics were too deep for the short-lasting study and resulted in further investigating these topics in a diploma thesis. The topics include the efficiency of the power supplies integrated into game consoles and analyzing the topology. This information then helps investigate the thermal properties, especially of the power supplies, which are the main factor for their life expectancy. The analysis results show that the overall performance is quite good, with the potential for improvement. The consoles keep at low temperatures, with the power supplies efficiencies close to 90% and higher. Concerning their thermal and power supply design, the producers chose different pathways but achieved good results. Still, there is some potential to improve efficiency to even higher levels with technology already available, taking into account the high number of units sold. Furthermore, adapting the cooling design to achieve lower temperatures for different modes of use, resulting in higher life expectancy.

Kurzfassung

Diese Diplomarbeit behandelt das Verbesserungspotential der Energieeffizienz und Lebensdauer von Spielekonsolen. Dazu werden Aspekte untersucht, welche maßgeblich dafür verantwortlich sind diese zu beeinflussen, wie die Effizienz der Netzteile und die thermischen Verhältnisse im Inneren der Konsole mit Fokus auf den Netzteilen. Die Diplomarbeit ist die Weiterführung der Themen einer Studie zur Überprüfung der von den Herstellern angegebenen Verbesserungen bezüglich nachhaltiger Produktpolitik im Rahmen der "Sustainable Product Policy Initiative". Das Ziel der Studie war die Analyse und Bewertung der Maßnahmen welche die Hersteller getroffen haben um die Produkte bezüglich Ressourcen- und Energieverbrauch nachhaltiger zu gestalten. Einige der Themen waren zu umfangreich für die kurze Zeit der Studie und wurden deshalb in dieser Diplomarbeit weitergeführt. Dies beinhaltet die genauere Analyse der Netzteile hinsichtlich der Effizienz und eingesetzten Technologie. Desweiteren wird unter Verwendung dieser Ergebnisse eine Analyse des thermischen Verhaltens bezüglich der Lebensdauer aufgrund von thermischer Alterung vorgenommen. Die Analyse ergibt eine hohe Effizienz der untersuchten Netzteile mit leichten Unterschieden zwischen den Modellen. Nichtsdestotrotz gibt es noch Verbesserungspotential nach oben welches bei der hohen Stückzahl an verkauften Einheiten einen großen Unterschied macht. Bezüglich des thermischen Verhaltens bewegen sich alle untersuchten Konsolen im akzeptablen Bereich. Durch eine Erhöhung der Effizienz und kleinere Verbesserungen im Kühldesign könnte auch hier eine Verbesserung der Lebensdauer erreicht werden.

Acknowledgements

I want to thank my supervisors Stefan Wilker and Thilo Sauter, for helping me bring this work to what it has become. Furthermore, I would like to thank my family and friends for their support. I would especially like to show gratitude to my partner Kerstin Stadlbauer who helped me through this tough time. Finally, I would like to show appreciation to all my colleagues who helped me in any way.

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Abbreviations

APU	Advanced or Accelerated Processing Unit
CPU	Central Processing Unit
DUT	Device under test
Eff	Efficiency
EU	European Union
GPU	Graphics Processing Unit
I_o	Output Current
ICT	Institute of Computer Techology
I_{o_acc}	Output Current Accuracy
kWh	kilo Watt hour
n.A	not applicable
P_{avg}	Average Power
PC	Personal Computer
PCB	Printed Circuit Board
PD	Power Delivery
PDP	Power Delivery Power
PF	Power Factor
PFC	Power Factor Correction
P_{in}	Input Power
P_{in_acc}	Input Power Accuracy
P_L	Dissipation Power
P_o	Output Power
POI	Points of Interest
PoS	Power Supply
R_{ja}	Thermal Resistance junction to ambiance
R_{jc}	Thermal Resistance junction to case
R_{jl}	Thermal Resistance junction to lead
RMS	Root Mean Square
SMPS	Switching Mode Power Supply
SOC	System on Chip
Tc	Case Temperature
TWh	Terra Watt hour
USB-C PD	USB-C Power Delivery
V_o	Output Voltage
V_{o_acc}	Output Voltage Accuracy
VRAM	Video Random Access Memory

1 Introduction

This diploma thesis deals with the thermal and electrical characteristics and issues to improve the energy efficiency and lifetime of videogames consoles without interfering with the user experience. The idea for this work originates in the Institute of Computer Techologies (ICT) review study for the self regulatory initiative of the product group videogames consoles. The goal of the study was to investigate whether the manufacturers of videogames consoles made a reasonable effort to create efficient products in terms of material efficiency, energy consumption, recycling, repairability, longevity, and further categories. The thesis starts with the topics of the study as foundation and produces detailed novel results in the consoles electrical and thermal analysis, including more investigations, and recommendations that were too vast for the study's short term.

Game consoles are sold worldwide in significant numbers. For example, the total number of game consoles sold until mid-2020 is about 1,5 billion units [22]. Assuming only a percentage of them are used for active play at any time, the amount of energy consumed still is considerable. The calculations in chapter 3.3 result in the total energy consumption of around 33 TWh per year of all game consoles. This is roughly the yearly consumption of a medium country such as Hungary or New Zealand.

The corona crisis in the year 2020 shows us that game consoles are a big part of our lives, having potential in leisure time activity when there is not much else to do. For example, the sales in videogames consoles increased by 155 % in week 12 of 2020, and overall game sales rose by 82 % in this week [13].

Those singled out facts alone lead to the assumption that optimizing game consoles concerning every part that saves resources are worth considering.

There are far too many aspects related to energy efficiency in consoles to be covered in one single thesis. This thesis's range lies in the subjects presented in the EU study with a focus on electrical and thermal analysis of the consoles and especially the power supplies (PoS) with recommendations for future videogames consoles generations.

1.1 Motivation

Whereas the total energy consumption, the materials, and the repairability of a game console is a question of price and design decisions, the efficiency of the power supplies and temperature gradient inside a console is also a question of technical finesse (although, of course, also a function of price).

The efficiency factor of a power supply follows a simple concept. The input power is not entirely available at the output because a part of the input power is lost in the transformation process and noticeable as heat. The factor of output power to input power is called efficiency η. This factor determines how much additional energy the process needs besides the energy used for the action wanted. Thus, a high factor is desired. Measuring the PoS input and output factor determines this factor under different load conditions.

An immediate assumption of this process is that if the factor is lower than one, some part of the energy fed into the PoS has to appear elsewhere. The main part of the energy is available at a lower voltage at the output. The remaining part is the heat, which heats the PoS.

The thermal energy raises the close area's temperature around the power supply, the air, and the console. Temperature concerns another part of this thesis, the thermal properties of consoles.

In the process of running games on a console, it warms up caused by different effects such as the one mentioned before. Additionally, using the console for its predestined actions, e.g., gaming or streaming causes the console to warm up. The operation is the starting point for thermal losses in the electrical components such as the APU (GPU, CPU, and more). These losses are, for example, switching losses, ohmic losses, leakage losses, and more. The excess heat needs to leave the device while using the console. Otherwise, the components inside would overheat. Thus, devices should be designed so that the consoles' components keep at a relatively cool temperature and operate reliably. Running consoles at a lower temperature increases the lifetime of certain components (e.g., see Section 5.2 component lifetime).

The main question is whether consoles have a proper design concerning their electrical and thermal properties and where and if there are options for improvement. Competitors may have the lead in the development of a product and therefore the other producers stress the development process where flaws can happen. If those flaws appear in a late stage of the development cycle it could be still present in the final design. So thermal and electrical measurements of different kinds under different load conditions help analyzing and identifying issues and improvement potentials. Furthermore, an analysis of the physical design provides more insight and understanding of the used parts. The data acquired in those steps then lead to different results and proposals for optimizations and regulators.

1.2 Problem Description

As previously stated, consoles need energy. They consume quite a lot of it when under operation and even when they are not in use. Looking into consoles reveals several components or devices that consume energy. Depending on the state the console is in, the distribution of power inside the device is different. When we take a look at Figure 1.1, we find several essential components. Starting at the power input, we find the power supply necessary for converting the electrical power to a level we can use, which is essential but produces waste heat. The PoS delivers no sort of information or gaming experience for the user but cannot be left out. After the conversion, the components of the console can use the energy. Depending on the console's state, different components draw more or less energy from the grid. For example, the APU can be responsible for a big part of the power consumption while gaming. However, while the console is in a rest mode or just in navigation mode, a low effort is put into complex calculations. Other components like the mainboard and peripherals become dominant in those scenarios.

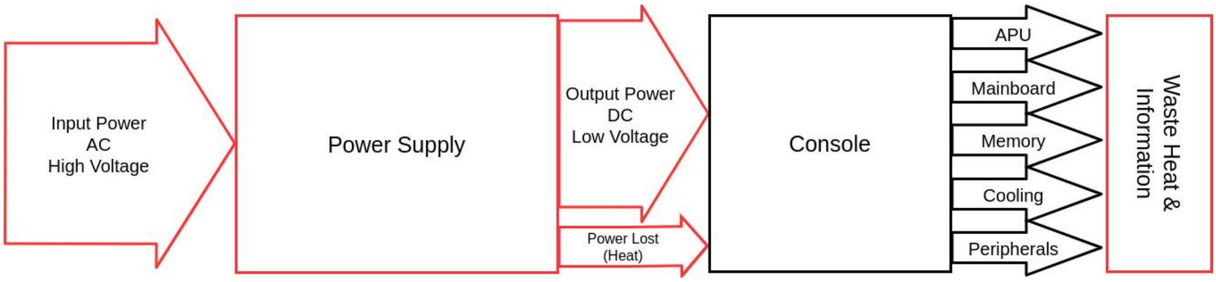


Figure 1.1: The way of power inside and into a gaming console with the investigated parts in red

There is only one part of the power distribution chain, continuously consuming energy independent of the specific usage scenario. It is the power supply producing waste heat from the moment the console draws energy from the grid. Every bit of energy that makes its way through the console has to pass this device. The console components can be optimized and adapted to consume less energy, which allows better performance at the same level of power. However, it always comes to deciding whether more gaming power or less energy consumption is the preferred strategy. When it comes to the power supply, the answer is simple from the user perspective. A better PoS needs less energy and thus costs the user less money for the same experience. So optimizing the power supply as much as possible would result in a better device without negatively affecting the user. It could even result in reducing energy consumption worldwide, and possibly some ecologically challenging power plants could be turned off (see Section 3.3) or switched to renewables.

Due to the continuous consumption of electrical power, large amounts of thermal energy accumulate in the devices while using different modes of consoles states. There are several sources in such systems that emit heat. The power supply that converts the electrical energy from low voltage (household level) to the extra-low voltage (according to IEC61140 [IEC16] protection against electric shock) needed in the devices. This process implicates the loss or transformation of energy to heat energy (see Figure 1.2). The remaining energy is fed into the system and used to process data for gaming, streaming, and others.

The primary consumers of the remaining energy are the APU (system on chip (SOC) with CPU, GPU, and others), the mainboard, the memory (GDDR5), storage devices (hard disks), and peripherals. All of them convert electrical energy into information and heat. This includes the parts mentioned in Figure 1.3.

The heat can be removed from the device by different means. The main categories for heat transfer are convection, conduction, and radiation. In consoles, the main factor responsible for cooling is by design forced convection cooling, which is usually a fan blowing through a heat-sink and the case. The main question is whether the implemented methods are enough for keeping the console at an adequately cool level.

To investigate this, thermal images and temperature monitoring can help find problematic areas and components in the console. Another factor for evaluating the quality of the thermal system is the efficiency of the power supply. Higher efficiencies directly reduce the amount of energy used and temperature, thus making the console more sustainable. The topics mentioned here have a considerable influence on the eco-friendliness of consoles and are therefore investigated in this thesis.

Investigating the other parts in Figure 1.1 like the APU, mainboard, and peripherals are also important. In Table 1.1 an overview for consumption values of a basic laptop without graphics is given. A direct translation of these values is not reasonable due to consoles being specially designed systems. Nevertheless, the stationary consoles and PCs' architecture are very similar and provide some insight into the power distribution. The PCs GPU and CPU correspond to the APU in consoles, whereas the mainboard is present in both devices. Concerning memory, consoles take a different approach than PCs, with only one type of memory present in the design. For comparison, the memory is divided into VRAM for the GPU and RAM for the CPU. The remaining parts are similar in both architectures. The total consumption in the referenced table is close to the measured consumption of the consoles (see Table 3.8).

The optimization of components inside is not the focus of this thesis due to complex relations that make comparisons difficult and too extensive.

Table 1.1: Power consumption of PC components similar to the ones used in consoles for comparing purposes to identify the ones with the highest consumption [3]

Component	Type	Watts per piece
AMD Athlon 5150 APU	CPU (Processor) Jaguar type	25 W
AMD Radeon R9 M280X	GPU (Graphics card) GCN v2	75 W
Mini ITX	Mainboard	30 W
SATA 5.4K RPM	Storage HDD	6,5 W
Blu-Ray Drive	Optical Drive	30 W
4GB DDR3	RAM (Random Access Memory)	3 W
80mm Fan	Fans	3 W
Total		172,5 W

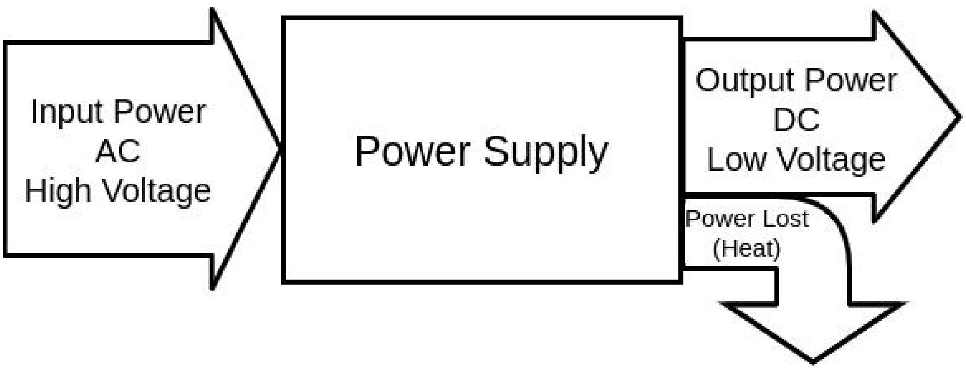


Figure 1.2: Power lost while transforming the electrical power. The factor describing output power to input power is called efficiency η

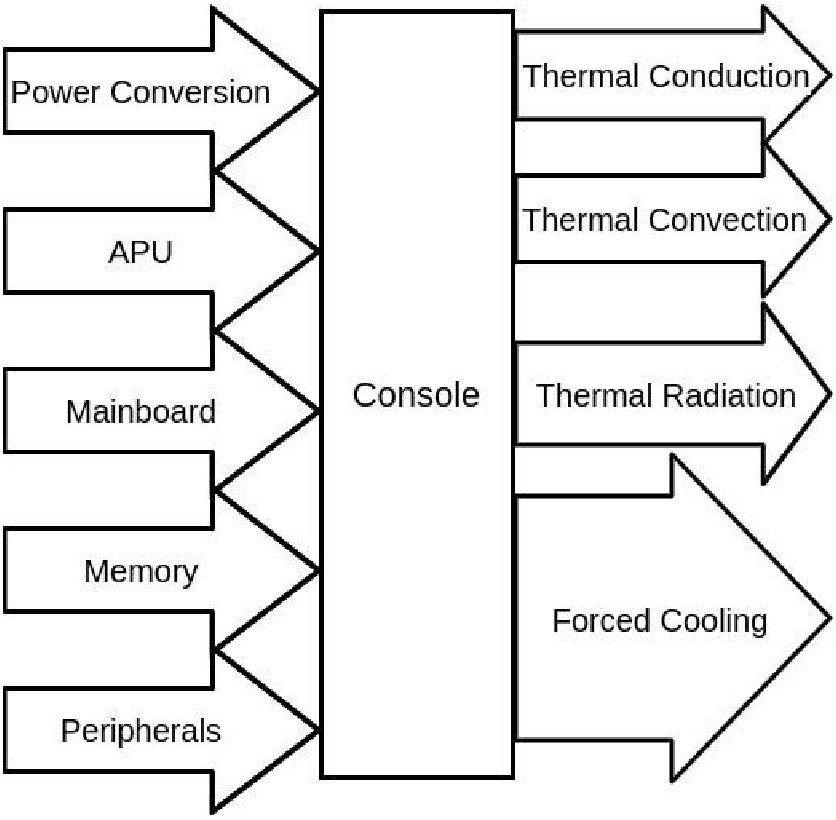


Figure 1.3: Heat sources that warm up the consoles and the means or mechanisms that absorb and transport the thermal energy away from the console based on [Rem00]

1.3 Methodical Approach

In order to evaluate the design of the console, carrying out different measurements is necessary. For energy efficiency testing, the PoS is extracted while disassembling the console. Then the measurement equipment is connected and powered on. Additionally, an electronically adjustable load is connected to the output of the PoS, according to Figure 4.13. After warming up all of the devices for an extended period, the measurement can start. Efficiency measurements are taken for five consecutive minutes in order to get consistent readings. For the thermal measurements, a different approach is used due to the whole console being inspected. The consoles have to be set up accordingly with consistent settings and software versions. The measurement devices are connected to the consoles and powered on. After a warm-up time, the consoles are put into the required mode (see Chapter 3 for a thorough explanation of the modes), and the measurement begins. For the thermal overview measurements, infrared pictures identify hot spots in the device. The hot spots identified in this step can be further investigated via thermal monitoring with temperature sensors. Based on these measurements and investigations, an evaluation of the design of the console is made. The analysis of the consoles in this thesis is only valid for the specific models taking part. For other models the results should be similar but it cannot be guaranteed that they are. Also this is just a snapshot of the current situation and design changes can happen frequently.

1.4 Structure

The thesis contains five different parts. The first part contains an introduction to this topic, related topics, and basic information. The second part discusses related work and regulations concerning energy efficiency and videogames consoles. The third and fourth part contains thermal and electrical analysis. It contains theory for the thermal measurements, efficiency measurements of the power supplies, and the consoles' thermal measurements. The last sections present the results, analysis, and discussion. A conclusion with outlook closes the thesis.

2 Related Work and Regulations

The ecodesign study [WLG+19] is not the first of its kind. Many different studies have been carried out about the behavior of consoles and power supply efficiency. This chapter provides an overview of relevant related work and regulations concerning this topic. This includes user behavior, power consumption, efficiency, and more.

2.1 Sustainable Product Policy

The European Union (EU) has put up an initiative for developing sustainable products that are sold or produced in the EU. The goal is to cover the demand for sustainable products and to reduce energy and resource consumption. Therefore the EU are trying to implement different measures to achieve that goal. For example, they introduced the ecodesign directive, which covers a wide range of products that sell in high quantities.

2.1.1 The Ecodesign Directive

The ecodesign directive [Par08] and energy labeling regulation is the legal framework for establishing rules for improving the environmental impact of products. This helps to improve the energy efficiency of products for the EU's 2020 energy objective [10]. For those products, the minimum efficiency is a mandatory requirement. For parts of these products, energy labeling regulations apply, giving specific information about every product's consumption in that group [Par17].

At the moment, there are 30 different groups of products that have regulations in place. These product groups are, for example, lighting, heaters, fridges, washing machine, and many more [9]. For most of the products, the ecodesign directive orders mandatory rules like power consumption, lifetime, efficiency, and more. There is a special agreement called the Voluntary Agreement covered in the next subsection for some product groups.

2.1.2 Voluntary Agreement

In contrast to other groups such as lighting, producers can voluntarily decide to regulate their products themselves. This is the case for game consoles, complex set-top boxes, and imaging equipment. These voluntary agreements promise to accelerate the rate with which the products are improved and lower the price compared to mandatory requirements [11]. There is a guideline for self-regulation measures under the ecodesign directive. In this voluntary agreement, estimations promise a saving of up to 41 TWh's of energy over the life-cycle of the 8th generation of game consoles (see Chapter 3 for a list of the 8th generation consoles). To check whether these voluntary agreements fulfill the European Commission's standards, it instructs independent third parties to review these agreements.

2.2 Other Studies

This section contains relevant studies and papers that worked on similar topics as the ones in this thesis. Most of the presented work uses or collects data for different consumption profiles and calculates an estimated energy usage for the different consoles. Also, the identification of different users and mode patterns is a complicated topic that is analyzed. The power supplies are partly covered but lack further investigation apart from the need for high-efficiency power supplies. Therefore, this thesis deals with the efficiency and life expectancy of the 8th generation videogames consoles.

2.2.1 Lawrence Berkeley National Laboratory

The Berkley Laboratory did a study on "video game console usage and national energy consumption" [DGP+15]. Due to rising energy consumption of electronic equipment and missing energy use data, they wanted to clarify game consoles consumption as they consume more and more of the total energy share. They claim that game consoles are present in nearly every second household. Therefore they present an analysis of game consoles where they equipped 880 households with 1176 simple power meters, including 113 consoles.

With the results from the measurements, they calculated an average for standby power and on-power, including several different modes in these two categories. One of their conclusions is that the primary uncertainty of game consoles' energy usage arises from incomplete data of user behavior.

Their results show lower power usage than previous studies but find several power-saving opportunities, including power management. Another interesting fact is that consoles are used more and more for tasks that do not include gaming, like streaming and other media consumption. Also, many users leave their consoles in idle mode the whole day, so it is essential to optimize it.

In 2019 they published an updated report on "A Plug-Loads Game Changer: Computer Gaming Energy Efficiency without Performance Compromise" [MBR+19]. This broad study of energy efficiency in computer and console gaming tests how it affects California's electricity market. They investigated gaming PCs as well as consoles, media streaming devices, and virtual reality equipment.

Their key findings include gaming representing one-fifth of California's total miscellaneous residential energy use. Future developments in the market could raise energy consumption by 114 % if people move to desktop gaming or fall by 24 % if the shift is towards consoles. Another interesting finding was that user behavior affects energy use more than technology. The energy efficiency savings opportunity is vast, with 50 % for personal computers and 40 % for consoles if the previous improvement trend continues.

2.2.2 National Resources Defense Council

NRDC published an issue paper about the 8th generation videogames consoles, "How Much Energy Do They Waste When You're Not Playing?" [DH14]. In the paper, the focus is on the energy consumption of the first models of the 8th generation, which includes the PS4, the Xbox One, and the Nintendo Wii U. Due to increased functionality and higher power, the consoles of the 8th generation consume considerably more power than the last models of the 7th generation.

Therefore an in-depth analysis and testing of the 8th generation power draw and energy consumption was conducted. The researchers focused on measuring the consumption in different modes, including navigation, media streaming, standby, and power-off. Moreover, they compared the results to the previous generation models. Furthermore, they made estimations of annual energy consumption and costs for each device, including carbon emissions. Additionally, the impact of settings concerning the behavior in different modes from the user was investigated, particularly when the consoles are not turned off after playing.

The measurements' results are later on used to give recommendations for improvements. This includes the option to enable USB ports when the console is off to prevent the users from leaving the console running while charging a controller only. Furthermore, reducing the power necessary for video streaming to those of efficient video players and more.

In "Power Supplies: A Hidden Opportunity for Energy Savings" [CC02], the authors discuss the potential that power supplies with low efficiencies have to improve power consumption. They provide an assessment of the power supply market in the United States with numbers for the type of power supply used and numbers for the market's sales and growth.

The figures suggest sales for internal power supplies in the range of $4 billion for the U.S market and $11.3 to $13,6 billion worldwide with the growth of 9 % per year starting from 2000. They estimate the total sales of power supplies from 1,5 to 2,5 billion units, with more than 6 billion units already in use at the time of the study. An analysis of several external and internal power supplies gives an insight into the market situation for different devices. The power supplies' efficiency ranged from 20 % to more than 90 % with linear converters at the lower end and switching mode power supplies ranging at the upper end.

One of the significant issues was that many of the power supplies provide low efficiency for partial loads. Additionally, standby power consumption is still considerably high. In addition to the numbers for power supplies in general, they provide an estimate for products that contain a power supply in the U.S with a total of 2,5 billion products. Another topic is the costs necessary to make power supplies more efficient. Their estimates are 30 % for power supplies up to 10 W, 20 % for units in the 10 W to 20 W region, and 10 % for models with higher specifications.

The conclusion is that due to the high number of products with power supplies, there is a high potential for energy savings. They recommend better labeling of power supplies, better research for efficient technology, to promote the smaller size of the more efficient technology and the energy savings and make it more straightforward for the end user what that saves on their energy bill.

2.2.3 Estimating the Energy Use of High Definition Game Consoles

The work of Webb et al. [WMFK13] examines the estimated energy consumption of high definition game consoles. The study collates, normalizes, and analyzes available data for power consumption and usage. Their estimates for consoles sold between 2005 and 2011 is 102 kWh per year and 64 kWh per year for new models sold in 2012. Due to significantly different data from other studies, it is hard to get representative numbers for energy consumption. User behavior and time in different modes are evaluated and combined to estimate a typical energy consumption profile. Their focus is on the definition of different modes and the time spent in them. For calculating the total energy consumption, a bottom-up approach combines the power and time spent in every distinctive mode to a total number. The evaluation has shown that for their analysis, 53 % of energy is used for gaming and 28 % for media consumption. Due to the different assumptions in the collected studies, they claim that savings could be very different if users behave differently.

2.3 Standards and Regulations

Due to the growing demand for electronic equipment, each device must consume less and less energy. Additionally, the power drawn should consist at best only of real power, keeping the amount of reactive power and harmonics at a minimum. Furthermore, standby consumption should be at a low level. There are regulations in place that define the constraints for different product groups like the Commission Regulation (EU) 2019/1782 [Com19] for external power supplies, the Commission Regulation (EU) No 801/2013 [Com13] and No 1275/2008 [Com08] for standby and off mode electric power consumption as well as norms that provide methods for the measurement of electronic equipment like IEC62087 [IECb] or IEC61000 [IECa]. These standards and regulations give a framework for creating products but do not give tight specifications on implementing this. Therefore, the implementation details of the different technologies in the consoles are unknown.

For power supplies that are sold separately and are not included in some products, efficiency values are provided in the datasheet most of the time. Also, the prior mentioned Commission Regulation (EU) 2019/1782 provides lower limits for these devices' efficiency. For internal power supplies, there is often no specification given as it is part of the product. Only the total amount of power needed is given in some cases. There is also no special regulation for internal power supplies, and the regulation for external power supplies does not apply. This is also the case for consoles. There is no information given from the producers about how efficient the power conversion is. The missing information does not mean that efficiency is low, but it would help consumers decide whether a product is energy efficient or not. Furthermore, it could prevent inefficient products from being sold.

3 Console Basics

This chapter contains information about consoles, their energy consumption, and power modes. The first part contains necessary information about the technology inside consoles with a list of specifications at the end. The second part evaluates the energy consumption of consoles worldwide, focusing on the 8th generation. The last part gives a basic understanding of the power factor concerning power supplies.

3.1 Power Modes

There are different power modes available the consoles can be in for better comparison. Since the consoles are capable of more than gaming there are more possibilities than previous generations offer. Table 3.1 lists the available modes with descriptions. There are different definitions for the modes available, whereas here the one from the review study is used [WLG+19].

3.2 Reviewed Consoles

The consoles reviewed for this thesis are only those that were for sale at the start of the EU review study. The stationary and hybrid consoles of the 8th generation include the PS4 models, the Xbox One models, the Nintendo Wii U, and Nintendo Switch, whereas the models tested are the Xbox One S and X, the PS4 Slim and Pro, and the Nintendo Switch. Only one version (meaning one revision) of the console is under investigation, and therefore, only an assumption of the general behavior of the series can be made, although other studies with different models (revisions) show similar results. Tests of the older versions can be found in other studies [DH14] [DGP+15] [WMFK13]. The stationary consoles all have similar designs as they are using x86 technology with graphics from AMD. The Nintendo Switch, on the other hand, uses a completely different design based on the Tegra X1, which is an ARM based device with included graphics from NVIDIA. Detailed descriptions and pictures of the consoles are shown on the following pages. This generation's game consoles focus is on multiplayer games interacting with other players over the internet. A specification list can be found in Table 3.2 and 3.3.

Table 3.1: Definition of the possible power modes used in consoles of the 8th generation [WLG+19]

Definition of Operational Modes	**Description**
Active Gaming	Mode in which the Games Console is actively performing its primary function of game playing
Media Playback	Mode in which there is decoding and playing of video files and codecs up to UHD content, on the Games Console's own optical discs, memory cards and streaming with media players
Navigation	Mode in which no other mode is engaged and the Games Console is displaying a menu of functions (the "Home Menu") from which the user may select applications, settings, social interaction via chat.
Low-power Standby	As defined in EU Regulation (EU) No 1275/2008(Annex II), only the following functions should apply: means a reactivation function, or reactivation function and only an indication of enabled reactivation function, and/or or information status display.
Networked Standby	Networked Standby: As defined in EU Regulation (EU) No 801/2013, means a condition in which the equipment is able to resume a function by way of a remotely initiated trigger from a network connection.
Rest	Game console state in which an active application is on hold, able to resume from a lower power state by awaking on controller or similar input. This mode can incorporate several features like enabling users to put a current game state on hold for a longer timeof period or, install updates with considerably reduced power consumption.

3.2.1 Sony PS4 Models

Sony first released the PS4 in November 2013, almost at the same time as the Xbox One. After the release of the first version, several others were introduced. The first version is not available to buy anymore due to more efficient ones being available. The available models include the Slim and Pro models investigated in this thesis.

PS4 Slim

The PS4 Slim was introduced in late 2016, offering the same experience as the older versions with an improved hardware design offering better wireless capabilities and lower power consumption. Additionally, due to the lower consumption and improved technology, the hardware fits a smaller case. The console is depicted in Figure 3.1.

PS4 Pro

The PS4 Pro was introduced in late 2016, close to the Slim model (Figure 3.2 shows the console). It offers an improved hardware design to allow gaming in 4k resolution and having better graphics in games that are optimized. Games that have been optimized have a logo on the front saying "PS4™ PRO ENHANCED" [2]. This model has a different APU with a higher clocking processor and more graphics cores also with a higher clock. Moreover, the Pro model offers the option to boost games that were initially developed for the older model.

Figure 3.1: PS4 Slim with associated controller

3.2.2 Microsoft Xbox One Models

Microsoft released their console, the Xbox One, close to the Sony PS4. Similar to Sony, they offer a model that is an improvement of the earlier model. Again the first model is no more available. The models released afterward include the Xbox One S and the Xbox One X, which are part of this thesis.

Xbox One S

The Xbox One S (Figure 3.3) was released slightly ahead of the PS4 Slim in June 2016. It offers almost the same functionality as the first model, having improved hardware with a new APU consuming less power. Additionally, it contains an upgraded Blu-Ray drive for 4k discs. Close to the end of the 8th generation, Microsoft introduced the Xbox One S "all digital" which is the same as the standard Xbox One S except not having any disc drive. This reduces the price of the console. Due to the late release of the "all digital" version and the small difference to the regular S model, it is not part of this thesis.

Xbox One X

The Xbox One X is similar to the PS4 Pro, an improved version of the initial model released in late 2017. It offers higher graphics and processing power with larger memory. The new hardware's full potential can only be experienced with optimized and marked games with "Enhanced upgrade". Figure 3.4 shows the console.

Figure 3.2: PS4 Pro with associated controller

Nintendo Switch

The Nintendo Switch is a hybrid console released in 2017 (Depicted in Figure 3.5). It is the successor of the previously sold Nintendo Wii U. Hybrid in this context means that the console can either be used with a TV as a stationary console or as a portable unit with detachable controllers. In late 2019 an improved model and a lite version were introduced. The improved model offers more extended playtime, better memory, and a brighter display. The lite model is a compact version that is designed to use as a portable device only. The improved and the lite model are not part of the analysis.

3.3 Evaluation of the Energy Consumption of Game Consoles

In Europe, we have around 37,2 million PS4, 7,8 million Nintendo Switch, and 10,5 million Xbox One consoles [22]. According to these numbers, gaming is pretty popular. These numbers only include the sales of consoles but do not include PCs and mobile gaming.

The ecodesign study [WLG+19] mentions that consoles have a share of about 25 % of the total gaming market. Typically people use consoles only for a fraction of time. Therefore, to estimate use times, duty cycles for the different modes have to be evaluated. The estimates for these duty cycles are depicted in Table 3.4.

Figure 3.3: Xbox One S with associated controller

Table 3.4: Estimed usage cycles of game consoles in hours per day [WLG+19]

Users	Gaming	Streaming & Media	Navigation	Networked Standby	Off
Light	0,28	0,18	0,09	23,03	0,47
Moderate	1,02	0,65	0,38	21,82	0,45
Intensive	2,36	1,5	0,65	19,64	0,41
Extreme	6,24	1,91	0,85	15,39	0,32

Combining these cycles with the numbers of each console sold (Table 3.6) and their respective user type distribution per system (Table 3.7), we get an estimate for the average usage of the consoles in each mode.

Table 3.5: Total sales of game consoles of the 8th generation worldwide (in thousands) [22]

Model	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
PS4	0	4 458	13 730	17 742	17 788	19 808	18 277	14 271	3 200	**109 280**
XBox One	0	3 064	7 231	8 385	7 980	7 644	6 829	4 969	1 032	**47 230**
Wii U	2 159	3 072	3 459	3 583	1 160	125	0	0	0	**13 970**
Switch	0	0	0	0	0	13 116	16 339	19 438	6 081	**55 190**

Figure 3.4: Xbox One X with associated controller

Table 3.6: Total sales of game consoles of the 8th generation worldwide divided into different versions based on Table 3.5 with assumptions from [12] and [22] (in thousands)

Model	First Release[4][20][23][18]	Total estimated units sold
Sony PS4	11/2013	35 930
Sony PS4 Slim	9/2016	58 675
Sony PS4 Pro	11/2016	14 669
Microsoft XBox One	10/2013	18 680
Microsoft XBox One S	7/2016	25 888
Microsoft XBox One X	10/2017	2 566
Nintendo Wii U	11/2012	13 558
Nintendo Switch	3/2017	48 893
New Nintendo Switch	9/2019	6 081

Table 3.7: User type distribution sorted by console for the 8th Generation [WLG+19, Chapter 4]

Model	Sony PS4	Microsoft XBox One	Nintendo Wii U	Nintendo Switch
Light	15 %	15 %	45 %	55 %
Moderate	40 %	40 %	30 %	26 %
Intensive	40 %	40 %	20 %	16 %
Extreme	5 %	5 %	5 %	4 %

Figure 3.5: Nintendo Switch with docking station and the Joy-con controllers

Unfortunately, the numbers of consoles sold in Table 3.5 are not divided into different versions, so an assumption based on [12] is necessary which results in the numbers in Table 3.6. This assumption includes counting every 5th PS4 sold from 2016 as a PS4 Pro and 4/5th as PS4 Slim. Models sold before 2016 are considered the initial model released in 2013. For the Xbox One models sold from 2013 until 2016 we consider being the initial release model (consumption for the different versions is similar) and every 5th Xbox sold from 2018 we consider an Xbox One X the rest we consider an Xbox One S. For the Nintendo Switch consoles sold until 2020 we consider the initial release model and the models sold in 2020 are considered the new revision that uses 40 % less energy on average based on [15].

The consumption data in Table 3.8 for the different modes is based on [WLG+19] for the newer models and on [DH14] for the older versions. For the networked standby, the average of power int the possible submodes is assumed as there is not enough data available to model this in more detail.

Table 3.8: The power consumption for different modes basend on [WLG+19], [DH14]

Model	Gaming	Streaming Media	Navigation	Networked Standby	Off
PS4	137,0 W	89,0 W	88,0 W	8,4 W	0,3 W
PS4 Slim	73,6 W	46,0 W	43,7 W	15,3 W	0,2 W
PS4 Pro	135,9 W	69,4 W	60,9 W	19,0 W	0,3 W
Xbox One	112,0 W	74,0 W	72,0 W	15,7 W	0,4 W
Xbox One S	65,4 W	34,8 W	27,9 W	7,2 W	0,3 W
Xbox One X	147,8 W	56,9 W	47,6 W	15,1 W	0,3 W
Nintendo Wii U	34,0 W	29,0 W	32,0 W	0,4 W	0,4 W
Nintendo Switch	12,9 W	8,1 W	5,0 W	6 W	0,4 W
Nintendo Switch (N)	9,0 W	5,7 W	3,5 W	4,2 W	0,2 W

Using these assumptions lead to the numbers in Table 3.9 and 3.10. The first one provides the consumption on a per console base, and the second one provides the consumption based on console type meaning the consumption of all the sold consoles in the world. Due to the high number of units sold for the PS4 Slim, it has the highest total energy consumption, and the Xbox One X has a rather low energy consumption due to the low number of total sales. In total, all the consoles consume an estimated amount of 33,21 TWh.

Table 3.9: Energy each console consumes in a year in kWh (sorted by type)

Users	PS4	Slim	Pro	Xbox One	One S	One X	Wii U	Switch	Switch (N)
Light	93,40	140,8	180,45	150,72	70,05	147,22	9,86	52,51	36,75
Moderate	151,28	166,42	227,09	194,35	93,48	195,27	27,23	55,25	38,67
Intensive	247,88	208,8	305,93	266,68	133,32	277,88	55,68	59,76	41,83
Extreme	448,60	299,28	483,66	417,26	222,07	475,79	109,88	70,22	49,16

Table 3.10: Energy each console type consumes in one year sorted by type in TWh

Users	PS4	Slim	Pro	Xbox One	One S	One X	Wii U	Switch	Switch (N)	Total
Light	0,50	1,24	0,40	0,42	0,27	0,06	0,02	0,39	0,03	3,33
Moderate	2,17	3,91	1,33	1,45	0,97	0,20	0,15	1,08	0,09	11,36
Intensive	3,56	4,90	1,80	1,99	1,38	0,29	0,30	1,17	0,10	15,49
Extreme	0,81	0,88	0,35	0,39	0,29	0,06	0,07	0,17	0,01	3,04
Total	7,05	10,92	3,88	4,26	2,91	0,60	0,54	2,81	0,24	33,21

Table 3.2: Specifications for the reviewed consoles part 2 [6] [14] [19] [8] [17]

Specs	**PS4**	**PS4 Slim**	**PS4 Pro**	**Xbox One**	**Xbox One S**	**Xbox One X**	**Nintendo Switch**
Models	CUH-10xx CUH-11xx CUH-12xx	CUH-20xx CUH-21xx CUH-22xx	CUH-70xx CUH-71xx CUH-72xx	1540	1681	1787	HAC-001 (Handheld) HAC-007 (Dock)
Processor	Semi-custom AMD "Jaguar" 8 Core, up to 1.6 Ghz, 2 MiB L2 Cache, 28nm process	Semi-custom AMD "Jaguar" 8 Core, up to 1,6 Ghz, 2 MiB L2 Cache, 16nm process	Semi-custom AMD "Jaguar" 8 Core, up to 1,6 Ghz, 2 MiB L2 Cache, 16nm process	Semi-custom AMD "Jaguar" 8 Core, up to 1,75 Ghz, 2 MiB L2 Cache, 28nm process	Semi-custom AMD "Jaguar" 8 Core, up to 1,75 Ghz, 2 MiB L2 Cache, 16nm process	Semi-custom AMD "Jaguar" 8 Core, up to 2,3 Ghz, 2 MiB L2 Cache, 16nm process	Custom NVIDIA Tegra Processor X1 Octa Core 1,02GHz
GPU	1.8 Teraflops 18 Comp.-Units 800Mhz AMD Radeon based	1,8 Teraflops 18 Comp.-Units 800Mhz AMD Radeon based	4.2 Teraflops 36 Comp.-Units 911Mhz AMD Radeon based	1,3 Teraflops 12 Comp.-Units 853Mhz AMD Radeon based	1,4 Teraflops 12 Comp.-Units 914Mhz AMD Radeon based	6 Teraflops 40 Comp.-Units 1172Mhz AMD Radeon based	256 Maxwell based Cuda cores with 307,2-921MHz
Rated power	230(250)W	165W	310W	220W	120W	245W	39W
Input	AC100-240V 50/60Hz	AC100-240V 50/60Hz	AC100-240V 50/60Hz	AC100-240V 50/60Hz	AC100-240V 50/60Hz	AC100-240V 50/60Hz	AC100-240V 50/60Hz
System Memory	8 GB GDDR5 (5 Available), 176 GByte/s	8 GB GDDR5 (5 Available), 176 GByte/s	8 GB GDDR5 (5,5 Available), 204GByte/s	8 GB DDR3 68 GByte/s 32MB ESRAM 218GByte/s	8 GB DDR3 68 GByte/s 32MB ESRAM 218GByte/s	12GB GDDR5 (9 Available) 326 GByte/s	4GB LPDDR4
HDD	500GB/1TB	500GB/1TB	1TB	500GB/1TB	500GB/1TB/2TB Elite Version with SSHD	500GB/1TB	FlashMem 32GB, microSD(H)(X)C up to 2TB
Media Type	Blu-ray Download	Blu-ray Download	Blu-ray Download	Blu-ray Download	4k Blu-ray Download	4k Blu-ray Download	Proprietary Game-Cards, Download
HDMI	1.4 (HDR)	1.4 (HDR)	1.4 (HDR)	1.4b (no HDR)	2.0 (out) 1.4b	2.0b HDR (out) 1.4b	1.4b

Table 3.3: Specifications for the reviewed consoles part 1 [6] [14] [19] [8] [17]

Specs	**PS4**	**PS4 Slim**	**PS4 Pro**	**Xbox One**	**Xbox One S**	**Xbox One X**	**Nintendo Switch**
Ethernet	Yes	10/100/1000	10/100/1000	10/100/1000	10/100/1000	10/100/1000	adaptor
WLAN	IEEE 802.11 b/g/n	IEEE 802.11 b/g/n/ac	IEEE 802.11 b/g/n/ac	IEEE 802.11 b/g/n dualband	IEEE 802.11 a/b/g/n/ac	IEEE 802.11 a/b/g/n/ac	IEEE 802.11 b/g/n dualband
Bluetooth	2.1 + EDR	4.0	4.0	2.1 + EDR	2.1 + EDR	4.0	4.1
Additional Connectivity	S/PDIF	–	S/PDIF	IR,S/PDIF	IR,S/PDIF	IR,S/PDIF	IR
USB	USB 3.1 Gen. 1	USB 3.1 Gen. 1	USB 3.1 Gen. 1	USB 3.1 Gen. 1	USB 3.1 Gen. 1	USB 3.1 Gen. 1	USB 3.1 Gen. 1
Video Modes	Games up to 1080p, Videos up to 4k	Games up to 1080p Videos up to 4k (no 4k Blu-ray)	Games up to 4k, Videos up to 4k	Games up to 1080p Videos up to 1080p (60 Hz)	Games up to 1080p (4k upscaling), Video up to 4k	Games up to 4k Videos up to 4k (120 Hz)	Games up to 1080p Videos up to 1080p (60Hz) handheld is 720p only
Online Features	Browsing Gaming Streaming	Browsing Gaming Streaming	Browsing Gaming Streaming	Browsing Gaming Streaming	Browsing Gaming Streaming	Browsing Gaming Streaming	Browsing Gaming
Battery	–	–	–	–	–	–	Li-Ion battery 15,95Wh
Display	–	–	–	–	–	–	LCD 6,2" 720p
Weight	2,8kg	2,1kg	3,3kg	3,5kg	2,9kg	3,8kg	Console: 297g Joy-Con: 98g
Size in mm W x H x L	305×53×275	265×39×288	305×53×275	343×80×263	295x65x230	300x60x240	203.1x102x13.9 Console only 239x102x13.9 with Joy-Cons

4 Electrical Analysis

This chapter provides an insight into the design of the power supplies for the stationary consoles. Therefore, the consoles were opened, and the topology of each power supply was identified. This information is necessary to identify possible hot spots in the thermal measurements later on. The second part of this chapter contains the efficiency measurements to evaluate the power conversion quality.

4.1 Switching Mode Power Supply Analysis

The analysis of the PoS used in consoles covers several topics. Reverse engineering the PoS provides an insight into the used components, the method of cooling, and potential faults in the design. Measurements of electrical parameters such as efficiency, power factor, power-off consumption help to categorize the PoS. Furthermore, thermal measurements are carried out to investigate the cooling design issues and, therefore, lifetime degradation.

4.1.1 Technology and Topology

To better understand the power supply measurements to a greater extent, an analysis of the power supply at the component level assists this process.

The three major power supply technologies are:

- Linear regulators
- Pulse-width modulated SMPS
- High-efficiency resonant technology SMPS

The efficiency of a PoS mainly depends on the topology. For example, according to Table 4.1, linear regulators which are easy to develop and relatively cheap do have the disadvantage of very low efficiency. On the other hand, there are resonant switching regulators with very high efficiency but lack fast development time and low cost. Due to the high production volume of game consoles, the cost is a lower priority for development. Therefore, all of the analyzed PoS use some SMPS, and this thesis focuses on the latter two of the previously mentioned technologies.

Table 4.1: Comparison of the four power supply technologies [Bro01]

	Linear Regulator	**PWM Switching Regulator**	**Resonant Transition Switching Regulator**	**Quasi Resonant Switching Regulator**
Cost	Low	High	High	Highest
Mass	High	Low-Medium	Low-Medium	Low-Medium
RF Noise	None	High	Medium	Medium
Efficiency	35-50 %	70-85 %	78-92 %	78-92 %
Multiple Outputs	No	Yes	Yes	Yes
Development Time	1 week	8 person month	10 person month	10 person month

Most of the standard power supplies for DC household equipment follow a similar scheme. They usually convert the low voltage AC input to a DC output. There are several essential blocks necessary, as can be seen in the block diagram in Figure 4.1. At the input, we have filters against electromagnetic interference, protection circuits against all sorts of faults, and potentially dangerous inputs. This is followed by the rectifier, which is often a bridge rectifier composed of diodes. The next block in the chain is the power factor correction unit or PFC. This part is not always necessary, depending on the device and power class. For example, low power supplies for lighting do not need a PFC [IECa].

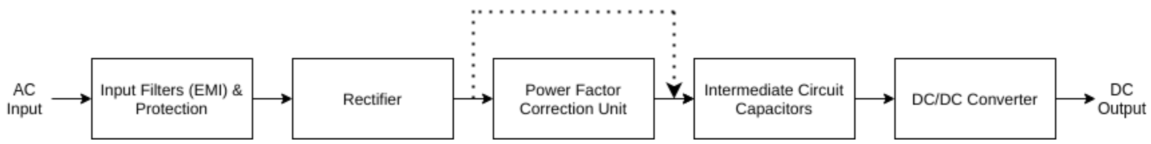


Figure 4.1: Block diagram describing the most important parts of a switching power supply

4.1.2 Analyzing Power Supplies

One of the first tasks analyzing the power supplies is disassembling the console and taking out the interesting parts. In all of the analyzed stationary consoles, the PoS is encased separately but built into the console. Depending on the PoS and console, one or two headers connect the power output with the mainboard. For getting a closer view of the actual PoS printed circuit board (PCB), the plastic case needs to be opened by prying open some clips and removing some screws. This unveils the main components on the top and some more on the bottom of the PCB.

4.1.2.1 Xbox One S Power Supply Analysis

The Xbox One S has a power supply with only one power output. Figure 4.2 depicts the top of the power supply with the components categorized into several sections. On the upper side is the AC Input for supplying the PoS from the power grid. The input gets filtered against electromagnetic interference, and some protective measures are applied to make the device safe. After this stage, the AC input is rectified via a bridge rectifier. The intermediate capacitor at the next part is charged via the PFC unit, which operates as a boost converter to make the current sinusoidal. The Voltage at this step is around 300 V DC. The following stage is the DC/DC converter. The topology of this converter is a flyback mode converter. It transforms the 300 V DC from the intermediate circuit to 12 V at the low voltage output.

Looking at the back of the PoS unveils a big metal shielding that has to be removed to look at the components. Three sections are marked in Figure 4.2 at the lower part. The input section, the active PFC plus the DC/DC converter's high voltage side, and the output with the DC/DC converter's low voltage side. Most of the parts concerning the circuit's high power path are on the front side, but the transistor (rectifier) responsible for charging the output transistor is located on the back.

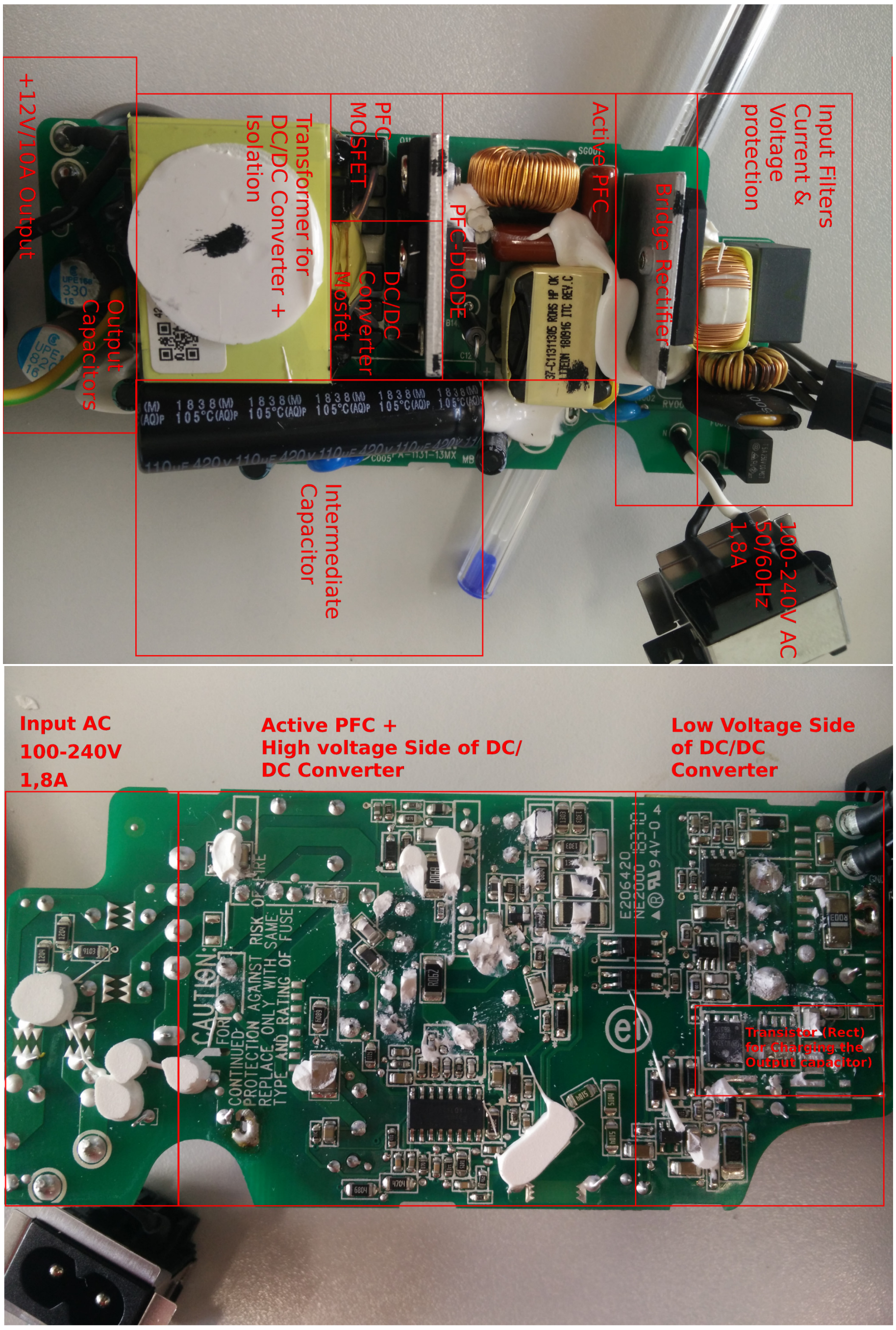


Figure 4.2: Front and back side of the Xbox One S power supply with block descriptions marked in red

Topology Analysis

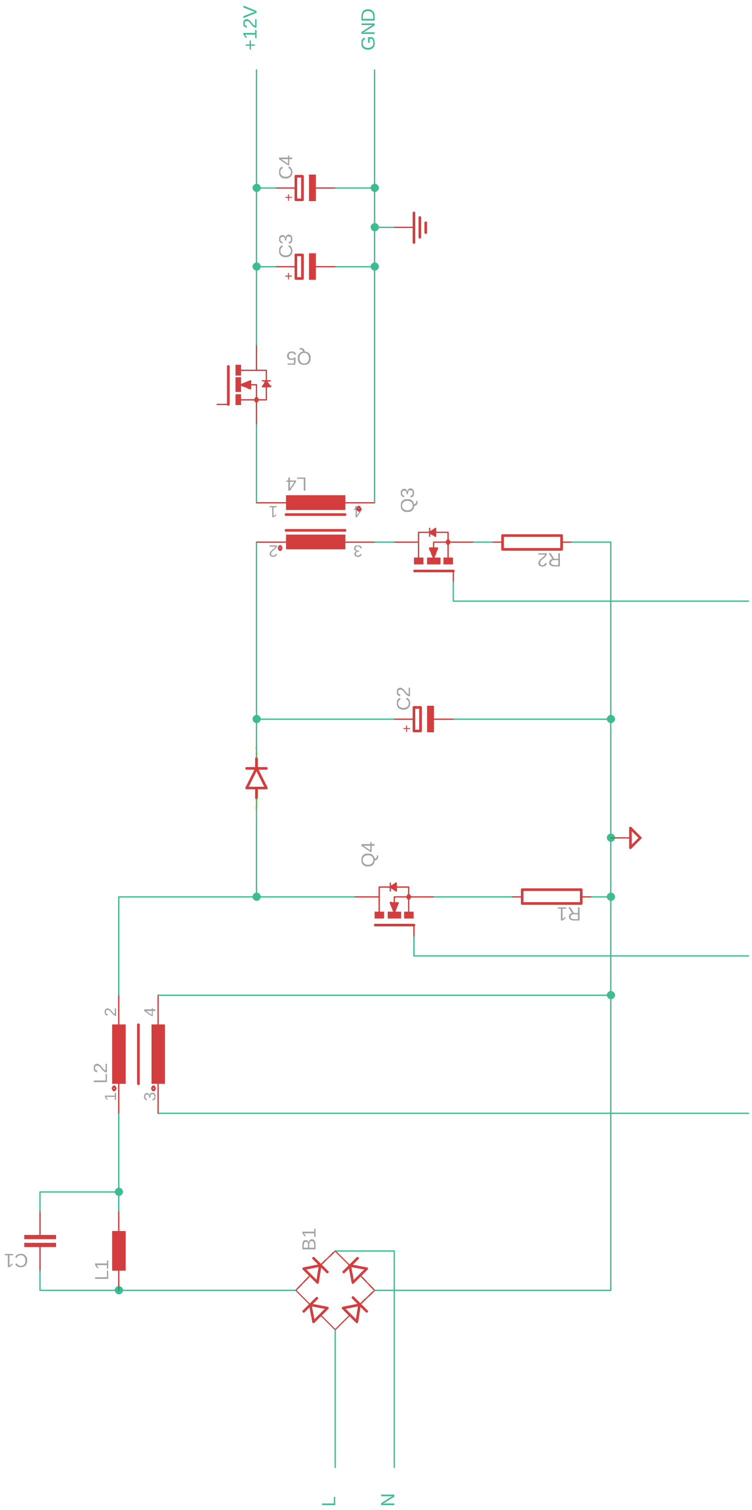


Figure 4.3: Topology analysis of the flyback mode converter of the Xbox One S power supply. The schematic shows important parts of the power path for the identification of the topology.

4.1.2.2 Xbox One X Power Supply Analysis

Similar to the Xbox One S PoS, the Xbox One X PoS also implements a single voltage output design. Nevertheless, due to the higher power demand of this model, the design is different. Figure 4.4 shows the front side of the PoS. The first stage of the PoS filters the input signal and protects the circuit against hazardous inputs. Afterward, the input is rectified at the bridge rectifier, and the PFC circuit charges the intermediate circuit capacitor located at the top right. For efficiency reasons, the DC/DC converter is based on a resonant converter topology with an LLC design incorporating a transformer, a separate inductance, output Mosfet rectifiers, and output capacitors, see Figure 4.5.

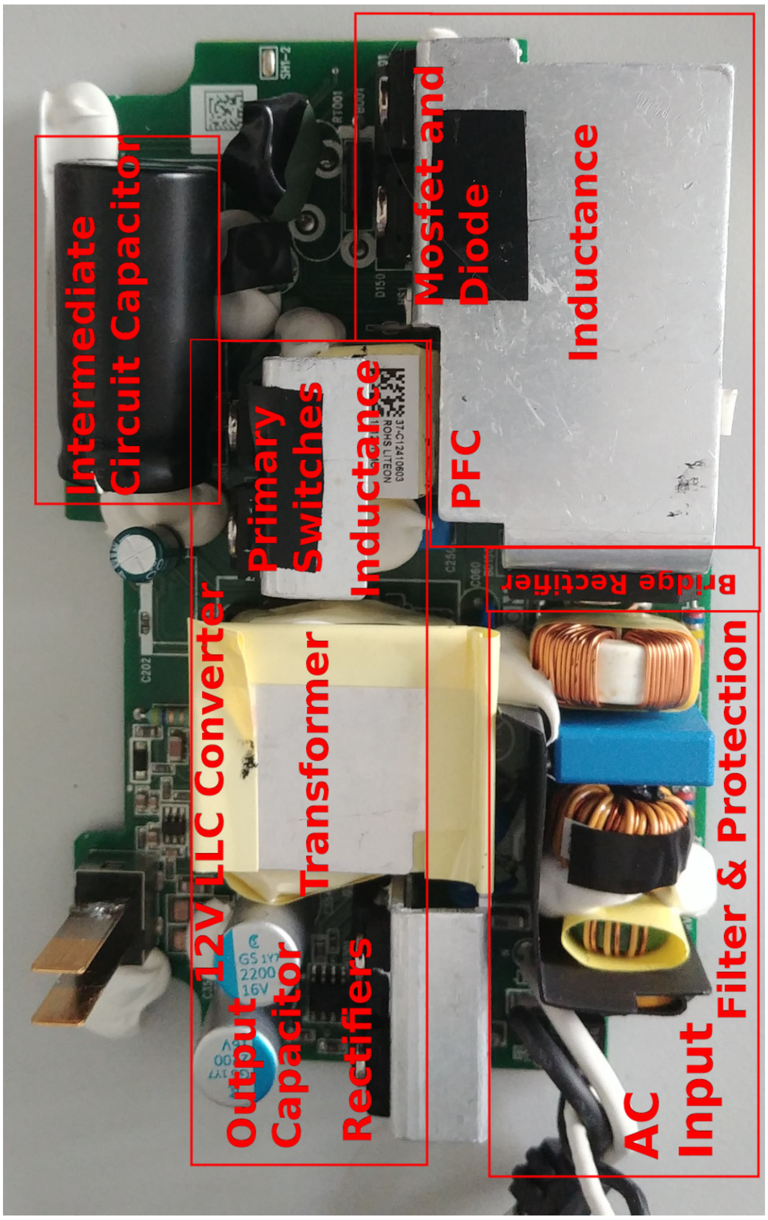


Figure 4.4: Front side of the Xbox One S power supply with block descriptions marked in red

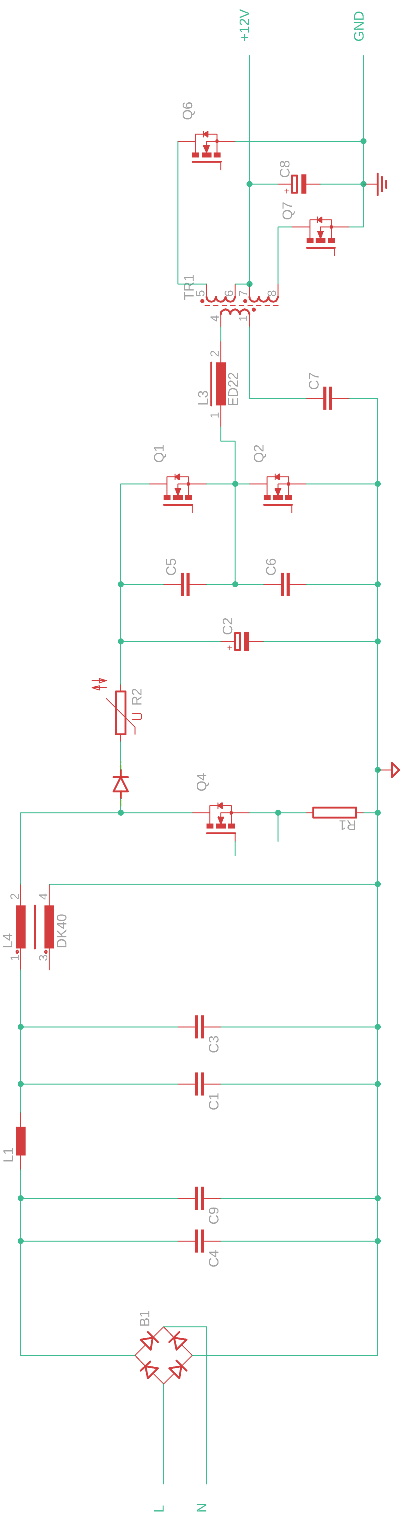


Figure 4.5: Topology analysis of the LLC resonant mode converter of the Xbox One X power supply. The schematic shows important parts of the power path for the identification of the topology.

4.1.2.3 PS4 Slim Power Supply Analysis

The PS4 Slim takes a different approach for the power supply. In order to lower the losses, two separate DC/DC converters are used, including a 5 V low power output for standby and low power modes and a 12 V high power output for an active operation like gaming, streaming, and updating. The designs for the two converters are different. The low power one is a standard flyback converter similar to the one in the Xbox One S PoS. On the other hand, the 12 V output has a very efficient resonant LLC converter design, enabling higher efficiencies for the high power range.

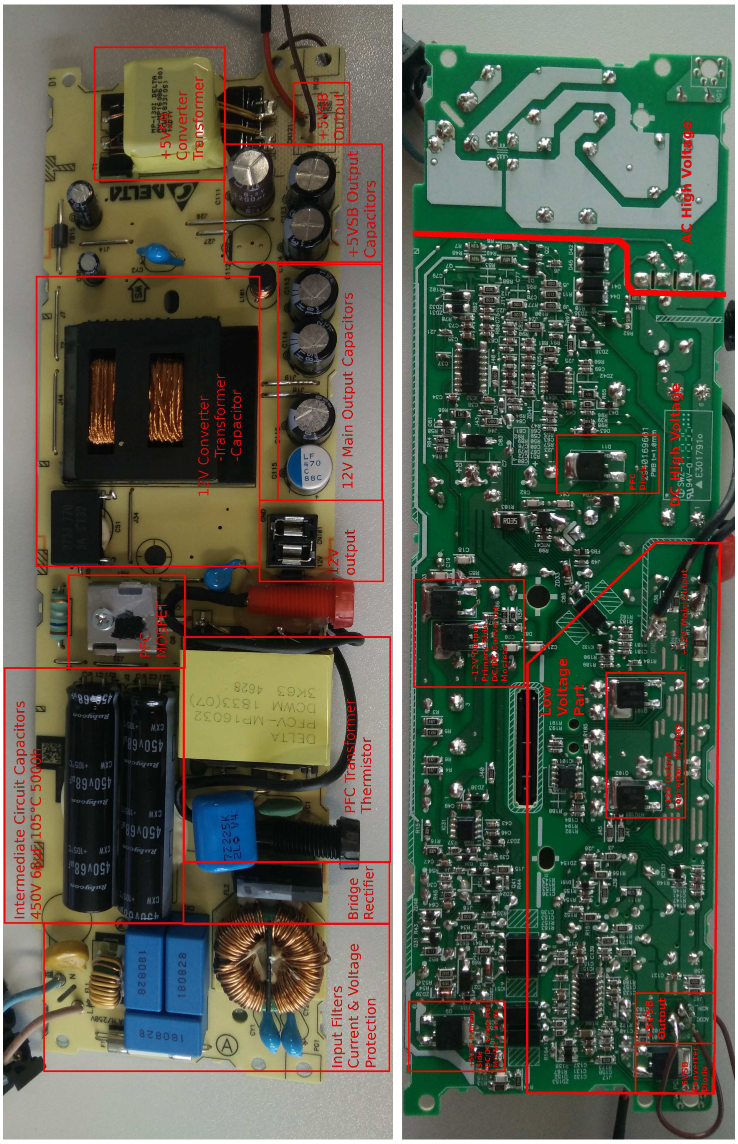


Figure 4.6: Front and back side of the PS4 Slim power supply with block descriptions marked in red

In Figure 4.6 the front and backside of the PoS PCB is depicted. The front shows the input filters and protection circuits at the bottom. The intermediate circuit capacitors are situated above those filters on the left. The bridge rectifier provides the rectified voltage for the active PFC situated above. On the upper part of the PCB, the two converters are placed. The 12 V output has a larger transformer compared to the 5 V output. The output capacitors with the connectors are placed on the top right. At the back of the PoS are mainly parts for controlling the circuits. Nevertheless, a few power parts are also situated here. The diode for the active PFC is situated at the back. The Mosfets for the 12 V LLC converter are on the left. The diode and the Mosfet for the 5 V flyback converter are also placed in the lower-left corner. The area marked with ”low voltage part” contains the diode for the 5 V flyback converter and the Mosfets acting as rectifiers for the 12 V converter.

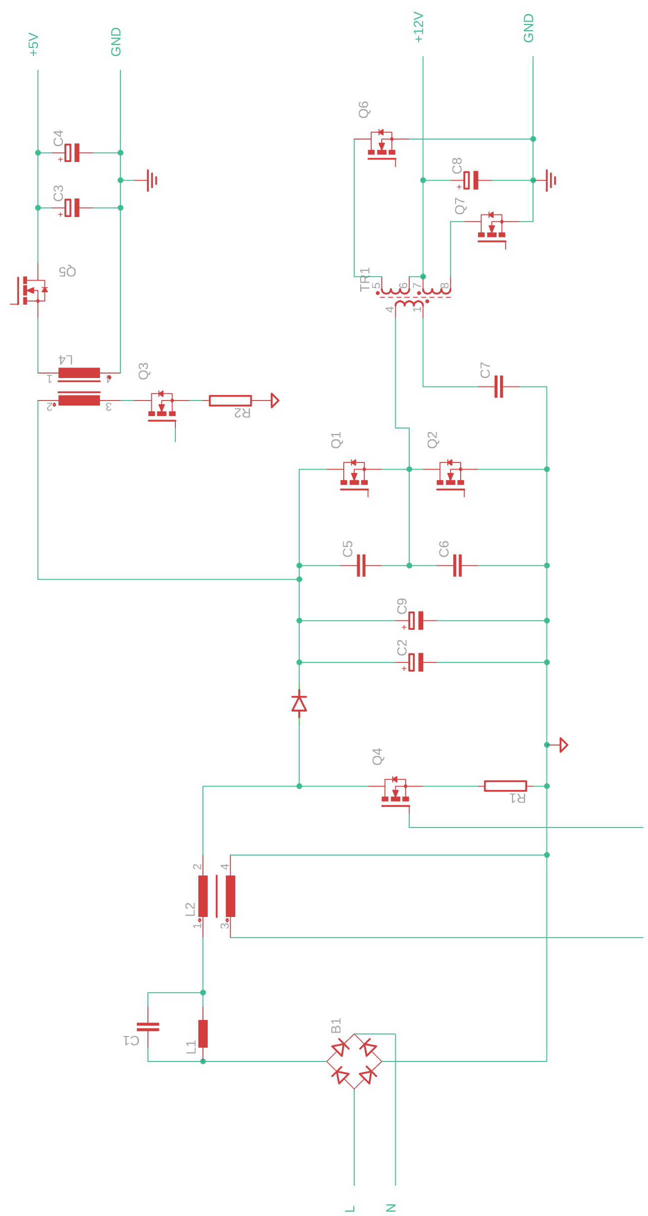


Figure 4.7: Topology analysis of the halfbridge resonant mode converter for the 12 V part and the flyback mode converter for the 5 V part of the PS4 Slim power supply. The schematic shows important parts of the power path for the identification of the topology.

4.1.2.4 PS4 Pro Power Supply Analysis

The PS4 uses a similar design as the PS4 Slim. The major difference is the power design goal. The PS4 Slim supplies 160 W of power, whereas the PS4 Pro provides 310 W, which is close to twice the power. In order to provide such a level of power, the PoS is substantially larger. Furthermore, the components directly responsible for converting power are capable of handling larger currents. Nevertheless, some of these components need larger heat-sinks in order to cool them reliable.

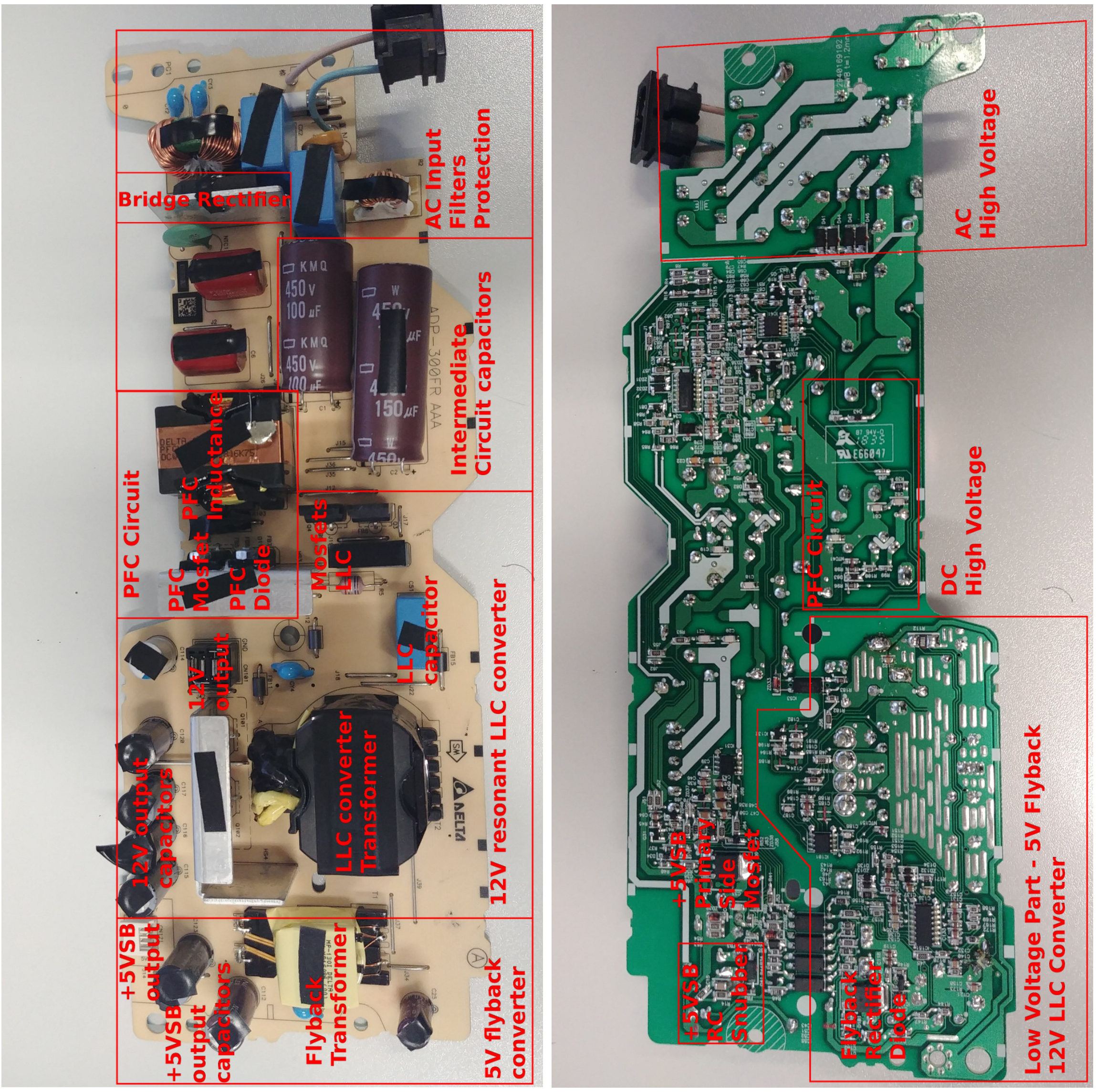


Figure 4.8: Front and back side of the PS4 Slim power supply with block descriptions marked in red

Figure 4.8 shows the front and backside of the PoS PCB. The front side contains most of the main components for the power path. The left side includes the components for the flyback converter producing an output voltage of 5 V. The 12 V resonant LLC converter is directly next to the flyback converter, including the output capacitors, the transformer, Mosfets, and the capacitor. The PFC circuit charging the intermediate circuit capacitor is located at the top with the Mosfet, diode, and inductance. At the right side of the PCB, the bridge rectifier and AC input can be found with protection and filter components. The backside mainly contains the controller logic and only a few components for the power path. The bottom left side is the low voltage area for both the 5 V flyback converter and the 12 V LLC resonant converter. The diode rectifier for the flyback converter is located there. Furthermore, the Mosfet and the RC snubber on the converter's primary side are located at the top left side.

4.1.3 Power Factor, Distortion and Total Harmonic Distortion

In a linear system that includes resistive components only, we have currents that are proportional to the voltage and in phase 4.9(b). Therefore according to Equation 4.1 the PF is 1. When we add inductive or capacitive components to the system, it changes the behavior. These components cause a phase shift of the current compared to the voltage 4.9(c). Thus the PF changes and becomes smaller than 1. This part of the PF is also called displacement. It becomes even more difficult if we bring nonlinear components into the system. For example, SMPS have this kind of behavior. Although the currents are no more sinusoidal, they have a periodic behavior 4.10(b). Therefore they can be divided into a DC component and harmonics according to Equation 4.2. When we consider the power grid as a perfect source, we should have no other components than the base frequency 4.3. Therefore real power can only come from the base frequency (e.g 50 Hz) 4.4. The PF is defined by the ratio between real power and apparent power. The real power we just defined. The apparent power includes all components of the current and voltage. Therefore, it is a multiplication of the base voltage with the current composed of the base frequency and the harmonics, including the DC component 4.5. The ratio between the base current and harmonics is also called distortion 4.7. On the other hand, the total harmonic distortion is the ratio between the distorted current and the fundamental current wave 4.8. With these equations, we can write the Power Factor as a product of displacement and distortion 4.9 [24].

$$PF_{simple} = cos(\theta_v - \theta_v) = displacement \tag{4.1}$$

$$I_{RMS} = \sqrt{I_{dc}^2 + \sum_{k=1}^{\infty} I_{k\_rms}^2} \tag{4.2}$$

$$V_{RMS} = V_{1\_RMS} \tag{4.3}$$

$$P_{real} = V_{1\_RMS} * I_{1\_RMS} * displacement \tag{4.4}$$

$$P_{apparent} = V_{1\_RMS} * \sqrt{I_{DC}^2 * \sum_{k=1}^{\infty} I_{k\_rms}^2)} \tag{4.5}$$

$$PF = \frac{P_{real}}{P_{apparent}} = \frac{I_{1\_rms}}{\sqrt{I_{DC}^2 * \sum_{k=1}^{\infty} I_{k\_rms}^2)}} * displacement \tag{4.6}$$

$$distortion = \frac{I_{1\_rms}}{\sqrt{I_{DC}^2 * \sum_{k=1}^{\infty} I_{k\_rms}^2)}} = I_{1\_rms}/I_{rms} = \frac{1}{1 + THD^2} \tag{4.7}$$

$$THD = \frac{\sqrt{\sum_{k=2}^{\infty} I_{k\_rms}^2}}{I_{rms}} \tag{4.8}$$

$$PF = distortion * displacement = cos(\theta_v - \theta_v) * \frac{1}{1 + THD^2} \tag{4.9}$$

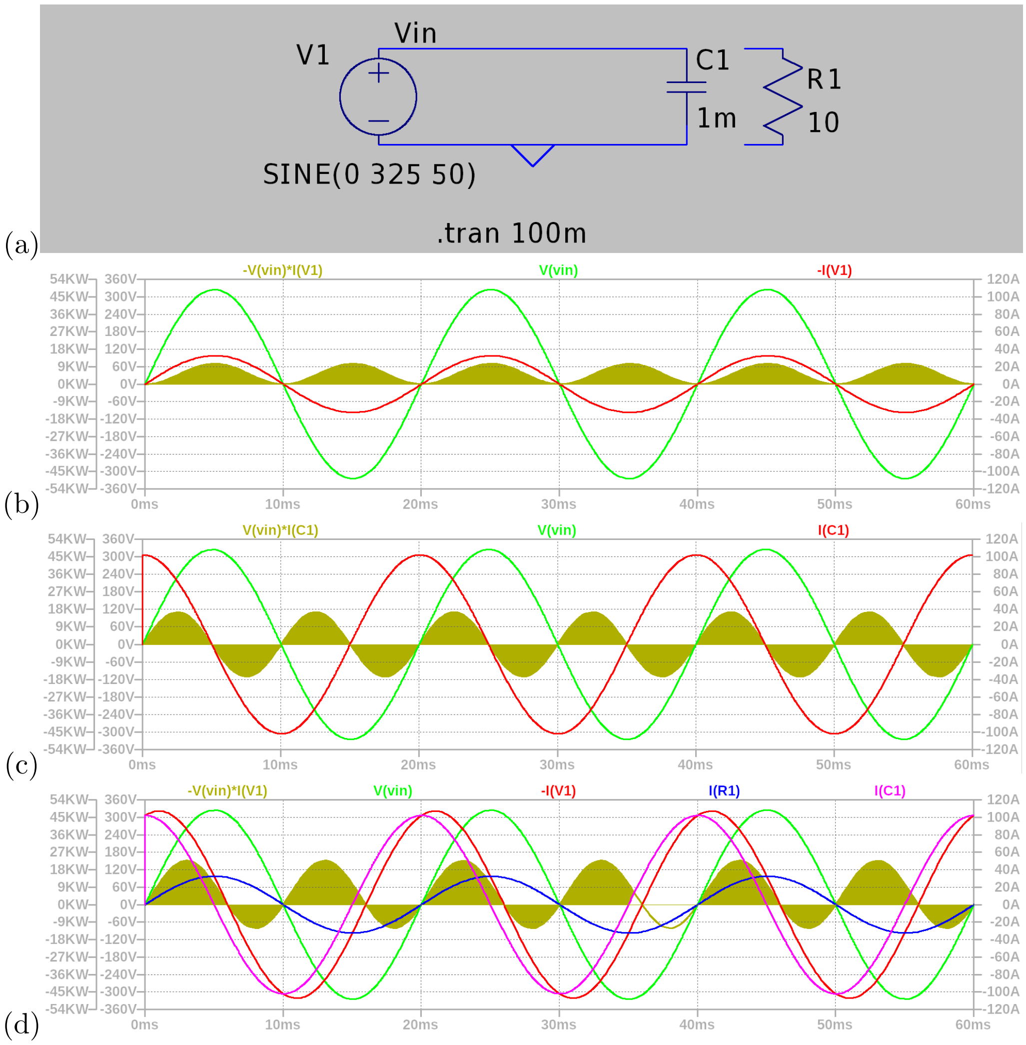


Figure 4.9: (a)Schematic for a reactive power circuit (optional resistor). (b) This waveform shows a circuit with real power only (yellow trace) due to no other component than a resistor being present (c) Reactive power only (yellow trace). The capacitor is the only component. (d)Circuit with the power trace in yellow, having real and reactive components due to the resistor and the capacitor both being present in the circuit

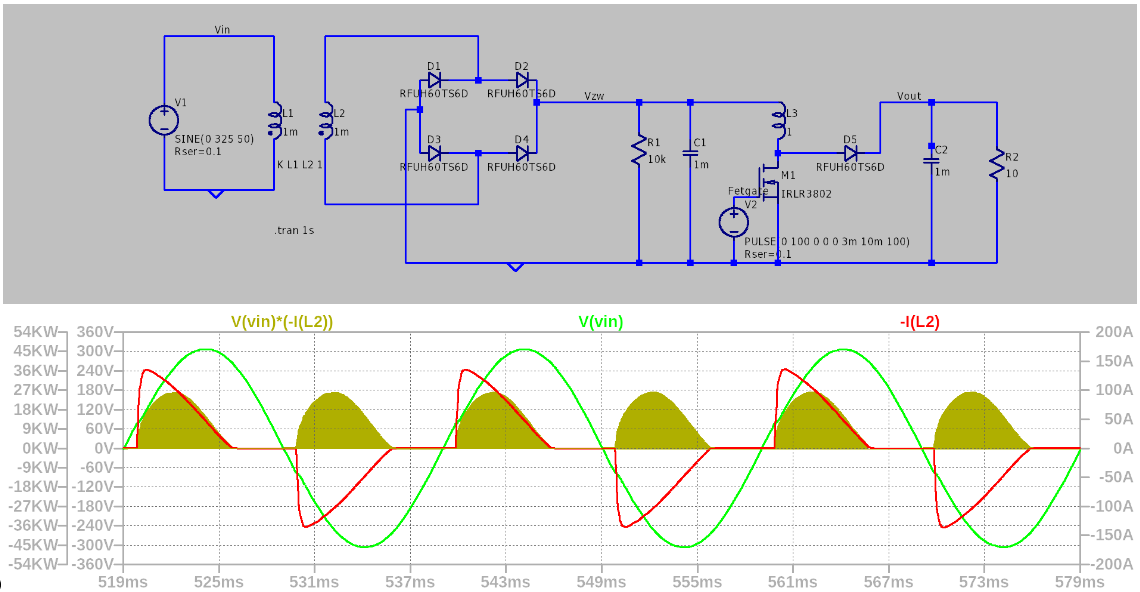
(a)
(b)


Figure 4.10: (a)Schematic for a basic rectifier with boost converter without power factor correction. (b) Distorted current waveform with grid voltage waveform

4.1.4 Power Factor Correction

Today power supplies or devices with built-in PoS have to follow specific rules concerning their operating conditions. For example, the harmonics of the input current must not exceed certain limits defined in the standard IEC 61000-3-2, as mentioned in Chapter 2.

For this purpose, the power supplies used in consoles and other devices have a so called power factor correction unit (PFC). This unit is responsible for drawing sinusoidal currents from the grid rather than currents that are out of phase or currents with non-linear parts. A PFC can either be classified as an active or passive design.

A passive PFC usually only uses passive components like chokes to filter the input current. They only provide minor improvements and usually find their way only to low power electronics.

An active PFC tries to remodel the current to mimic the sinusoidal behavior of the input voltage. They are often modeled as a power supply inside a power supply. Instead of controlling the output voltage or current, it controls the input current. In Figure 4.11 an example for a PFC corrected current is depicted achieved through switching components and energy storage (e.g., boost converter).

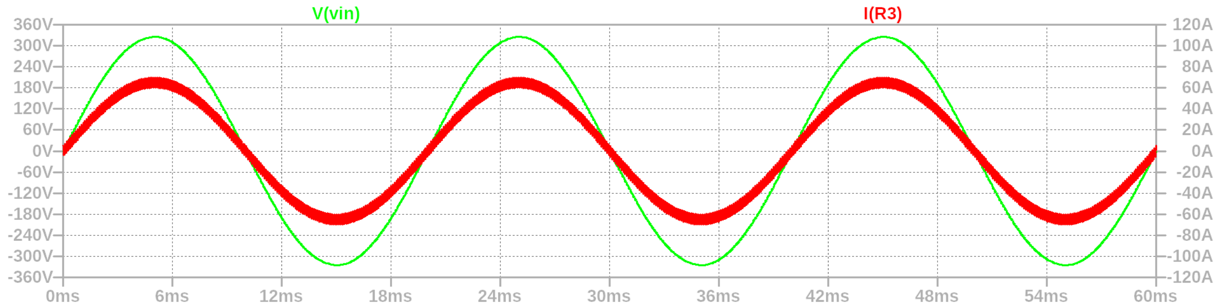


Figure 4.11: Current and voltage waveform example for a PFC corrected current. The current is switched with a high frequency and is therefore looking continuous

4.2 Electrical Measurements

This section provides the measurements and procedure for the efficiency measurements for all the investigated consoles. Furthermore, a comparison with real consumption data gives an insight into the relevant operating area of the power supplies. If a secondary voltage output is available, both of the outputs are measured separately. If the power supply is capable of switching between several output voltages, the standard condition and the one used in operation with the console are tested.

Power Supply Efficiency Measurements

To measure a device's efficiency, parameters at the input and output have to be measured and set into relation. In the case of an electronic power supply, the input and output power are of concern. Therefore a power meter accurately measures the power at the input of the device under test (DUT). The output power is calculated from measuring the output voltage and the output current.

4.2.1 Measurement setup

The setup for the measurement is shown in Figure 4.12. For the Nintendo Switch, a USB power delivery (PD) controller acts as a setup device between load and power supply. It ensures that the power supply outputs the correct voltage and current levels according to the PD specification [21]. Without such a device, the power supply falls back to the default mode operating at 5 V. The Nintendo Switch power supply does only support two modes of operation. It operates either at 5 V/1,5 A or 15 V/2,6 A, which is against the specification. According to the specification, a USB-C PD power supply with a PDP of 39 W has to operate at 5 V/3 A, 9 V/3 A and the maximum power at 15 V [21, chapter 10.2.2]. The Switch power supply is missing the 9 V and does only provide 1,5 A at the 5 V setting. The voltage/current and power flow in USB-C Power Delivery is negotiated via the USB-C CC lanes [21, chapter 2.1]. The power supply not only supplies the DUT with power, but it also supplies the USB-PD controller. Thus the correct power value can only be obtained by measuring the current before and after the controller.

Table 4.2: Measurement instruments overview

Model	Type	Measure
Chroma 66205	Power Meter	Input power P_{in}
Chroma A662022	Current-shunt AC Side	Attachment to measure P_{in}
Voltcraft VC650BT	Voltmeter	Measuring the output voltage V_o
Höcherl & Hackl ZSAC4244	Adjustable Constant Load	Adjusting the output power P_o
Murata DC Shunt	Current-shunt DC Side	Measuring the output current I_o
Agilent U1251B	Millivoltmeter	Measuring the shunt voltage V_{Io}
PD Buddy Sink	USB-C PD Controller	Power Delivery Setup

Table 4.3: Consoles under test with rated power and their respective voltage and current capabilities

Model	Rated Power[W]	V_{o1} [V]	I_{o1} [A]	V_{o2} [V]	I_{o2} [A]
PS4 Slim (CUH-2216B)	165	12	13	4,8	1,5
PS4 Pro (CUH-7216B)	310	12	23,5	4,8	1,5
XBox One S (1681)	120	12	10	-	-
XBox One X(1787)	245	12	20,42	-	-
Nintendo Switch	39	5	1,5	15	2,6

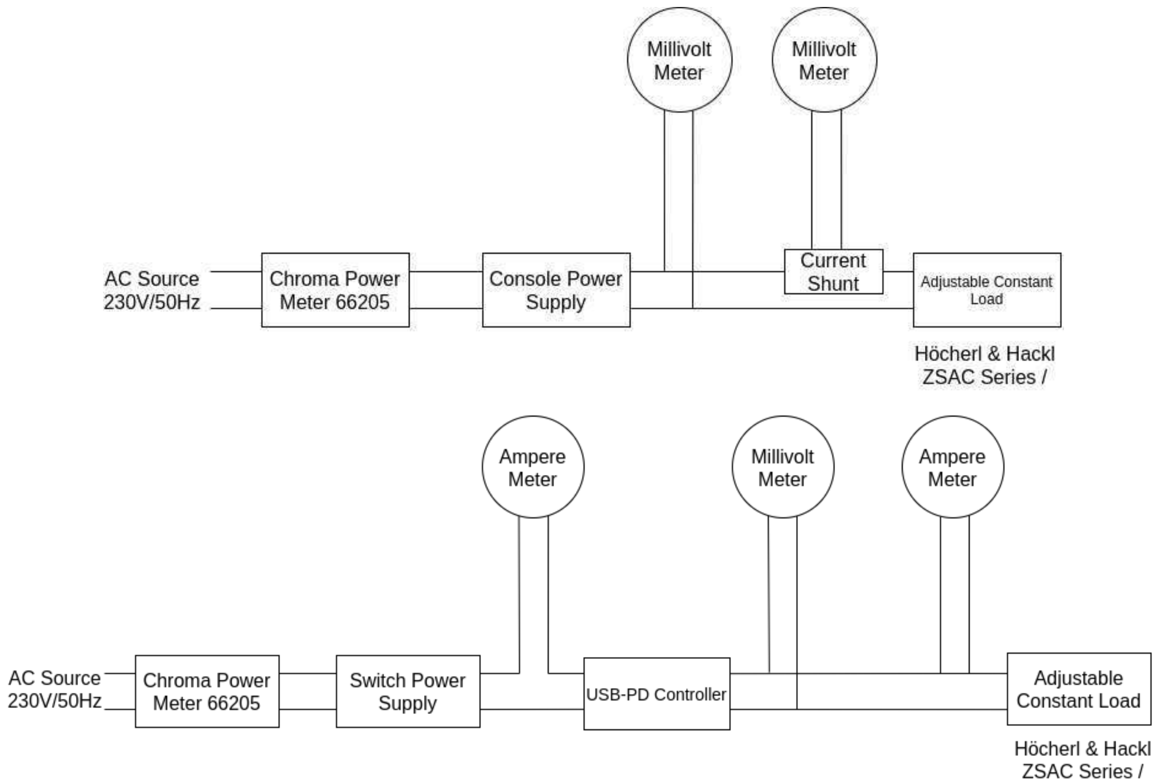


Figure 4.12: Setup for measuring the consoles. The upper setup is for the stationary consoles, the lower for the Nintendo Switch (Necessary due to the power delivery supply, which needs a configuration link while in use. [16])

Figure 4.13: Setup in the lab. The power supply is located at the left, the adjustable load at the right, meters and other measurement instrumentation in the middle. [WLG+19]

According to the work of [Kar20], there are interesting points in the power consumption range. Those points represent different modes of operation. There are power-off, different rest modes (also with or without enabled USB), navigation mode, streaming/watching movies (in different resolutions), and the largest power draw gaming. If the console's power supplies were ideally designed, they would have the best efficiencies at these points, respectively areas.

Table 4.4: Power consumption (30 min measurements) in different modes in order to correlate the efficiencies to those of interest [Kar20]. Low power modes are the rest modes for the PS4 models and instant on modes for the Xbox One models

Mode	Xbox One S	Xbox One X	PS4 Pro	PS4 Slim	Switch
Full Shutdown	0,33 W	0,29 W	0,25 W	0,24 W	0,35 W
Navigation min	25,48 W	44,27 W	56,20 W	43,41 W	5,02 W
Navigation max	30,26 W	50,94 W	65,59 W	44,07 W	5,06 W
Low Power min	0,34 W	0,29 W	0,95 W	1,00 W	3,19 W
Low Power max	9,37 W	17,56 W	9,05 W	8,20 W	13,85 W
Low Power + Update	16.91 W	40.76 W	52,69 W	41,55 W	-
Media/Streaming min	23,12 W	43,11 W	49,88 W	42,41 W	8,10 W
Media/Streaming max	46,57 W	70,62 W	88,85 W	49,61 W	8,10 W
Active Gaming min	55,60 W	123,77 W	106,56 W	64,38 W	9,1 W
Active Gaming max	75,18 W	171,84 W	165,20 W	82,75 W	16,6 W

Measurement Procedure

In order to get reliable values from the measurement, a specific measurement procedure ensures correct data. Several steps make sure that the power supplies are in a known condition. These include

1. Connect the PoS to measurement equipment and the AC supply.
2. Wait for 30 minutes to warm up the PoS.
3. Set the desired load at the adjustable current load.
4. Wait another ten minutes to let the PoS settle.
5. Start the measurement and measure for five consecutive minutes.
6. Stop the measurement.
7. Calculate the average over the values from the five-minute measurement.
8. Continue to measure other interesting points by following steps 3 to 7 again.

4.2.2 Xbox One S and X

The Xbox One X and S both have a power supply with a single voltage output design but different topologies (see Section 4.1.2). Therefore the 12 V output has to be active all the time. Nevertheless, both supplies establish to achieve low active values for the power-off state. Even for loads under 10 % of the maximum power, the PoS have reasonably high efficiencies.

The Xbox One S consumes the least amount of power overall compared with the other stationary consoles. Gaming is around 55 W to 75 W, which is about 40 % to 60 % of the maximum load of the PoS and the region with the highest efficiency. Navigation is from 25 W to 30 W, where the efficiency is also very high at values close to 90 %. For media of streaming, the range is from 23 W to 47 W, also in a high-efficiency region. If the console is in low power mode, the efficiency goes down rapidly, but it is not that big of an issue due to the low consumption.

Table 4.5: Efficiency measurements XBox One S. Rows in orange are mainly used by the different modes of the console

Load [%]	P_{in}[W]	I_o [A]	V_o [V]	P_o [W]	Eff[%]	PF	V_{o_acc} [%]	I_{o_acc} [%]	P_{in_acc} [%]
0	0,2	0,00	12,00	0,00	0,00	0,00	0,13	-	0,48
5	6,9	0,500	12,00	6,00	86,96	0,44	0,13	0,50	0,14
10	13,6	1,000	12,00	12,00	88,24	0,50	0,13	0,40	0,16
20	26,8	2,000	12,00	24,00	89,55	0,56	0,13	0,35	0,13
25	33,6	2,500	12,00	30,00	89,29	0,57	0,13	0,34	0,19
30	40,2	3,000	12,00	36,00	89,55	0,57	0,13	0,33	0,17
40	53,2	4,000	11,99	47,96	90,15	0,56	0,13	0,32	0,16
50	66,4	5,00	11,99	59,95	90,29	0,92	0,13	0,50	0,15
60	81,5	6,00	11,99	71,94	88,27	0,93	0,13	0,47	0,14
70	94,6	7,00	11,99	83,93	88,72	0,93	0,13	0,44	0,13
75	101,2	7,50	11,98	89,85	88,78	0,92	0,13	0,43	0,14
80	107,8	8,00	11,98	95,84	88,91	0,93	0,13	0,42	0,14
90	121	9,00	11,98	107,82	89,11	0,93	0,13	0,41	0,14
100	134,6	10,00	11,97	119,7	88,93	0,94	0,13	0,40	0,13
110	148,1	11,00	11,97	131,67	88,91	0,94	0,13	0,39	0,13

The Xbox One X has higher CPU and GPU power and, therefore, higher power consumption in the different modes. For gaming, which is between 124 W and 172 W, the efficiency is over 93 %. This corresponds to the range with the highest efficiency of the power supply. For navigation, which ranges from 44 W to 51 W, the efficiency is still above 91 %. Consuming media or streams puts the power consumption between 43 W and 71 W, having similar efficiency values as the navigational mode. Due to the higher range of the power supply than the Xbox One S the efficiency with 80 % and lower at very low loads is inferior to the One S PoS.

Table 4.6: Efficiency measurements Xbox One X. Rows in orange are mainly used by the different modes of the console

Load [%]	P_{in}[W]	I_o [A]	V_o [V]	P_o [W]	Eff[%]	PF	V_{o_acc} [%]	I_{o_acc} [%]	P_{in_acc} [%]
0	0,167	0,00	12,04	0,00	0,00	0,00	0,13		0,55
1,25	4,0	0,255	12,04	3,07	76,83	0,20	0,13	0,69	0,18
2,5	8,4	0,511	12,04	6,15	73,17	0,49	0,13	0,50	0,19
5	15,3	1,021	12,04	12,29	80,35	0,66	0,13	0,40	0,15
10	28,2	2,042	12,03	24,57	87,11	0,77	0,13	0,35	0,21
20	53,9	4,084	12,02	49,09	91,08	0,86	0,13	0,32	0,16
25	66,9	5,11	12,02	61,36	91,72	0,89	0,13	0,50	0,14
30	80,0	6,13	12,02	73,63	92,04	0,90	0,13	0,46	0,14
40	105,2	8,17	12,01	98,10	93,25	0,92	0,13	0,42	0,14
50	131,3	10,21	12,00	122,52	93,31	0,93	0,13	0,40	0,13
60	157,3	12,25	12,00	147,02	93,47	0,94	0,13	0,38	0,15
70	183,5	14,29	11,99	171,39	93,40	0,94	0,13	0,37	0,14
75	196,5	15,32	11,99	183,63	93,45	0,94	0,13	0,37	0,14
80	209,6	16,34	11,99	195,87	93,45	0,94	0,13	0,36	0,14
90	236,4	18,38	11,98	220,17	93,13	0,95	0,13	0,35	0,13
100	263,2	20,42	11,97	244,43	92,87	0,95	0,13	0,35	0,21
110	290,6	22,46	11,97	268,87	92,52	0,96	0,13	0,34	0,20

4.2.3 PS4 Pro and Slim

The PS4 Pro and Slim both have PoS with two outputs. One with a 5 V output designed for low power and standby and another with 12 V output for high power output designed for gaming, streaming, navigation, and other modes with higher power consumption. The 12 V output is turned off when the console is in low power mode and becomes active when it is turned on.

The PS4 Slim is the model with less power, similar to the Xbox One S. It consumes between 43 W and 44 W in navigation mode with an efficiency of 91 % and higher. Gaming is mainly in the region of 64 W to 83 W and an efficiency of 90 %. In streaming and media consumption mode, the power consumption is between 42 W and 50 W having an efficiency of 91 % and more. For the low power modes, only the 5 V output is responsible for supplying power with efficiencies close to 80 % except for modes enabling USB output where the 12 V output is also active but less efficient in this region. There is no measured value for power consumption of less than 9 W at 12 V, but as the values for 5 % and 10 % load suggest, the efficiency is likely even lower.

Table 4.7: Efficiency Measurements PS4 Slim

Load 12V [%]	P_{in}[W]	I_o [A]	V_o [V]	P_o [W]	Eff [%]	PF	V_{o_acc} [%]	I_{o_acc} [%]	P_{in_acc} [%]
0	1,41	0,000	11,91	0,00	0,00	0,00	0,13	-	0,15
5	9,70	0,650	11,91	7,74	79,81	0,31	0,13	0,45	0,18
10	18,0	1,300	11,91	15,48	86,02	0,48	0,13	0,38	0,14
20	33,7	2,600	11,91	30,97	91,89	0,62	0,13	0,34	0,19
25	42,4	3,250	11,91	38,71	91,29	0,66	0,13	0,33	0,17
30	50,6	3,900	11,91	46,45	91,80	0,70	0,13	0,33	0,16
40	68,6	5,20	11,9	61,88	90,20	0,76	0,13	0,49	0,14
50	85,1	6,50	11,91	77,42	90,97	0,80	0,13	0,45	0,14
60	101,7	7,80	11,9	92,82	91,27	0,83	0,13	0,43	0,13
70	118,3	9,10	11,9	108,29	91,54	0,85	0,13	0,41	0,14
75	126,6	9,75	11,9	116,03	91,65	0,86	0,13	0,40	0,14
80	135,8	10,40	11,9	123,76	91,13	0,87	0,13	0,40	0,13
90	152,6	11,70	11,9	139,23	91,24	0,89	0,13	0,39	0,15
100	169,5	13,00	11,9	154,70	91,27	0,90	0,13	0,38	0,14
110	186,7	14,30	11,9	170,17	91,15	0,91	0,13	0,37	0,14

Load 5V [%]	P_{in}[W]	I_o [A]	V_o [V]	P_o [W]	Eff [%]	PF	V_{o_acc} [%]	I_{o_acc} [%]	P_{in_acc} [%]
0	0,058	0,000	4,81	0,00	0,00	0,00	0,26	-	1,39
10	1,065	0,150	4,81	0,72	67,75	0,04	0,26	0,23	0,17
20	1,933	0,299	4,81	1,44	74,41	0,08	0,26	0,22	0,14
25	2,416	0,375	4,80	1,80	74,51	0,10	0,26	0,21	0,22
30	2,785	0,450	4,80	2,16	77,55	0,11	0,26	0,52	0,21
40	3,568	0,600	4,80	2,88	80,72	0,14	0,26	0,47	0,18
50	4,476	0,750	4,80	3,60	80,44	0,17	0,26	0,43	0,17
60	5,350	0,900	4,80	4,32	80,75	0,19	0,26	0,41	0,16
70	6,110	1,050	4,80	5,04	82,49	0,22	0,26	0,40	0,15
75	6,560	1,125	4,80	5,40	82,31	0,24	0,26	0,39	0,15
80	7,106	1,200	4,80	5,76	81,06	0,25	0,26	0,38	0,14
90	7,877	1,350	4,80	6,48	82,27	0,27	0,26	0,37	0,14
100	8,850	1,500	4,80	7,20	81,36	0,30	0,26	0,37	0,13
110	9,745	1,650	4,79	7,90	81,10	0,32	0,26	0,36	0,13

The PS4 Pro is the performance model with higher consumption values compared to the PS4 Slim. For the navigation mode, the consumption is between 56 W and 66 W, with an efficiency of about 92 %. For gaming at 107 W to 165 W, the efficiency is 91 % and higher. Streaming and media consumption has an efficiency of around 92 % at 50 W to 89 W. Like the Slim version, the Pro can also power the USB port while in a low power mode with the 12 V output active. In the case of the Pro model, the efficiency of the 5 V output is even higher, especially at very low loads, decreasing the consumption in low power modes significantly.

Table 4.8: Efficiency measurements PS4 Pro

Load 12V [%]	P_{in}[W]	I_o [A]	V_o [V]	P_o [W]	Eff [%]	PF	V_{o_acc} [%]	I_{o_acc} [%]	P_{in_acc} [%]
0	1,41	0,000	11,92	0	0,00	0,05	0,13	0,00	0,15
5	16,6	1,180	11,91	14,05	84,66	0,36	0,13	0,38	0,10
10	31,1	2,350	11,91	27,99	90,00	0,53	0,13	0,34	0,12
20	60,4	4,701	11,91	55,99	92,70	0,66	0,13	0,32	0,15
25	75,4	5,88	11,9	69,97	92,80	0,70	0,13	0,32	0,14
30	92,0	7,05	11,9	83,90	91,19	0,73	0,13	0,31	0,13
40	122,9	9,40	11,9	111,86	91,02	0,77	0,13	0,41	0,12
50	152,3	11,75	11,89	139,71	91,73	0,81	0,13	0,39	0,12
60	181,8	14,10	11,89	167,65	92,22	0,84	0,13	0,37	0,12
70	211,8	16,45	11,88	195,43	92,27	0,86	0,13	0,36	0,12
75	226,9	17,63	11,88	209,44	92,31	0,88	0,13	0,36	0,12
80	241,8	18,80	11,88	223,34	92,37	0,88	0,13	0,35	0,12
90	271,8	21,15	11,87	251,05	92,37	0,90	0,13	0,35	0,13
100	302,6	23,50	11,86	278,71	92,11	0,91	0,13	0,34	0,12
110	334,0	25,85	11,85	306,32	91,71	0,92	0,13	0,34	0,12

Load 5V [%]	P_{in}[W]	I_o [A]	V_o [V]	P_o [W]	Eff [%]	PF	V_{o_acc} [%]	I_{o_acc} [%]	P_{in_acc} [%]
0	0,0528	0,0000	4,80	0,00	0,00	0,00	0,26	0,00	1,52
10	0,9137	0,1498	4,80	0,72	78,70	0,03	0,26	0,23	0,18
20	1,815	0,2996	4,80	1,44	79,24	0,05	0,26	0,22	0,14
25	2,224	0,3755	4,80	1,80	81,04	0,06	0,26	0,21	0,13
30	2,686	0,452	4,80	2,17	80,77	0,08	0,26	0,52	0,21
40	3,518	0,601	4,80	2,88	82,00	0,10	0,26	0,47	0,19
50	4,386	0,750	4,80	3,60	82,09	0,12	0,26	0,43	0,17
60	5,216	0,901	4,80	4,32	82,91	0,14	0,26	0,41	0,16
70	5,998	1,050	4,80	5,04	84,03	0,16	0,26	0,40	0,15
75	6,495	1,124	4,80	5,40	83,07	0,17	0,26	0,39	0,15
80	6,914	1,201	4,80	5,76	83,38	0,18	0,26	0,38	0,14
90	7,701	1,350	4,80	6,48	84,15	0,20	0,26	0,37	0,14
100	8,628	1,501	4,80	7,20	83,51	0,23	0,26	0,37	0,13
110	9,498	1,650	4,80	7,92	83,38	0,24	0,26	0,36	0,13

4.2.4 Nintendo Switch

The Nintendo Switch provides an external power supply. The PoS has a USB-C connector for the console or the docking station. It provides different voltages via the USB power delivery standard. The standard output voltage is 5 V, while the Nintendo Switch uses 15 V as a supply voltage.

Due to low values of power consumption, efficiency plays a lesser role in this console. Interesting to note is that the low power modes consume more power than the stationary consoles with an efficiency of around 79 %. For Gaming, depending on whether a controller is connected and charging or not, the consumption is between 9 W and 17 W. The efficiency is 86 % at the lower load rising to 88 % at the higher load. Media consumption has a power consumption of 8 W with around 85 % efficiency.

Table 4.9: Efficiency measurements Nintendo Switch

Load 5V [%]	$\mathbf{P_{in}}$[W]	$\mathbf{I_o}$ [A]	$\mathbf{V_o}$ [V]	$\mathbf{P_o}$ [W]	**Eff** [%]	**PF**	$\mathbf{V_{o\_acc}}$ [%]	$\mathbf{I_{o\_acc}}$ [%]	$\mathbf{P_{in\_acc}}$ [%]
0	0,1157	0	5,23	0	0,00	0,03	0,24	0	0,75
5	0,2373	0,0000	5,23	0,00	0,00	0,07	0,24	0	0,42
10	1,207	0,1496	5,22	0,78	64,87	0,26	0,24	0,23	0,16
20	2,159	0,2995	5,21	1,56	72,39	0,34	0,24	0,22	0,13
25	2,626	0,3753	5,20	1,95	74,26	0,36	0,24	0,21	0,21
30	3,080	0,451	5,20	2,35	75,97	0,34	0,24	0,52	0,20
40	3,975	0,601	5,19	3,12	78,34	0,40	0,24	0,47	0,18
50	4,814	0,750	5,18	3,89	80,70	0,42	0,24	0,43	0,16
60	5,780	0,900	5,17	4,65	80,50	0,44	0,24	0,41	0,15
70	6,695	1,051	5,16	5,42	80,93	0,45	0,24	0,40	0,14
75	7,051	1,125	5,15	5,79	82,17	0,46	0,24	0,39	0,14
80	7,550	1,200	5,15	6,18	81,85	0,47	0,24	0,38	0,14
90	8,531	1,350	5,14	6,94	81,34	0,50	0,24	0,37	0,14
100	9,479	1,500	5,13	7,70	81,18	0,51	0,24	0,37	0,13
110	10,418	1,650	5,12	8,45	81,09	0,52	0,25	0,36	0,13

Load 15V [%]	$\mathbf{P_{in}}$[W]	$\mathbf{I_o}$ [A]	$\mathbf{V_o}$ [V]	$\mathbf{P_o}$ [W]	**Eff** [%]	**PF**	$\mathbf{V_{o\_acc}}$ [%]	$\mathbf{I_{o\_acc}}$ [%]	$\mathbf{P_{in\_acc}}$ [%]
0	0,4513	0,000	14,97	0,00	0,00	0,13	0,12	0	0,27
10	4,869	0,256	14,98	3,83	78,73	0,43	0,12	0,22	0,16
20	9,081	0,520	14,98	7,79	85,78	0,49	0,12	0,49	0,13
25	11,24	0,433	14,98	9,74	86,63	0,51	0,12	0,45	0,17
30	13,38	0,780	14,99	11,69	87,39	0,53	0,12	0,43	0,16
40	17,72	1,040	15,00	15,60	88,05	0,54	0,12	0,40	0,14
50	22,08	1,300	15,00	19,50	88,33	0,53	0,12	0,38	0,13
60	26,40	1,560	15,01	23,42	88,71	0,53	0,12	0,36	0,21
70	30,68	1,820	15,02	27,34	89,10	0,51	0,12	0,35	0,20
75	32,80	0,498	15,02	29,29	89,30	0,50	0,12	0,35	0,19
80	34,96	2,080	15,03	31,26	89,43	0,50	0,12	0,35	0,19
90	39,44	2,340	15,03	35,17	89,18	0,51	0,12	0,34	0,18
100	44,09	2,600	15,03	39,08	88,63	0,51	0,12	0,34	0,17
110	48,37	2,860	15,04	43,01	88,93	0,52	0,12	0,33	0,16

5 Thermal Analysis

Analyzing the thermal behavior of electronic devices is rather difficult due to several constraints. The thermal performance depends highly on the operating conditions. Most of the time, it is necessary to open the device in order to get to the crucial parts of the design like the power components, because those are the components that tend to break if they get too hot. Unfortunately, opening the device changes the way the cooling system works. For example, a fan that is usually blowing surrounding air from outside the device may not be able to do that sufficiently because of a missing case. Another example of the inverse effect would be a component that is generally in a very confined space without enough freshly circulated air being able to reach that point. Removing certain parts can improve the airflow, making it impossible to detect the fault. For analyzing the correct thermal behavior, the device should be kept in the original state, but it is difficult to look for issues without being able to look inside. Here another concept can help to overcome this issue. Opening the device beforehand, like in Chapter 4, helps to get a proper understanding of the function of specific areas. After analyzing the basic concept, taking infrared pictures with thermal cameras shows spots with higher temperatures. In many cases, these concern components with higher power consumption. The components with potential cooling problems should be a goal of investigation. This can be done by carefully putting the device back together. For monitoring these components under real conditions, small thermocouples need to be attached to these components with wires inserted through small openings in the device. Afterward, the device can be put back into the original condition. After turning the devices back on, different load scenarios should reveal potentially optimizable behavior.

5.1 Thermal Measurement Basics

There are many different means to measure temperature. Only a few of those methods are relevant and provide accurate results for console measurements. In this section, those methods are presented, and the physical background is explained. In [Bla04], an overview for different measurement techniques is given upon which the decision is based partly.

5.1.1 Thermal Conduction Basics

Heat generation is a big issue in electronic devices like consoles. Due to voltage conversion, semiconductor operation, and other component losses, parts of the electric energy convert into heat. Therefore, the devices need cooling, which is accomplished by different mechanisms such as convection, radiation, and conduction.

According to the second law of thermodynamics, conduction heat transfers from higher temperature locations to locations of lower temperature. Submicroscopic particles inside every material cause heat conduction. In the case of gases, the velocity and kinetic energy depend heavily on the temperature. Slower Particles colliding with faster particles transmit energy and, therefore, also heat. When slower particles collide with faster particles, the faster particles give part of their energy to the slower particles, noticeable as heat transport.

Electrically conductive materials use the means of lattice vibrations or phonons to transport heat. Errors in the lattice of the material can cause a reduction in heat transfer. In metals, electron gas is not only responsible for transporting electrical energy. They also transport heat in interdependence with the lattice.

This current is called the thermal flow rate ϕ and is measured in Watts as represented in Equation 5.1. The equation for heat conduction is the simplified form of a homogeneous solid body with two parallel surfaces. $\mathrm{T_{W1}}$ is the temperature of the hotter surface, and $\mathrm{T_{W2}}$ is the temperature of the colder surface. A is the cross-sectional area through which the heat flows, δ is the thickness of the plate, and λ is the specific coefficient for the conduction of heat for the specific material. A mandatory precondition is the timely constant temperature at all points [Fas05].

$$\phi = \lambda * \frac{A}{\delta}(T_{W1} - TW2), [\phi] = W \tag{5.1}$$

Therefore, a more general approach is the diffusion Equation 5.2, where ρ is the density $\mathrm{c_p}$ the specific heat capacity at constant pressure and λ_x λ_y λ_z are the heat conductivities in all spatial directions which are in general temperature and position dependent [Fas05].

$$\frac{\partial}{\partial x}(\lambda_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(\lambda_y \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(\lambda_z \frac{\partial T}{\partial z}) = \rho c_p \frac{\partial T}{\partial t} \tag{5.2}$$

In the case of isotropic and temperature-independent conduction, the equation can be reduced to the form in Equation 5.3. The factor a contains all the thermal properties of the material in Equation 5.4[Fas05].

$$a * (\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}) = \frac{\partial T}{\partial t} \tag{5.3}$$

$$a = \frac{\lambda}{\rho * c_p} \tag{5.4}$$

5.1.2 Heat Transfer

In electronic components and devices, the heat conduction in one material is of concern, but the transfer from one material to another is also essential (e.g., the transfer from a transistor to a heat sink). Air and other impurities caused by improper mounting of two bodies often worsen the transfer and inhibit the proper thermal energy flow. An electronic component improperly mounted on a heat sink can have a significant difference in temperature at the boundary surface. The following Equation 5.5 describes such a transfer. α stands for the heat transfer coefficient.

$$\phi = \alpha * A * \Delta T \tag{5.5}$$

With a known Area A the thermal resistance can be defined as follows in Equation 5.6. Important to know is that the transfer is dependent on pressure and decreases with higher pressure.

$$R_{th} = \frac{\Delta T}{\phi} = \frac{1}{\alpha * A}, [R_{th}] = \frac{K}{W} \tag{5.6}$$

The heat that originates from the inside of components has several ways to leave. On the one hand, through-hole components only have their pin connectors to transfer the heat and, on the other hand, surface mounted devices where the body connects to the PCB via solder pads. In both cases, a heat-sink improves heat transfer significantly [Rem00].

5.1.3 Temperature and Thermal Resistance of Electronic Components

A homogeneous material's thermal resistance can be defined based on its geometry and thermal conductance, similar to the electric resistance. The electric field can be seen as the thermal flux 5.7 and the electric current can be seen as the rate of thermal flow 5.8 [Rem00].

$$\mathbf{q} = -\lambda * grad(T) = \lambda * \frac{T_1 - T_2}{d} \tag{5.7}$$

$$\phi = \mathbf{q} * A = \lambda * \frac{T_1 - T_2}{d} * A = \lambda * \frac{A}{d} * (T_1 - T_2) \tag{5.8}$$

A comparison of Equation 5.6 with Equation 5.8 results in the thermal resistance of electronic components in Equation 5.9.

$$R_{th} = \frac{d}{\lambda * A} = \frac{T_1 - T_2}{\phi} \tag{5.9}$$

Essential for this definition is that the two surfaces' temperatures between which the thermal current ϕ is flowing have to be constant. If a transistor is considered the component, T1 could be the temperature inside at the junction, T2 could be the ambient temperature, and the thermal flow could be the electrical power P_{el}, resulting in the Equation 5.10. In the component in Figure 5.1, there is also another more relevant path available through the heat sink. In this case, the thermal resistance is a series connection of the resistance from junction to case, the case to heat-sink resistance, and at last heat sink to the ambiance (see Equation 5.11). Due to the much lower resistance in this path, most of the thermal flow takes this path. Therefore the second path can be neglected in case of adequately mounted heat-sinks or contact with the PCB.

$$R_{th,j-amb} = \frac{T_J - T_{amb}}{P_{el}} \tag{5.10}$$

$$R_{th,j-amb} = R_{th,JC} + R_{th,CS} + R_{th,CA} \tag{5.11}$$

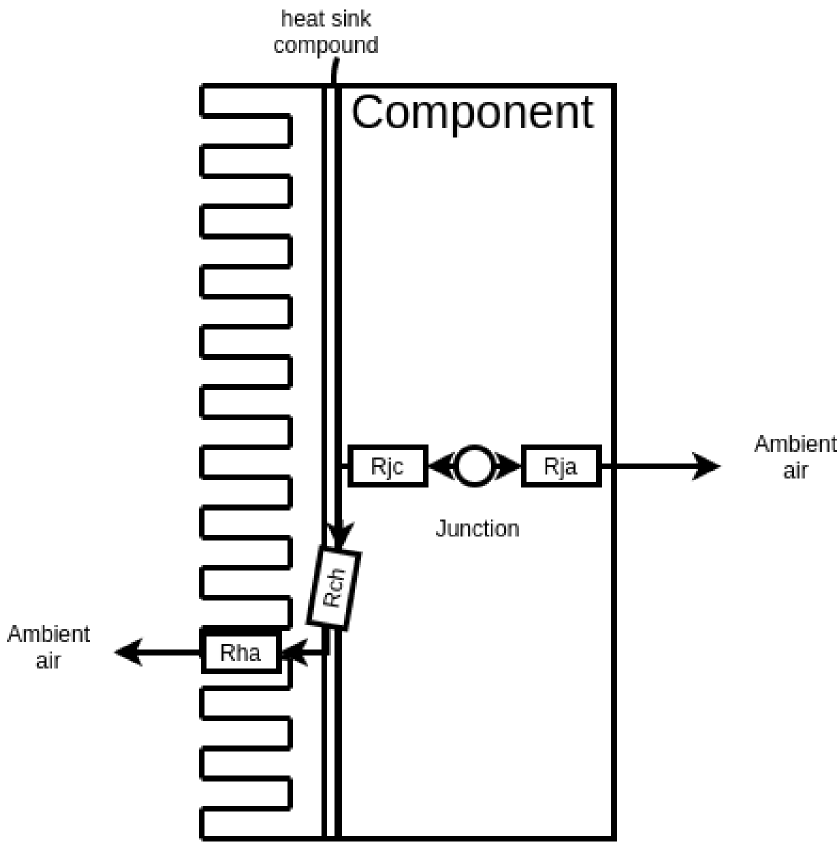


Figure 5.1: Two paths the thermal flow can take to leave the component on the basis of an electronic component mounted to a heat sink

5.1.4 Temperature Measurement Basics

There are a lot of different ways to measure temperature. One of the easiest is the analog thermometer in a room with a liquid that expands with higher temperatures like mercury. Although that works very well in rooms, it is not very well suited to measure an electronic component's temperature, even less if we want to measure in a small closed box. Therefore another technique is needed. One possibility to measure temperature with an electronic device is the Seebeck effect used for thermocouple elements. Another option to measure the temperature without contact is thermography, where the infrared radiation of a solid body is measured and transformed into the body's temperature.

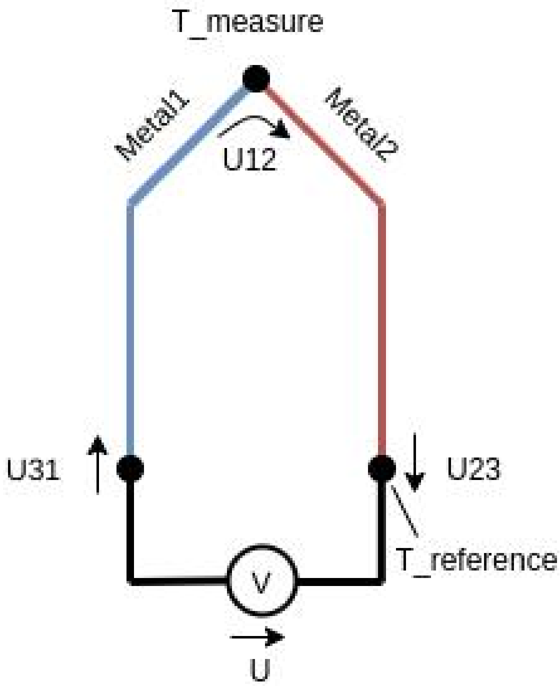


Figure 5.2: Measuring temperature with a thermocouple element based on the Seebeck effect [5]

The Seebeck effect phenomenon is based on the fact that electrons leave metals of the surface easier when the temperature is higher [Fas05]. Additionally, this phenomenon is dependent on the material. Two different metals connected create a voltage-dependent temperature. If we take the illustration in Figure 5.2, we can see that two different metals are connected at the measuring point, and this results in a voltage, dependent on the two coefficients k_{M1} and k_{M2} according to Equation 5.12. The voltage cannot be measured directly due to the third metal of the measuring equipment introducing two other contact voltages according to Equation 5.13. Therefore the sum of all voltages results in the term in Equation 5.14. If the temperature T_2 is known, the voltage is representative of the temperature at the measuring point.

$$U_{12} = (k_{M1} - k_{M2}) * T_1 \tag{5.12}$$

$$U_{23} = (k_{M2} - k_{M3}) * T_2, U_{31} = (k_{M3} - k_{M1}) * T_2 \tag{5.13}$$

$$U = U_{12} + U_{23} + U_{31} = (k_{M1} - k_{M2}) * (T_1 - T_2) \tag{5.14}$$

5.1.5 Thermography

Thermography is a method to determine the temperature of an object by measuring the emitted radiation. The radiation emitted is described at its simplest form by the Planck's radiation law in Equation 5.15. This form represents the radiation depending on the wavelength where λ is the wavelength in µm, T the absolute temperature, c the speed of light, k the Boltzmann constant, and h the Planck's constant.

$$I(\lambda) = \frac{2 * c_0^2 * h}{\lambda^5 * (e^{\frac{hc_0}{\lambda * k * T}} - 1)}, [I(\lambda)] = \frac{W}{m * m} \tag{5.15}$$

Due to practical reasons it is easier to use the radiation density q or hemispherical emissive power E which neglects the wavelength's dependence and results from integrating the spectral density over the spectral range.

$$E = \int_{\lambda=0}^{\lambda=\infty} I d\lambda \tag{5.16}$$

This relation is called the Boltzmann law. Unfortunately, both equations are only valid for solid black bodies. Therefore a correction factor has to be included in order to get a proper value. This emission factor is called emissivity with the symbol ϵ, which considers that different materials having the same surface temperature radiate at different intensities. Furthermore, it depends also on the condition of the surface. In Table 5.1, a few materials are listed that give an overview. Interesting to note is that the same material can have a broad range of emissivity due to the surface's condition. For example, a polished aluminum plate has a lower emissivity than a corroded aluminum plate [Rem00].

Table 5.1: Emissivity of different materials [Fli17, Chapter21:Emissivity tables],[OIA16], [SSZI04]

Material	Description	ϵ
3M type 32,88 super 33	vinyl electrical tape	$\sim$ 0,96
Aluminum	polished	0,04-0,06
Aluminum	heavily oxidized	0,2-0,3
Aluminum-dioxide (Al_2O_3)	from pure to activated powder	0,16-0,46
Glass pane	non coated	0,97
Gold	polished	0,02
Plastic	glass fiber laminated (e.g PCB)	0,91-0,94
Plastic	PVC polyvinyl-chloride	0,93-0,94
Plastic	polyurethane isolation board	0,29-0,55
Plastic	PET polyethylene terephthalate (capacitor sleeves)	0,81
Rubber	hard, soft , gray, rough	0,95
Silver	polished, pure	0,02-0,03
Skin	human	0,98
Special Coating	spray Paint	0,97
Water	ice and liquid	0,95-0,98

5.2 Component Lifetime

Component lifetime depends very much on the ambient conditions. For example, high temperatures lower the lifetime of many elements. Also, humidity can be an issue if the device is in an uncontrolled environment. Typically the humidity in a house is relatively constant, but the temperature is not due to several reasons. This is mainly a cause of the self-heating property of electronic devices. Another factor is air circulation that depends on the place of operation and placement or distance of the components in the device.

A typical issue in electronic devices is the lifetime of electrolytic capacitors as they are a chemical component, and the lifetime depends on the chemical reactants.

Arrhenius Law

The Arrhenius law is a well-known chemical equation for the correlation of chemical reaction and temperature. It states that the process of a chemical reaction is sped up upon the rise of temperature. For example, milk that is stored at higher temperatures goes bad earlier. As a rule of thumb, the chemical reaction rate rises by the factor of 2 for every 10 °C. The Equation 5.17 includes a factor A for the specific process, the activation energy E_A, R for the universal gas constant, and T for the absolute temperature.

$$k = Ae^{\frac{-E_A}{R*T}} \tag{5.17}$$

Semiconductor Reliability

The reliability of semiconductors is a complex topic, as it depends on many factors. After the production of a component, it is usually tested for proper function. If an issue is detected, the component is removed from the production line and is often analyzed. The rest of the components are usually operated at higher temperatures called a burn-in test to examine if they fail at higher stress conditions. This testing process should eliminate outliers in the production process that only fail at the limit of the specified operating boundaries. The failures in time usually provide a failure rate curve with the form of a bathtub [LB17]. In the beginning, the failure rate is rather high due to imperfect production. After a certain period, the rate falls to an acceptable level and continues to stay there until the end of life comes close, where more and more of the components start to fail, which is the second half of the bathtub. For a visual representation see Figure 5.3.

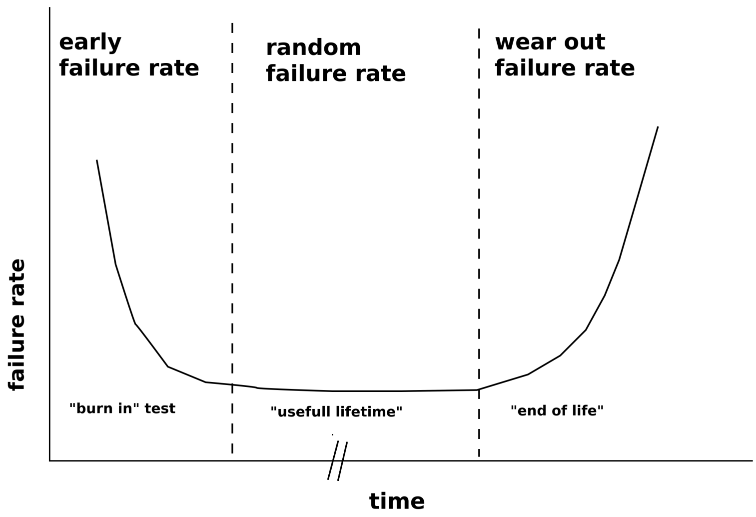


Figure 5.3: Bathtub curve for semiconductor reliability. Early failures are detected with a burn in test to lower operational failures. At the end of the product life the failure rate increases due to wear out failures.

For the time where the failure rate is the lowest, the product should be in operation. In this region, there are still some failures, but at an acceptable level. The most common defects that are known to damage components in this phase are hot carrier injection (HCI), time dependant dielectric breakdown (TDDB), and negative bias temperature instability (NBTI). An overview of relevant effects for failures can be found in [LS14]. In [QB06], acceleration factors for temperature and voltage-dependent failure are modeled for the three mentioned defects. They are based on the Arrhenius equation but introduce different activation energies and voltage accelerations coefficients for different operating conditions. Nevertheless, the effects are still dependent on temperature, but the temperature dependency depends on the operation's stress conditions. Therefore lower temperatures should improve reliability even though the effect is different as the standard Arrhenius equation would suggest.

Capacitor Lifetime

According to the manufacturer of electrolytic capacitors, a capacitor's lifetime can be modeled with the Arrhenius equation. The modified version of the equation for capacitors can be found at Equation 5.18. The estimated lifetime L is dependent on the specified lifetime L_0, the maximum category temperature T_{max} of the capacitor series, and the ambient temperature T_a. This equation is an excellent approximation for the critical range of the operating temperature of the capacitor. Under 60 °C and above 105 °C, the equations deviation cannot be neglected. An approximation for this equation is that the lifetime doubles with every 10 °C of temperature under the operating limit.

$$L = L_0 * 2^{\frac{T_{max}-T_a}{10}} \tag{5.18}$$

5.3 Thermal Measurements

The longevity of a console depends on a list of individual factors. This can be the cooling design, selecting the proper components (especially concerning degradation caused by higher temperatures), and the proper fabrication of the product. Another essential part is the ambiance factor. The consoles are sold to many different regions of the world, where very high or low temperatures are part of daily life.

For testing the thermal behavior and identify weak spots in the design, thermal measurements were conducted with the stationary consoles. Due to the Nintendo Switch's low power consumption and the more complicated process of opening the device without damage, this type of measurement was not conducted for the hybrid console. In a first step measuring the Xbox One S and the PS4 Slim gave a first impression and led to further steps for improving the second round measurements in which the Xbox One X and the PS4 Pro were measured.

Consoles are a closed design ready to use for the consumer. Therefore they are constructed safely in order for the consumer to use. Due to that, the electronics are encapsulated in a case that is not supposed to be opened.

In order to analyze the console thermally, it has to be taken apart to some extend. The plastic cases protecting the inner electronics have to be removed, including some screws fixing the device. Depending on the specific console, different parts can be found inside.

Parts of a console:

- Mainboard with APU, heat-sink, VRAM, and other integrated circuits
- Power supply in a separate case inside the main case
- Cooling devices like heat-sinks, shields, and fans
- Disk drive
- Hard disk drive
- Mechanical components for stability

After opening a device, the next step is to evaluate parts and components of interest. A big part of all of the stationary consoles is the power supply, and another the mainboard with several integrated circuits, APU and VRAM. Due to many electronic components in a console, the measurement has to be done part by part. Therefore at first, the PoS is taken apart and then the mainboard.

Structural analysis of the design reveals points of interest (POIs) where airflow is restricted, and the temperature could be higher than continuous operation allows. Additionally, taking thermal images while running the console open can help to find more POIs.

Running the console with the case open instead of close alters the usual conditions. Therefore it is not suitable to take the temperature readings from the thermal camera and make assumptions about longevity. Instead, it offers a starting point for further analysis.

For the measurements where the consoles operate close to real life, another type of temperature measurement is useful. Thermocouples attached to the previously identified spots (or components) can be left inside the console, and the cable can be guided through cooling vents in the case. This allows us to close the console and put it back to regular operation. With those sensors, it is possible to monitor the temperature for the whole time.

Apart from running the console with the attached sensors, further measurements help to confirm the results. This ensures that the consoles are inside the specifications.

Further measurements:

- Power consumption with a power meter
- Reference ambient air temperature
- Wind speed around the console with an anemometer

The setup for measuring the first round of consoles is shown in Figure 5.4. This shows the console positioned on a flat surface with the anemometer positioned next to it. Above the console, the thermal camera used in this round is mounted. The console is directly connected to the power meter for measuring power consumption.

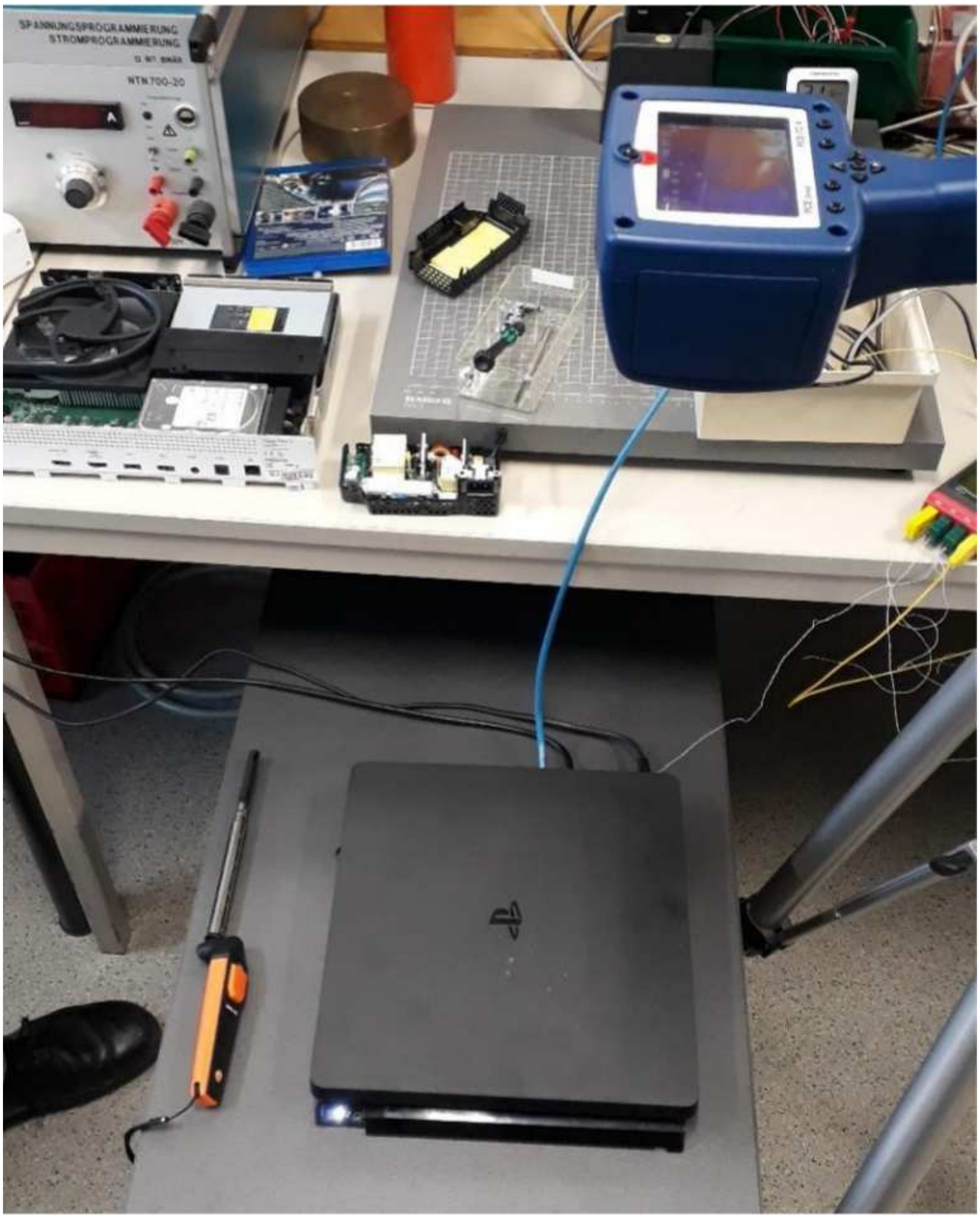


Figure 5.4: Setup for the thermal measurements with the infrared camera

5.3.1 Small Standard Models

In the first round of measurements, only the smaller standard version of the stationary consoles was analyzed.

5.3.1.1 PS4 Slim

The first measurements were taken with the PS4 Slim, also used in the power supply efficiency measurements. At first, an image was taken from the back with a metal cover used as a heat spreader shown in Figure 5.5. Apart from the openings for the air convection, there are no peaks in the temperature distribution. In the next step, the cover is removed, and again, a thermal image is made. This unveils the VRAMs that are placed close to the APU. Figure 5.7 with the corresponding temperature scale shows a peak temperature of about 84 °C. This temperature is very high as the maximum temperature of these VRAMs is only 95°C. Due to the missing heat-spreader, the temperature under real conditions should be lower. To further investigate if this could be a problem, measurements with the thermocouples should give more insight.

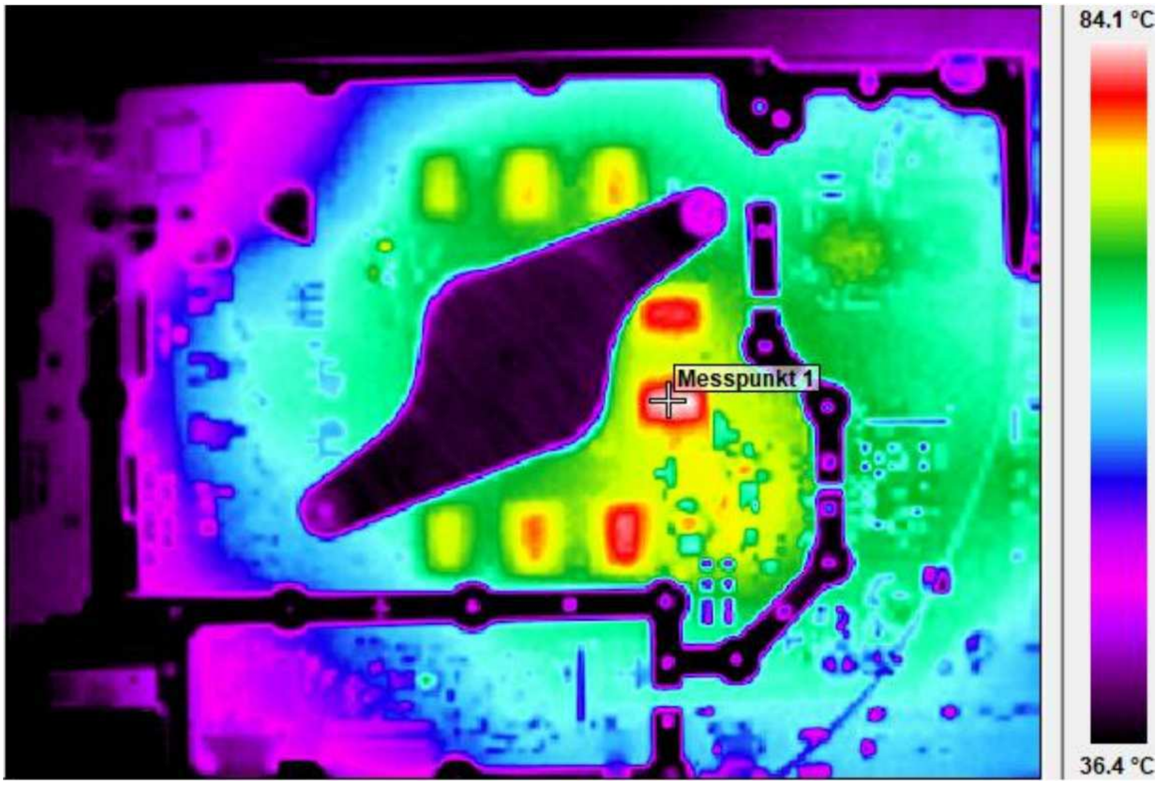


Figure 5.5: Thermal image of the PS4 Slim Mainboard with focus on the VRAM without heatshield

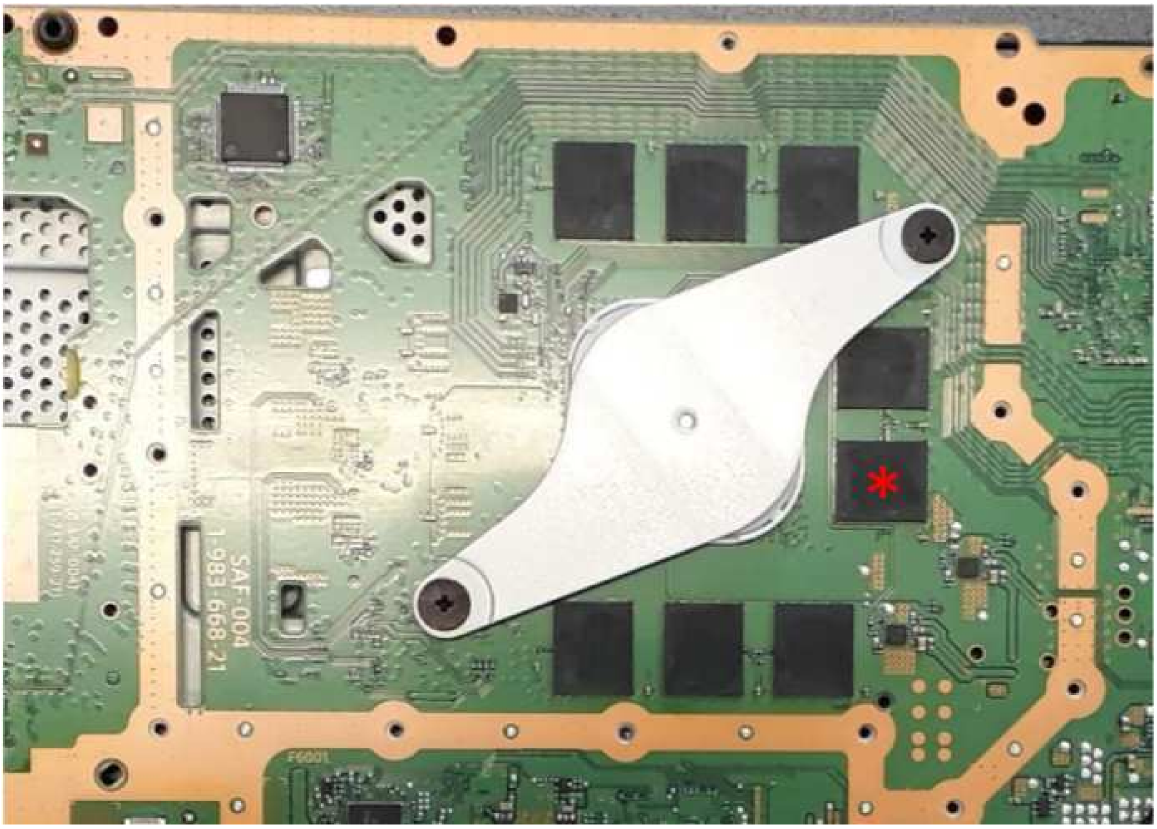


Figure 5.6: Image of the PS4 Slim Mainboard with focus on the VRAM

The thermal images' experiences help identify components for the single sensor measurements with a k-type thermocouple. The thermocouple is mounted on the VRAM marked in Figure 5.6. Afterward, the console is reassembled to restore normal working conditions. Table 5.2 shows the results of the temperature monitoring under different loads and scenarios.

While gaming, the temperature is the highest due to the higher power consumption and computing effort. Star Wars Battlefront 2 is used for the test, where the average power consumption is about 85,5 W. This lead to a temperature of 68 °C.

For testing the effectiveness of thermal pads for VRAMs, one measurement uses a thermal pad, and the other does not.

Finally, the console is tested when navigation through the main menu, which is a typical usage scenario when the console is waiting to be used. In this scenario, the VRAM was slightly cooler even though the power consumption is only slightly lower than before.

Mode	**Termperature**	**Average Power**	**Notes**
Game: Star Wars Bf 2	68 °C	85,5 W	Fully assembled console
Blu-Ray: Avatar	64 °C	47,9 W	Thermal pads attached
Blu-Ray: Avatar	71 °C	47,9 W	Thermal pads removed
Navigation	56 °C	43,6 W	Fully assembled console

Table 5.2: VRAM temperature monitoring for the PS4 Slim

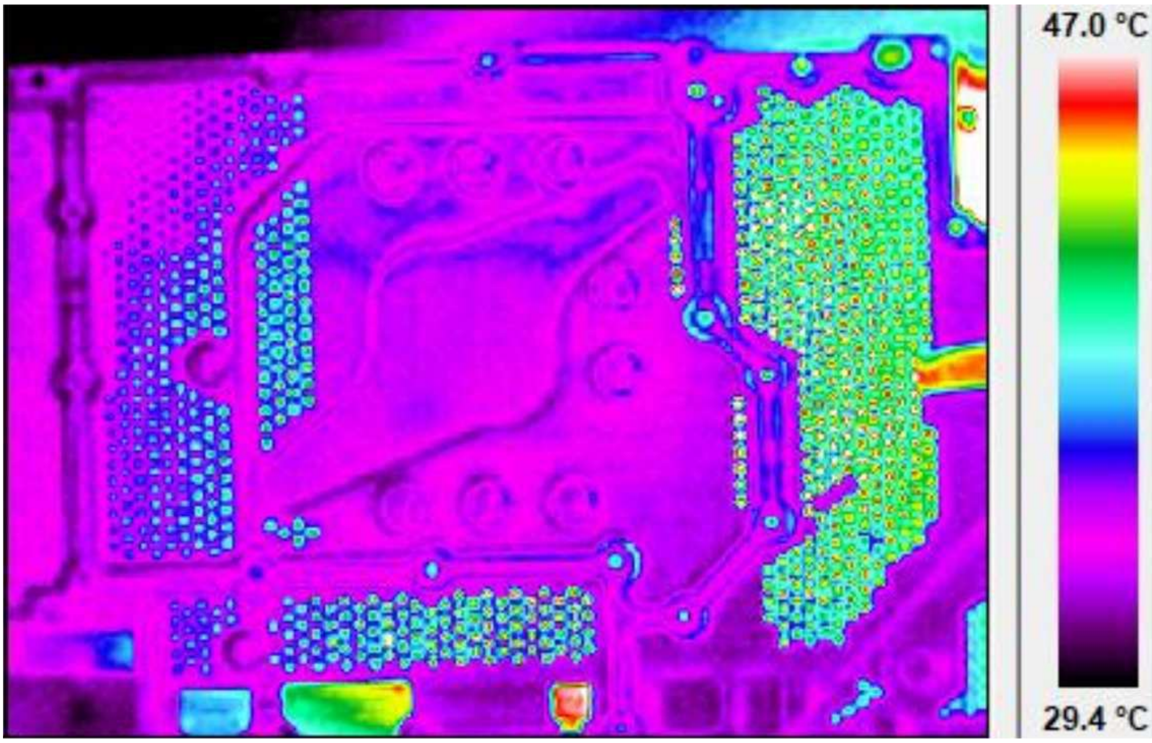


Figure 5.7: Thermal image of the PS4 Slim with focus on the VRAM with heatshield

PS4 Slim Power Supply

Similar to the measurements taken in the last part, the power supply of the PS4 Slim is tested. Thermal images and temperature monitoring are carried out.

A picture of the power supply in Figure 5.8 shows the main components of the power supply, whereas a few components are on the back. A quick look with the thermal camera shows nothing interesting at the back. On the top, there are the power semiconductors, the transducers, the rectifiers, capacitors, and more. After taking the first image with the thermal camera, a power Mosfet seemed to be the most interesting. The main capacitors are close to the Mosfet and due to the technology used for the capacitors susceptible to damage caused by higher temperatures. The rectifier also seemed to be at a higher temperature. In order to confirm this, the components were coated with a thermal compound. This thermal compound has an emission factor of 0,98 and ensures that the temperature reading is correct. The following measurement confirmed the previous assumption. Therefore these three points were selected for the temperature monitoring in the next step.

For temperature monitoring, the k-type thermocouples were used again. They were attached to the components, and the power supply was reassembled and put back into the console. For the test, a game was started. At the beginning of the test, the temperature rose to a peak of 81 °C at the transistor, 54 °C at the capacitor, and 68 °C at the rectifier, but after a couple of minutes, the temperature dropped again and settled to lower values of 65 °C at the transistor, 48 °C at the capacitor and 56 °C at the rectifier. An overview of the values can be found in Figure 5.3. The capacitor's proximity to the transistor did not lead to a high temperature and potentially shorter lifetime. The single fan design could explain the higher temperature at the beginning of the test. An assumption for that issue would be that the fan is controlled by the APUs temperature only, and at first, the temperature is not so high due to the large heat-sink. A second temperature sensor in the power supply that works as a second input could prevent this behavior.

Table 5.3: PS4 Slim power supply monitoring

Mode	**Part**	**Peak Temperature**	**Settled Temperature**
Gaming: Star Wars Bf 2	Transistor	81 °C	65 °C
Gaming: Star Wars Bf 2	Rectifier	54 °C	48 °C
Gaming: Star Wars Bf 2	Capacitor	68 °C	56 °C

Figure 5.8: Top view of the PS4 Slim Power Supply

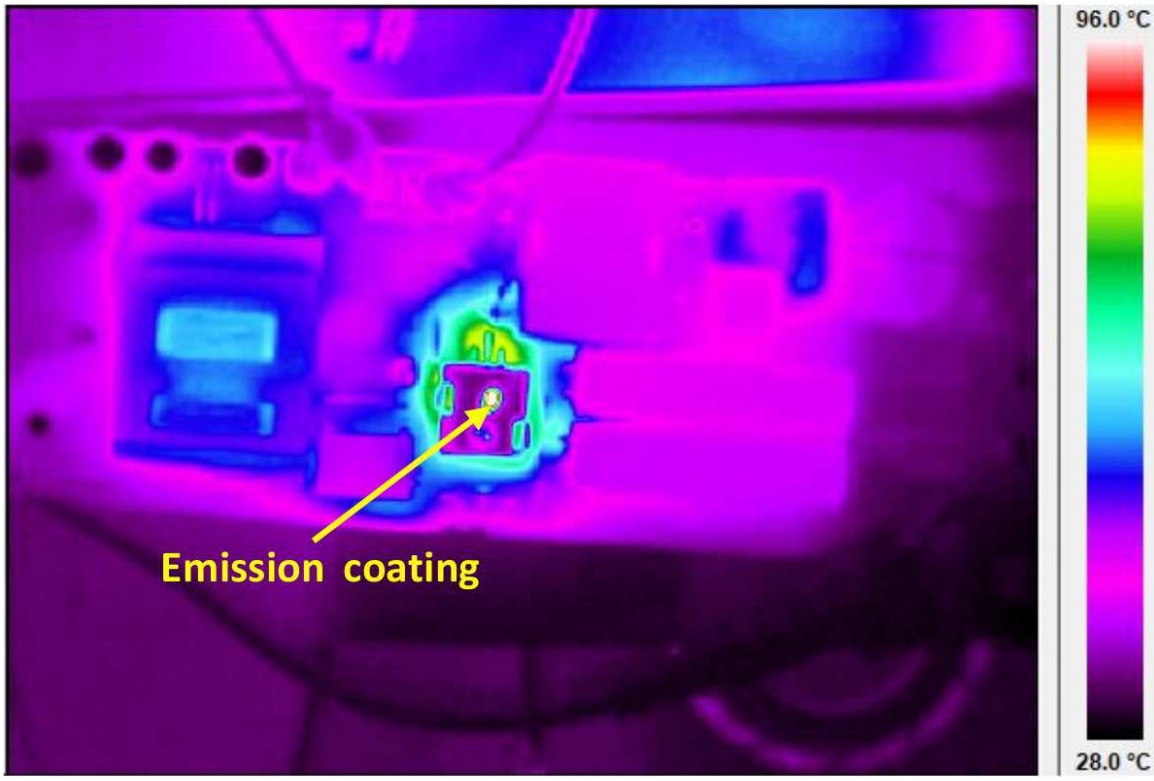


Figure 5.9: Thermal image of the PS4 Slim power supply top view

5.3.1.2 Xbox One S

In this section, the Xbox One S is tested similar to the PS4 Slim before. Again a thermal image is taken to investigate whether there are any hot spots. Afterward, these hot spots are probed with the temperature sensor and monitored for an extended period.

In Figure 5.10 the setup for this console is depicted. This time the camera is connected to a PC to see the images more clearly right away. Figure 5.12 shows the thermal image with the interesting points marked. The three points represent a VRAM (Messpunkt 3), the South Bridge (Messpunkt 1), and a Dual Mode Display Port to HDMI Retimer (Messpunkt 2).

After mounting the temperature sensors, the console was operated under different load scenarios with an open and closed console. Table 5.4 shows the results for the measurement.

Mode	South Bridge	DP to HDMI	VRAM	Power Consumption	Notes
Navigation	49 °C	39 °C	34 °C	30,17 W	open console
Blu-Ray: Avatar	46 °C	46 °C	40 °C	38,03 W	fully assembled
Gaming: Star Wars Bf 2	54 °C	46 °C	46 °C	72,48 W	open console
Gaming: Star Wars Bf 2	55 °C	55 °C	51 °C	73,36 W	fully assembled

Table 5.4: Temperature monitoring Xbox One S mainboard

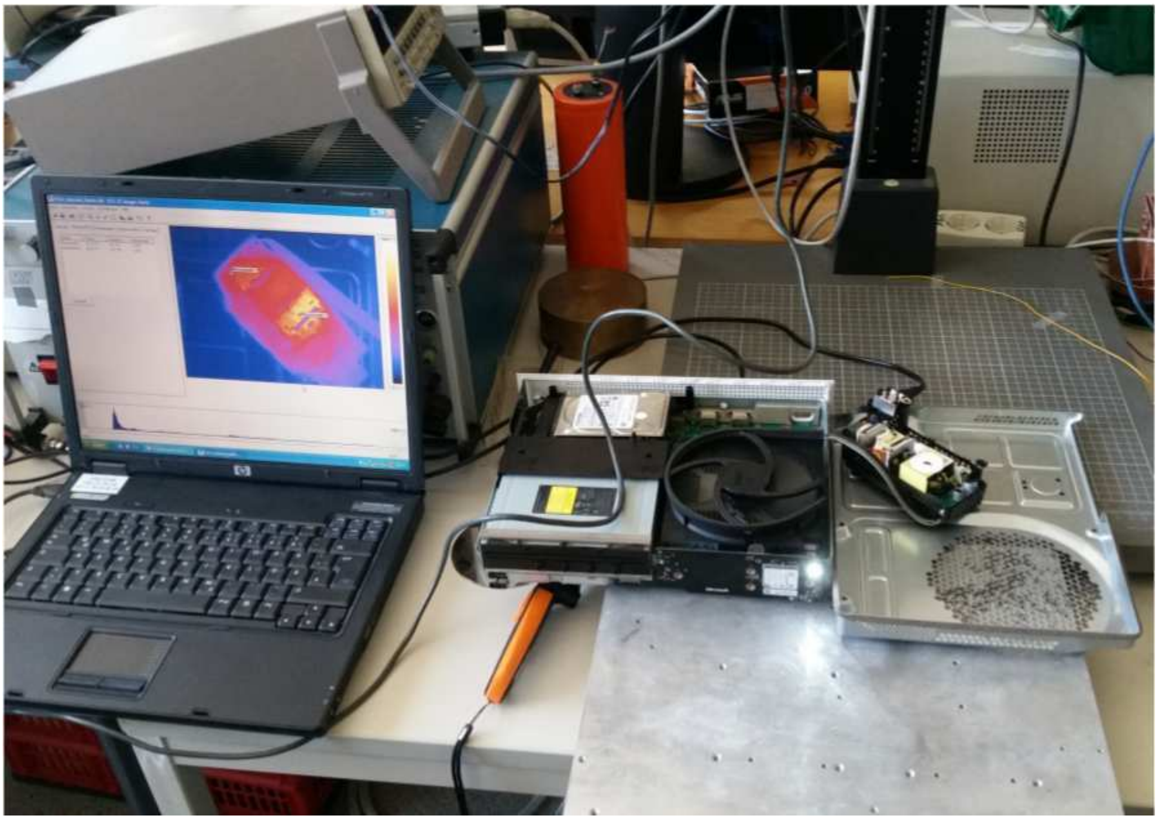


Figure 5.10: Setup for measuring the Xbox One S

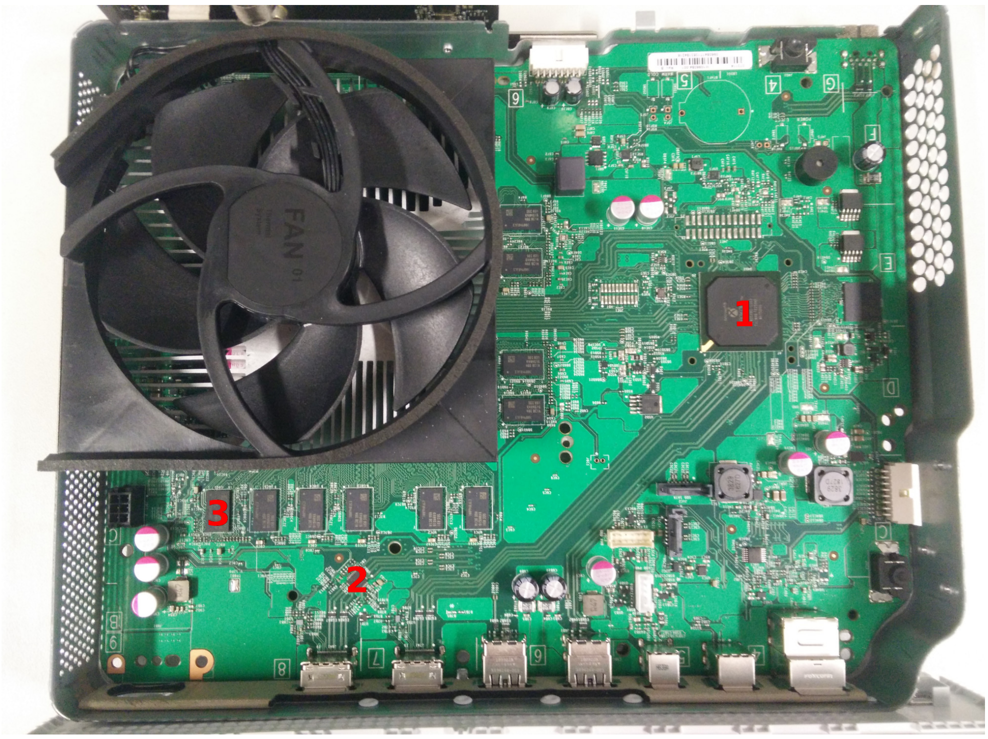


Figure 5.11: Top view of the Xbox One S mainboard with highlighted measuring points

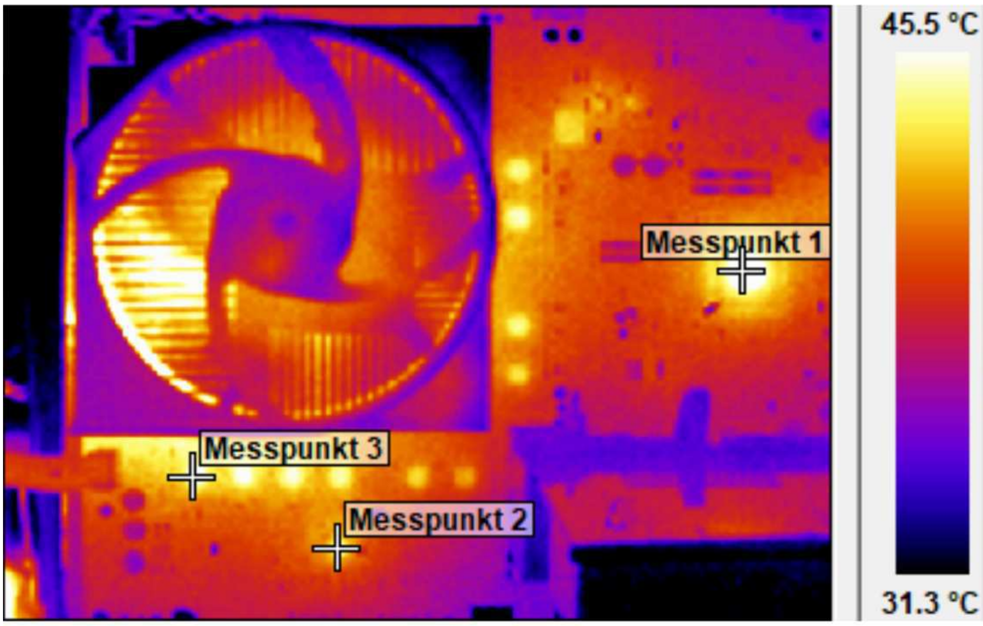


Figure 5.12: Thermal image of the Xbox One S mainboard

Xbox One S power supply

The power supply of the Xbox One S is separately enclosed. Opening the case exposes the main components. The thermal image shown in Figure 5.14 reveals three zones of interest. In Figure 5.13 these points can be identified better and correspond to a transistor heat sink (number 2), an electrolytic capacitor (number 3), and another capacitor (number 4).

Monitoring these points resulted in fairly low temperatures, except capacitor number 4 went up to 81 °C. The placement close to the border could be the reason, affecting the airflow. Also, there is no opening for the air at that position. Repositioning the capacitor or changing the form of the case could solve this issue. In Table 5.5 the maximum values for the monitoring can be found.

Mode	Transistor 2	Capacitor 3	Capacitor 4	Power Consumption	Notes
Navigation	47 °C	42 °C	45 °C	30,1 7W	open console
Blu-Ray: Avatar	44 °C	39 °C	48 °C	38,03 W	fully assembled
Gaming: Star Wars Bf 2	90 °C	63 °C	65 °C	72,33 W	open console
Gaming: Star Wars Bf 2	60 °C	49 °C	81 °C	73,51 W	fully assembled

Table 5.5: Temperature monitoring Xbox One S power supply

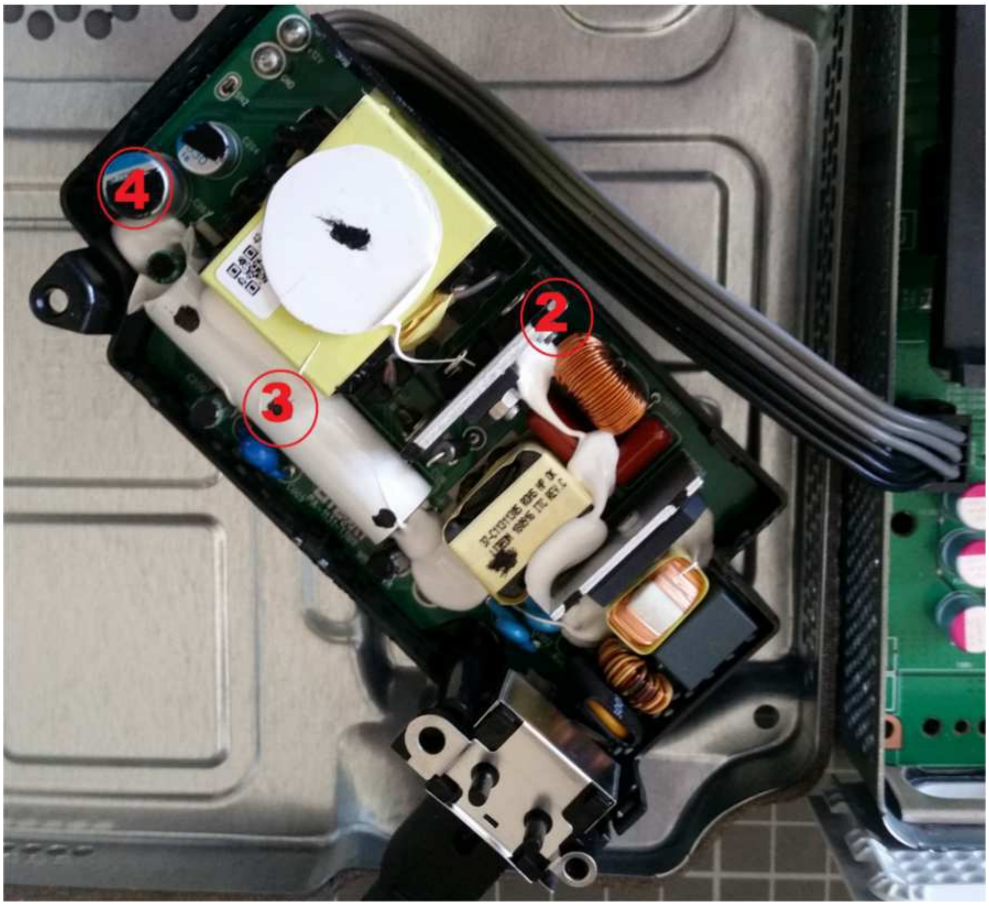


Figure 5.13: Top view of the Xbox One S power supply with highlighted measuring points

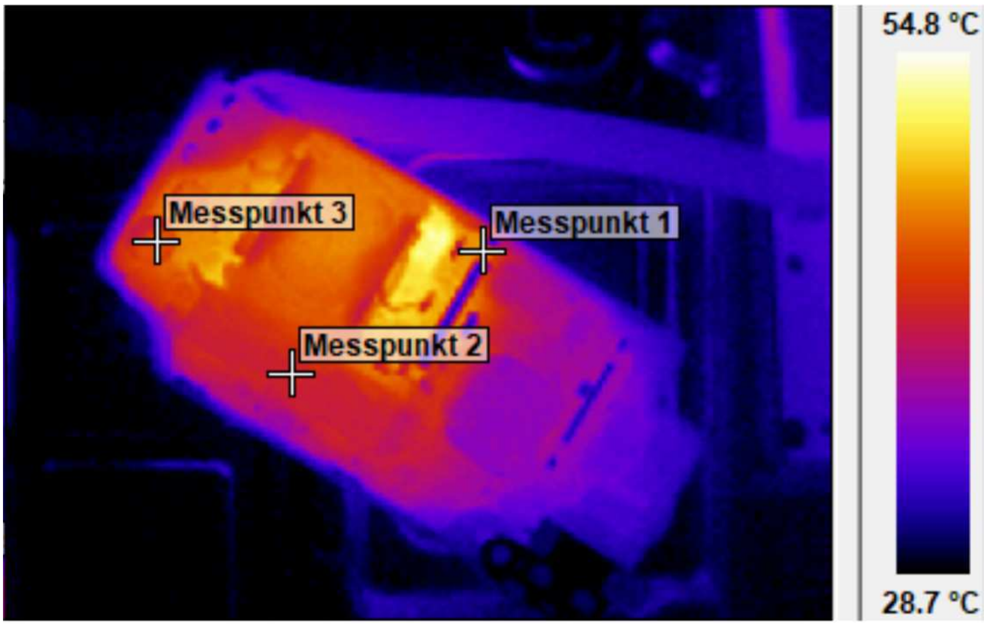


Figure 5.14: Thermal image of the Xbox One S power supply with highlighted measuring points

5.3.2 Performance Models

The second round of thermal measurements tests the performance models like the PS4 Slim and the Xbox One X. The differences to the first round are the use of more detailed imaging equipment and a temperature logger capable of monitoring eight channels and saving it directly to a PC.

Figure 5.15 shows the setup for the performance models on the basis of the PS4 Pro. The setup includes the thermal camera, a monitor for testing purposes, an anemometer and the temperature logger in the back.

Figure 5.15: Setup for measuring the PS4 Pro with the thermal camera adapted for PCBs

5.3.2.1 PS4 Pro

The design of the PS4 Pro is similar to the PS4 Slim. Differences are the higher power consumption and the larger form factor for better cooling. There is one fan in the console with an air intake from the top. The fan supplies the APU's heat-sink with fresh air, which flows into the power supply afterward, leaving the console at the back. Therefore the air temperature cooling the PoS is already warmed up. The left part of the power supply and the mainboard's backside do not have any substantial airflow.

Figure 5.16 shows the images from the thermal camera with the components of interest except the APU for reference. Some of the components are proprietary hardware without further information available concerning their function in the console.

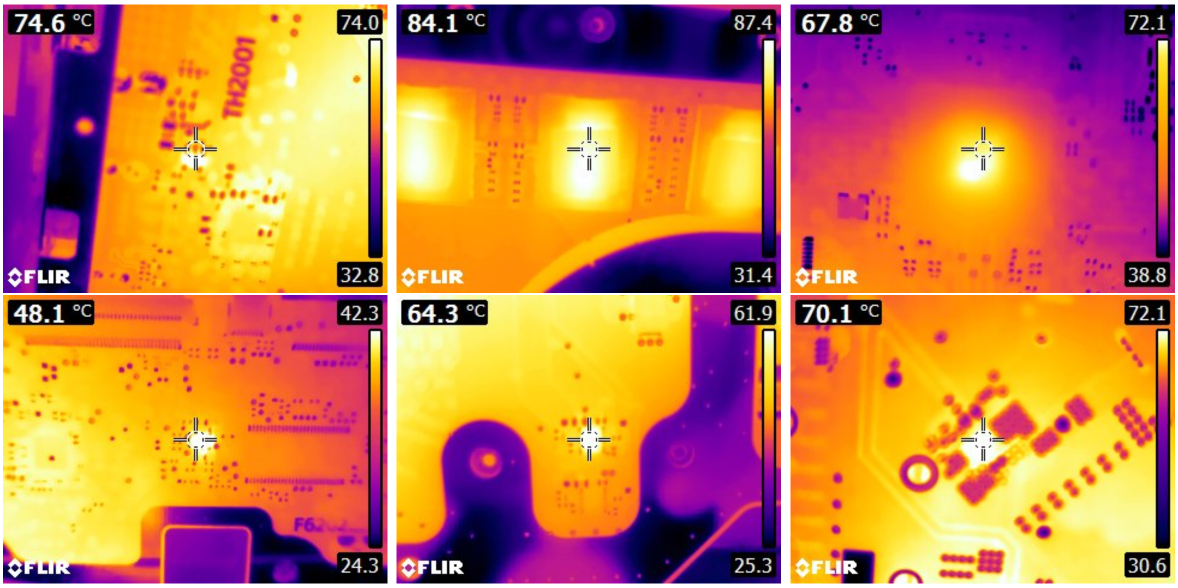


Figure 5.16: a) IC RH25H1 b) VRAM c) Southbridge c) IC 93RH4 d) IC D3528HG e) IC 8233736B0

Figure 5.17 shows the selected points for temperature monitoring directly on the mainboard overview. This includes two VRAMs used with and without a thermal pad, the APU backplate for reference, and the other ones representing proprietary integrated circuits.

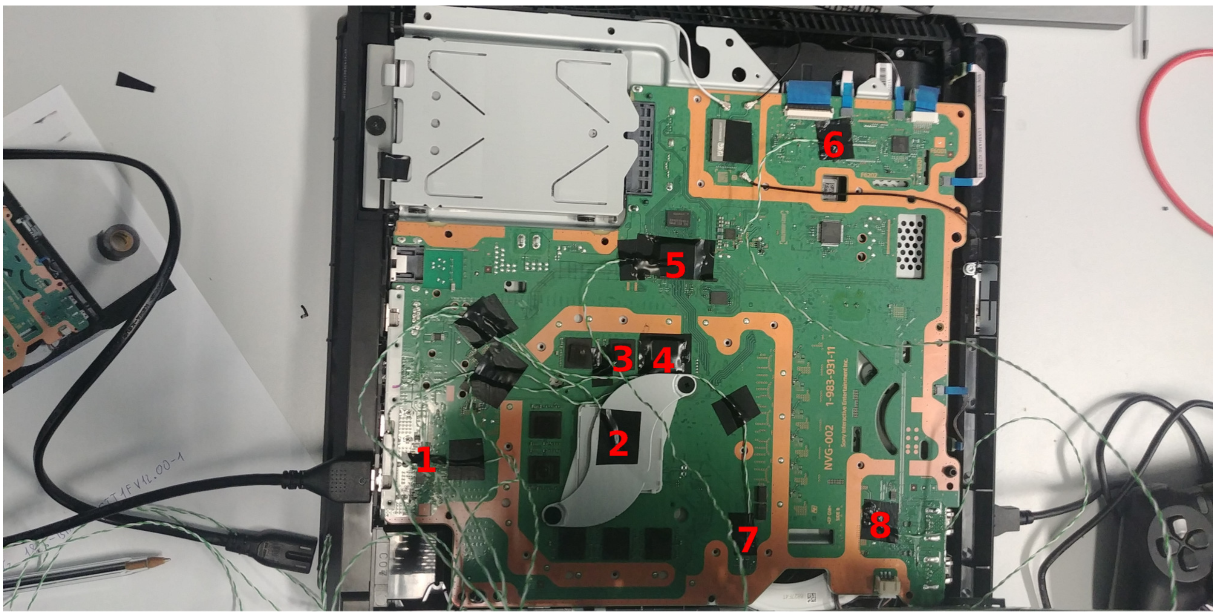


Figure 5.17: Measurement points for the PS4 Pro mainboard

Figure 5.18 shows the results for the temperature monitoring for the three different modes navigation, gaming, and Blu-Ray.

In navigation mode, all the components keep under a temperature of 55 °C. The VRAM with and without heat-sink compound have similar temperatures. In gaming mode, the temperature rises to higher values, where the VRAM reaches the highest temperature at around 73 °C. Also, the APU and three integrated circuits reach temperatures of 65 °C and more. In Blu-Ray mode, the temperature trend is very similar to navigation. The main difference is that the IC 93RH4 reaches a higher temperature than before, possibly due to being responsible for the disk drive.

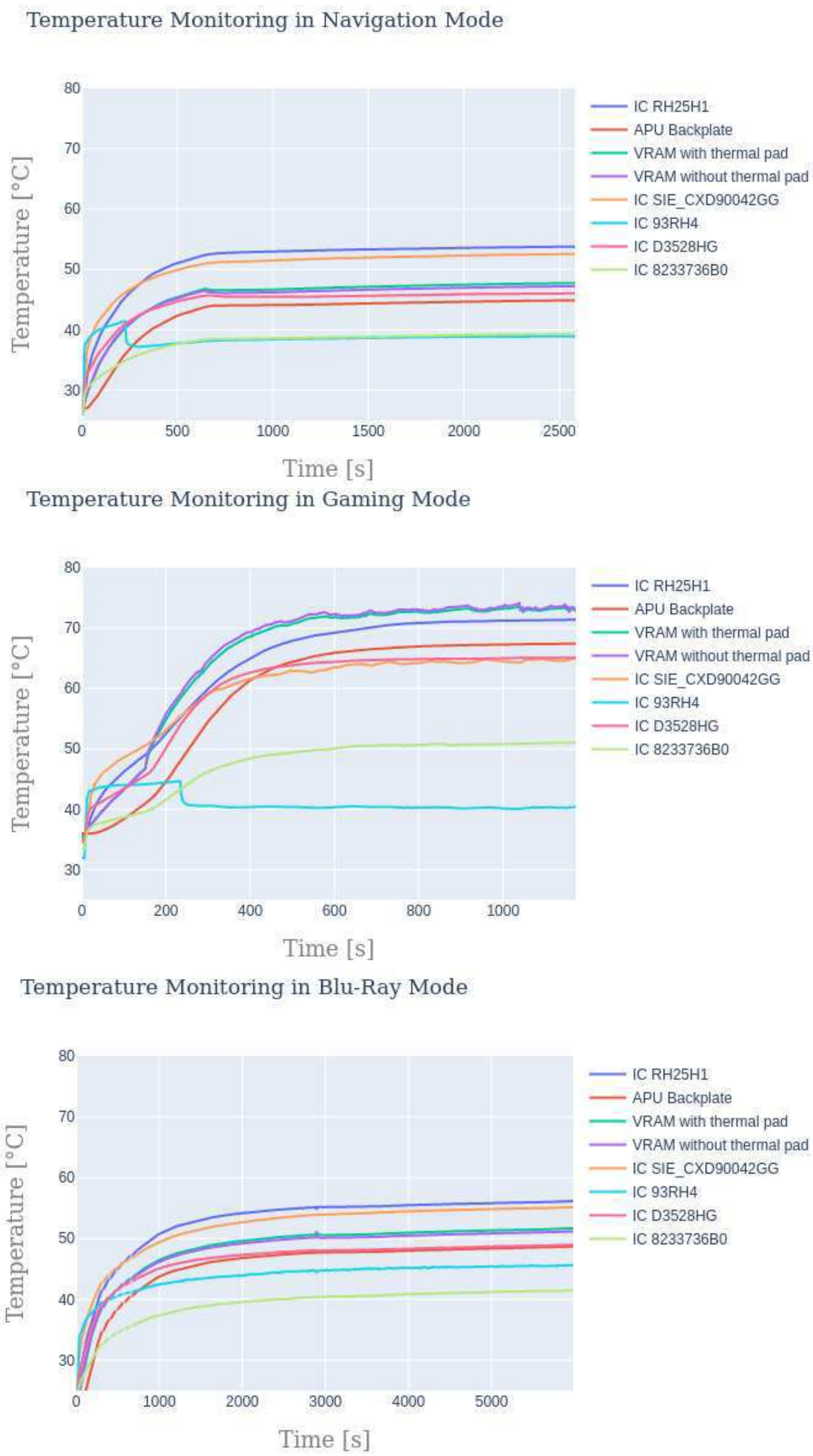


Figure 5.18: Temperature curves for the PS4 Pro mainboard monitoring for a) navigation mode b) gaming mode c) blu-ray mode

PS4 Pro Power Supply

The next measurement step involves the PoS of the PS4 Pro. The process of finding the relevant parts and monitoring the temperature is similar to the mainboard. Under normal operating conditions, the PoS is embedded into the device with a separate case and connectors. In order to analyze the components for hot spots, the PoS is removed and connected with separate wires. Afterward, powering up the console is done with care and under continuous monitoring of the surface temperatures to avoid overheating without the airflow from the console. Figure 5.19 shows detailed images of the components for the temperature monitoring measurements.

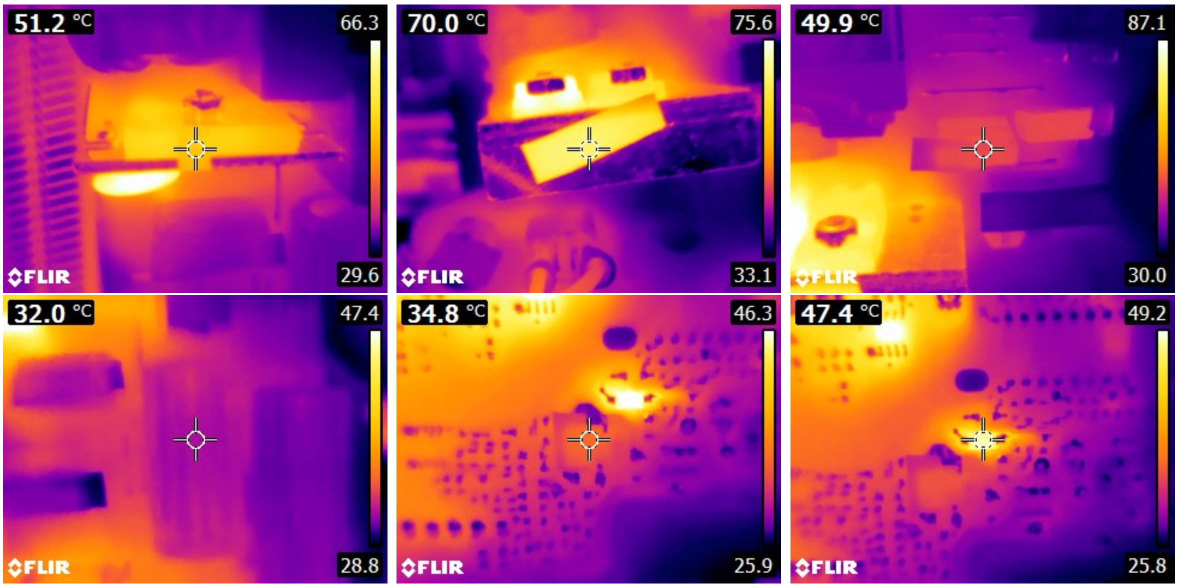


Figure 5.19: a) Bridge Rectifier b) PFC Mosfet and Diode on heat-sink c) two Mosfets for resonant converter d) Intermediate circuit capacitors e) flyback Mosfet bottom side f) diode bottom side

Figure 5.20 shows all the measurement points for the PoS at the top and bottom. This includes 1) diode D21, 2) Mosfet Q9 3) 12V output capacitor C116, 4) diode D11, 5) mosfet Q102, 6) capacitor C2, 7) Mosfet Q3 and 8) the bridge rectifier.

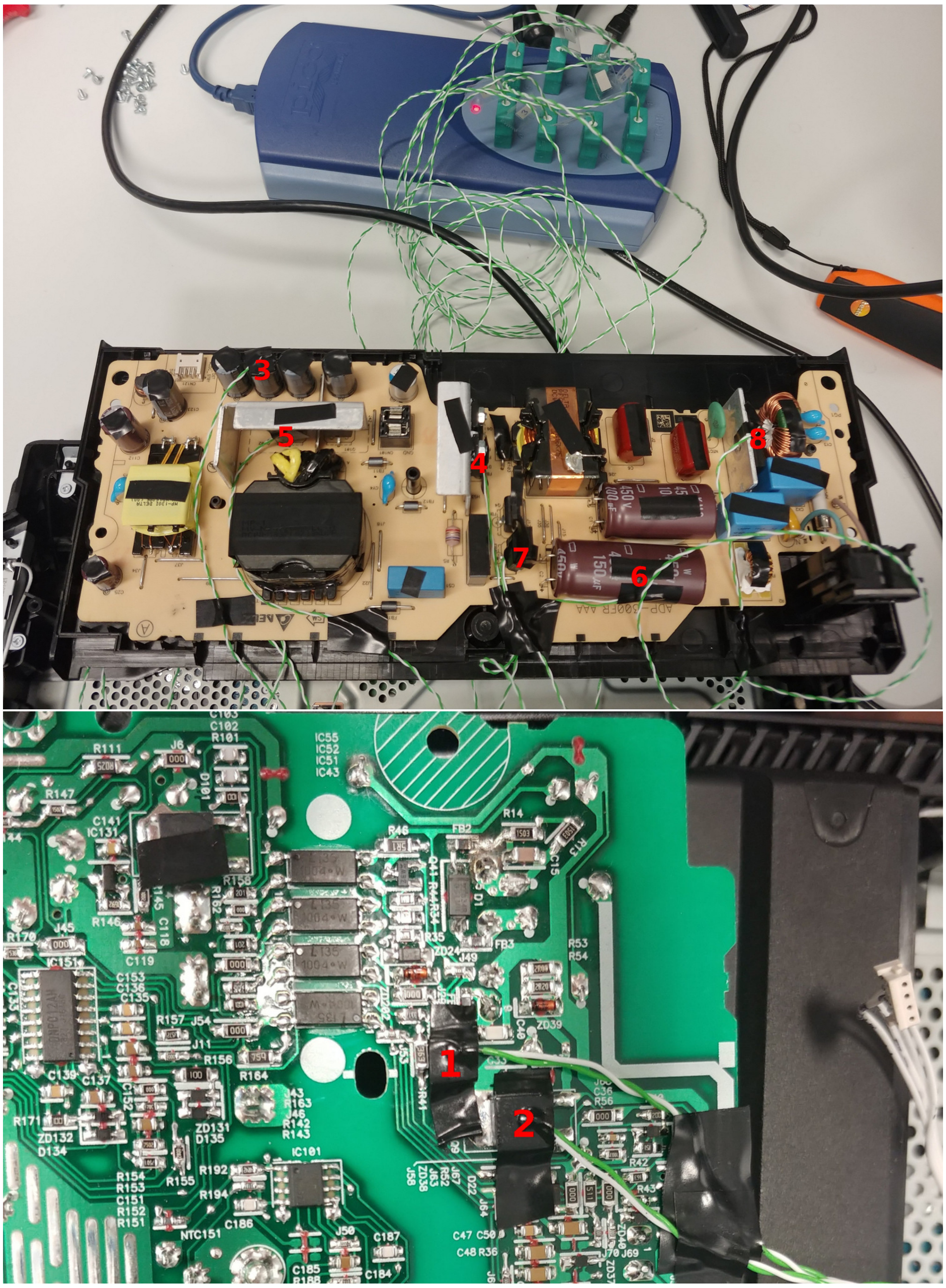


Figure 5.20: Measurement points inside the PS4 pro power supply a) top b) bottom

Figure 5.21 shows the results for the temperature monitoring of the PoS for the three different modes: navigation, gaming, and Blu-Ray mode.

In navigation mode, all the components keep under a temperature of 50 °C. In gaming mode, the temperature rises to 73 °C, falling slightly afterward. The Mosfet Q102 reaches the highest temperature after a peak of the diode D11. At the end of the measurement, the sensor detached from the diode D11, thus lowering the temperature.

In Blu-Ray mode, the temperature trend is very similar to navigation, reaching a slightly higher final temperature.

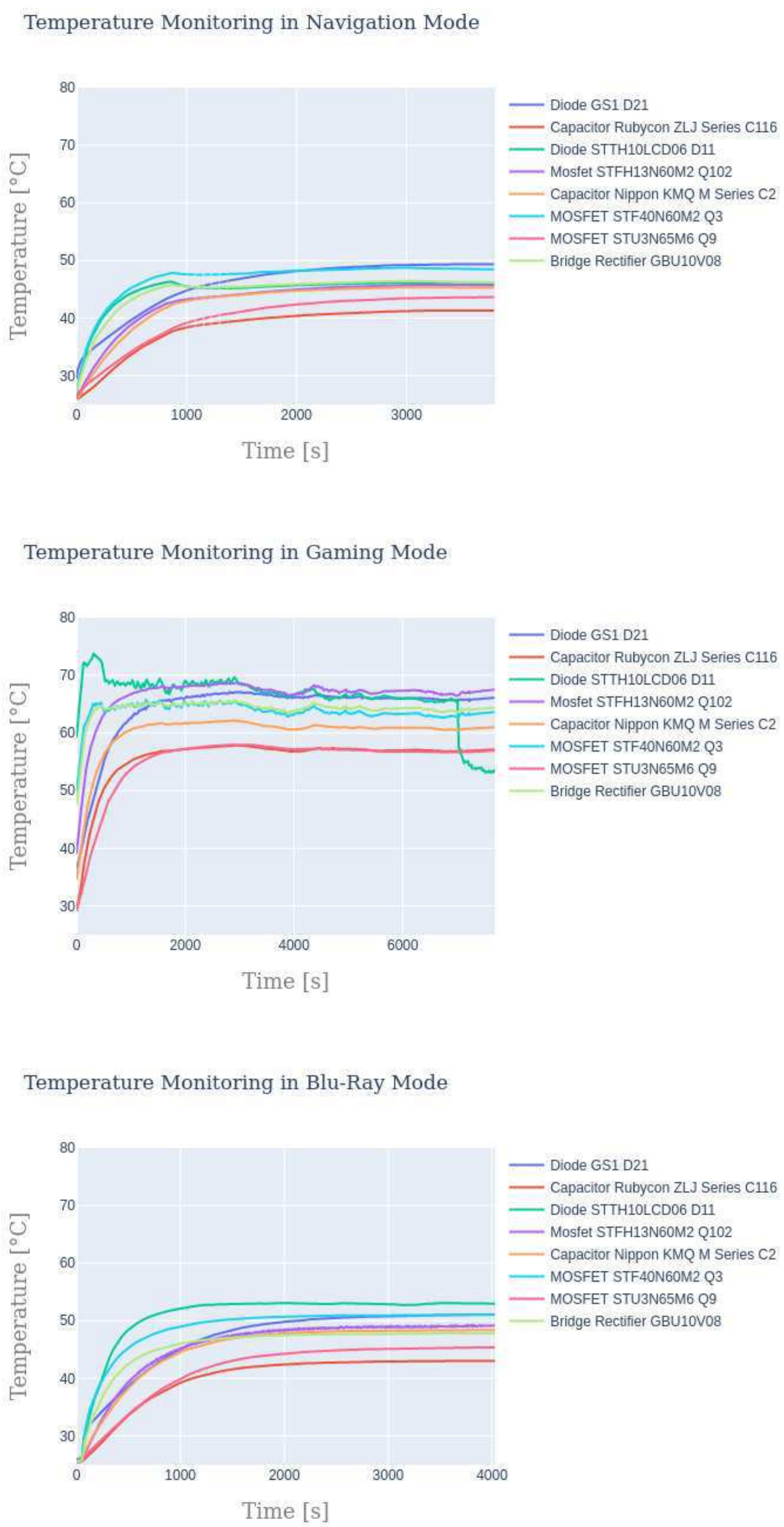


Figure 5.21: Temperature curves for the PS4 Pro power supply monitoring for a) navigation mode b) gaming mode c) blu-ray mode

5.3.2.2 Xbox One X

The measurement procedure for the Xbox One X is the same as for the PS4 Pro. The design of the console is different compared to the other consoles. The PS4 models have a similar internal design, whereas the Xbox One S and the Xbox One X have more similarities on the outside. The Xbox One X integrates a fan blowing through a heat-sink and the air leaving the case at the back with a small window to the side where the PoS lies. In contrast, the Xbox One S has a fan on top of the APUs heat-sink sucking the air through openings in the case, the power supply, other components, and finally, through the heat-sink. The air leaves the case at openings in the case at the top.

Analyzing the Mainboard with the thermal camera unveiled a couple of interesting points depicted in Figure 5.22. The POIs are a step-down converter, a capacitor, an IC for supplying the CPU core voltage, and a diode. In the case of the Xbox One X, the APUs heat-sink directly cools the VRAM. The thermocouple is inserted between the VRAM chip and the heat-sink compound, not changing the cooling system's setting. Additionally to the components on the mainboard's front side, there are also components on the back. The console's metal case directly cools the south-bridge, and therefore in order to keep the cooling system untouched, three more chips are selected for monitoring the temperature without checking them with the thermal camera. As there are few relevant components on this side of the mainboard, this should not be an issue. See Figure 5.23 for all the POIs.

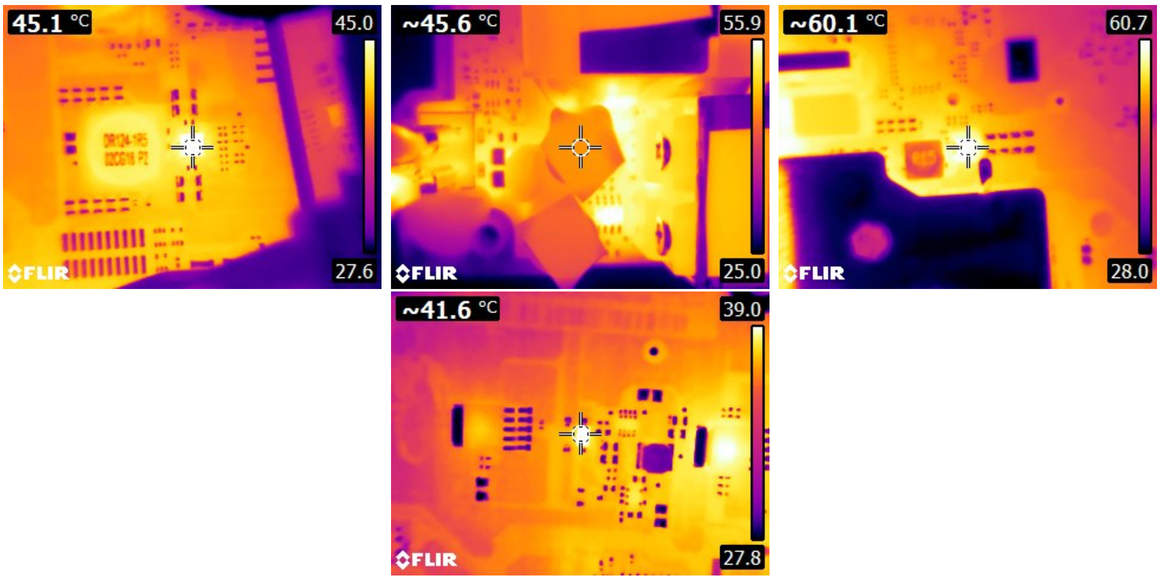


Figure 5.22: a)Step Down Converter b)Capacitor GS Series c)IC for CPU core voltage d)Diode SXF5

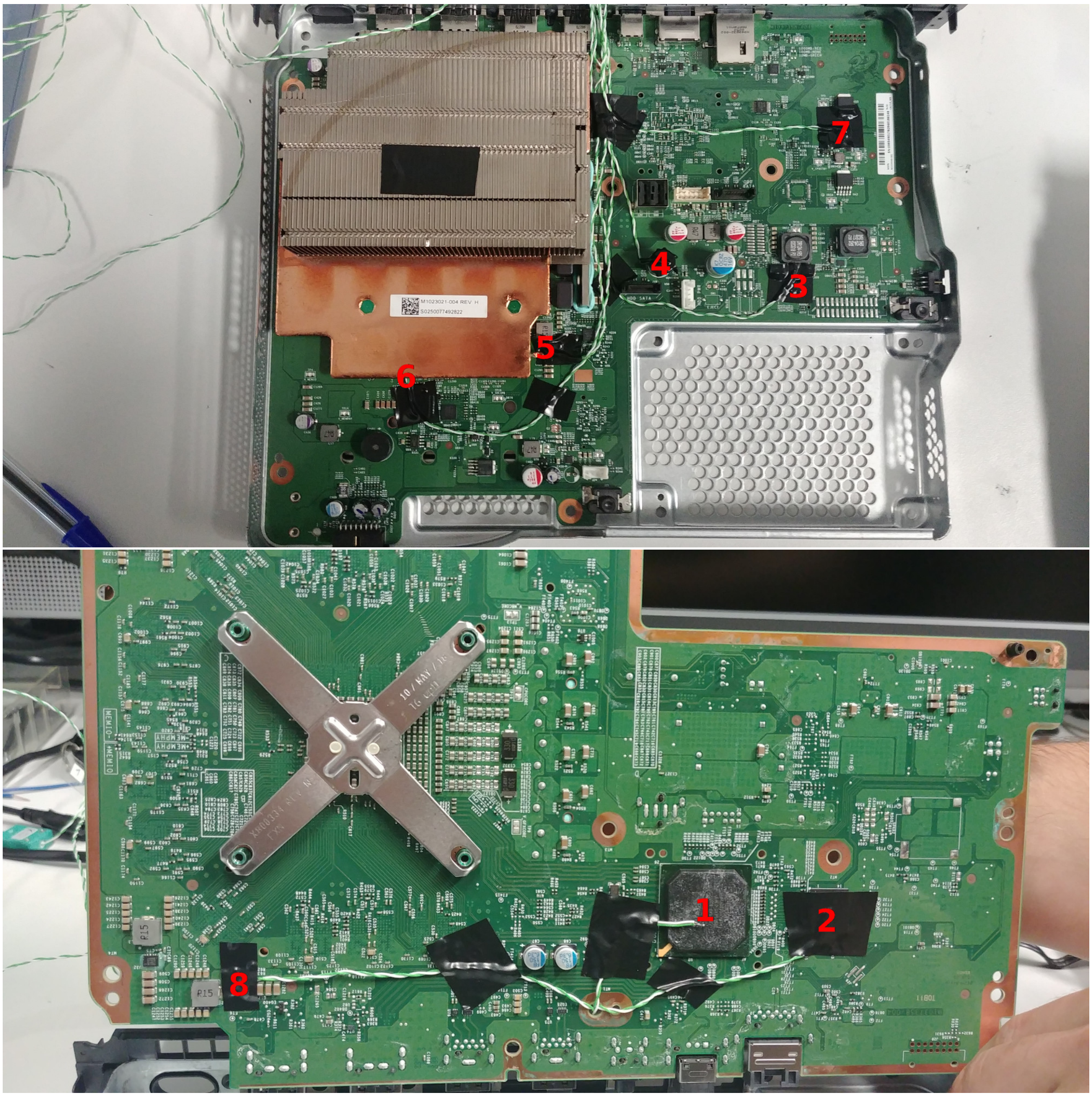


Figure 5.23: Measurement points for the Xbox One X mainboard

The temperature monitoring measurements for the Xbox One X mainboard show similar results for navigation and Blu-Ray mode. The top temperatures are approximately 60 °C for a proprietary IC and the VRAM. The other components keep at cooler temperatures between 45 °C and 55 °C. In Blu-Ray mode, the end of the movie introduces a shift in power distribution, which is visible due to the core voltage IC cooling down slightly.

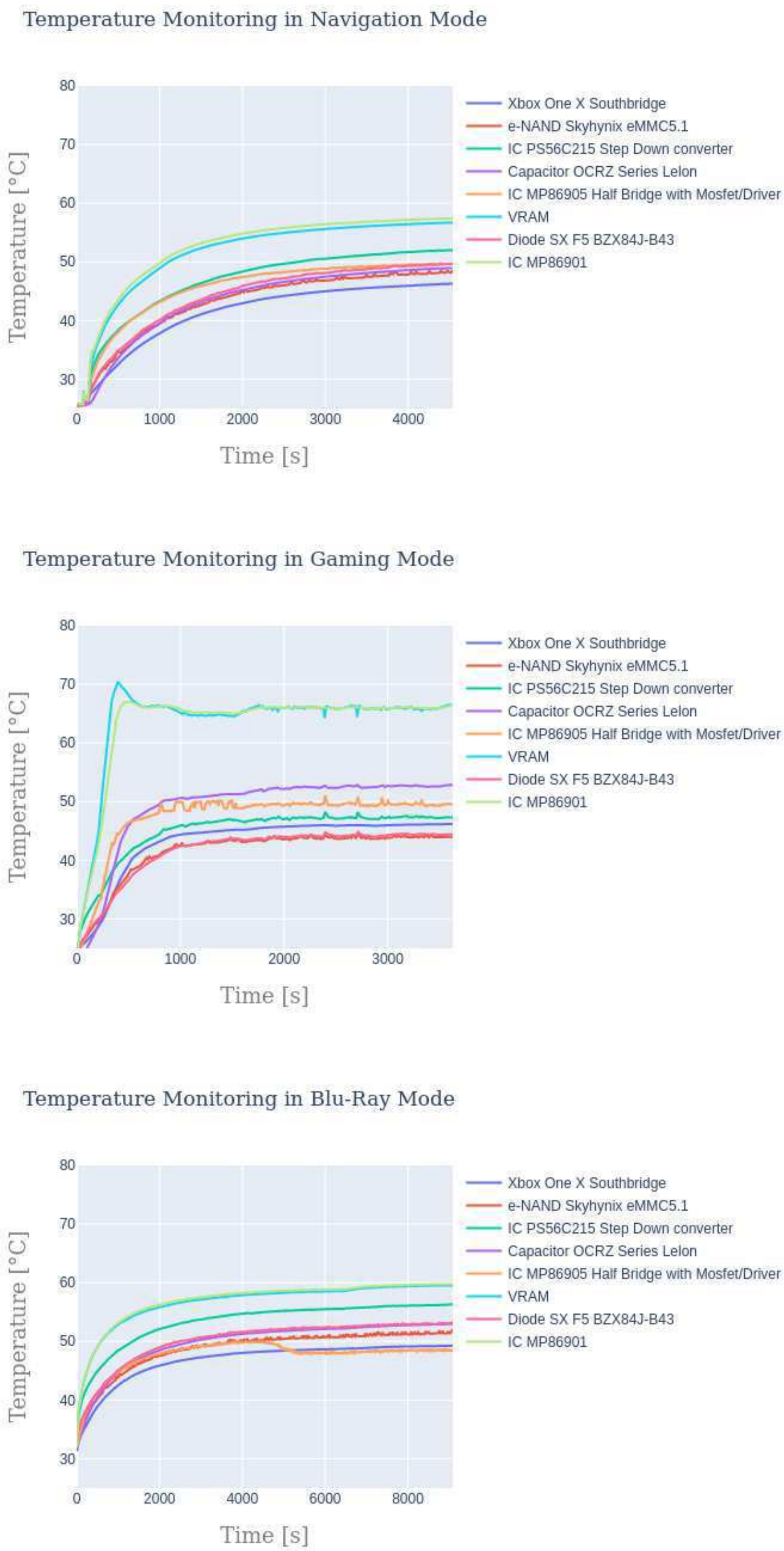


Figure 5.24: Temperature curves for the Xbox One X mainboard monitoring for a) navigation mode b) gaming mode c) blu-ray mode

Xbox One X Power Supply

The PoS of the Xbox One X is built into the console, like in all the other stationary consoles. In this case, only a small opening from the heat-sink supplies the PoS with fresh air. Additionally, the output vent for the PoS is rather small compared to the other consoles. The measurements with the thermal camera show several POIs in Figure 5.19. Mainly the semiconductors for power conversion and ICs for the SMPS converter.

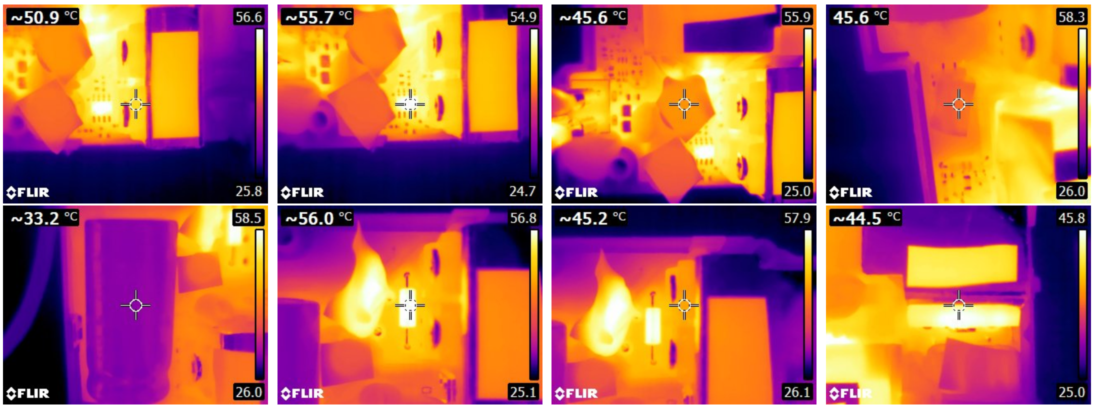


Figure 5.25: a) Mosfet Q301 b) IC TEA1995T c) Capacitor GS series d) Capacitor HW series e) Capacitor MK series f) Ferrite bead g)Mosfet Q101 h)Bridge rectifier

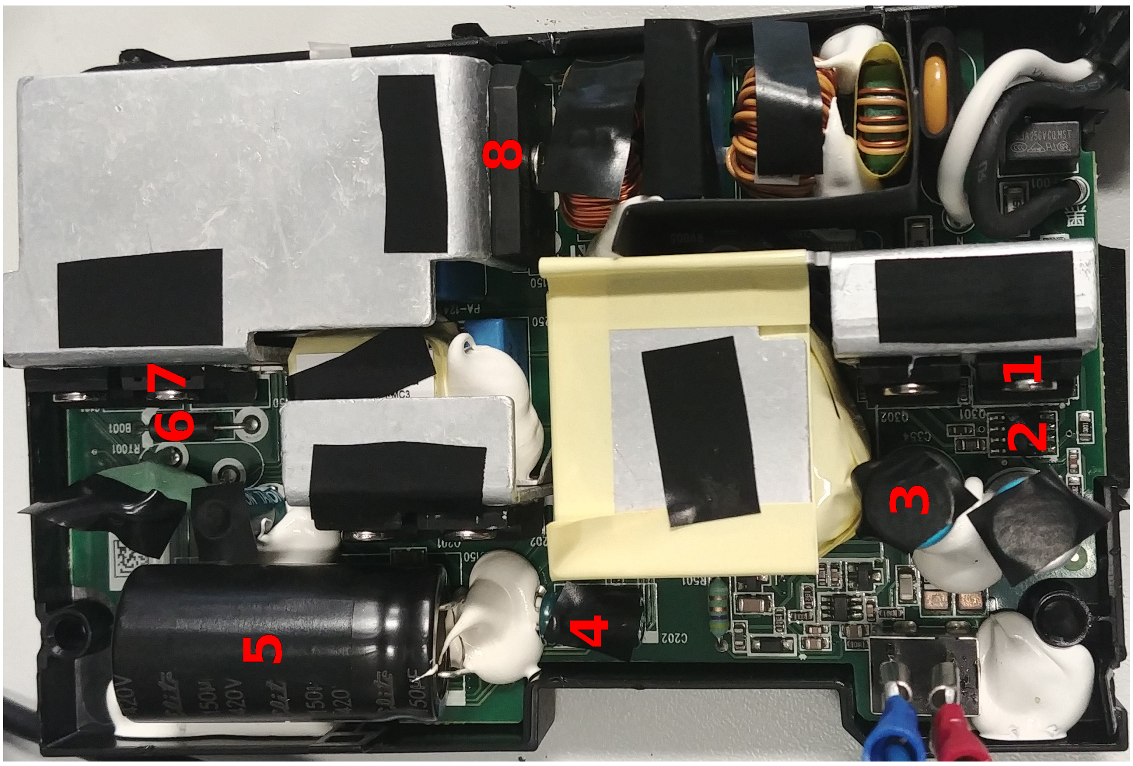


Figure 5.26: Measurement points inside the Xbox One X power supply

The three modes' temperature curves show similar curves for all the three modes, with the gaming mode reaching the highest temperatures. The ferrite bead reaches almost 80 °C, but this should not be an issue for this kind of component. The SMPS Controller and the Q101 Mosfet also reach 66 °C. The intermediate circuit capacitor C353 is the hottest of the three investigated and reaches a maximum temperature of about 65 °C.

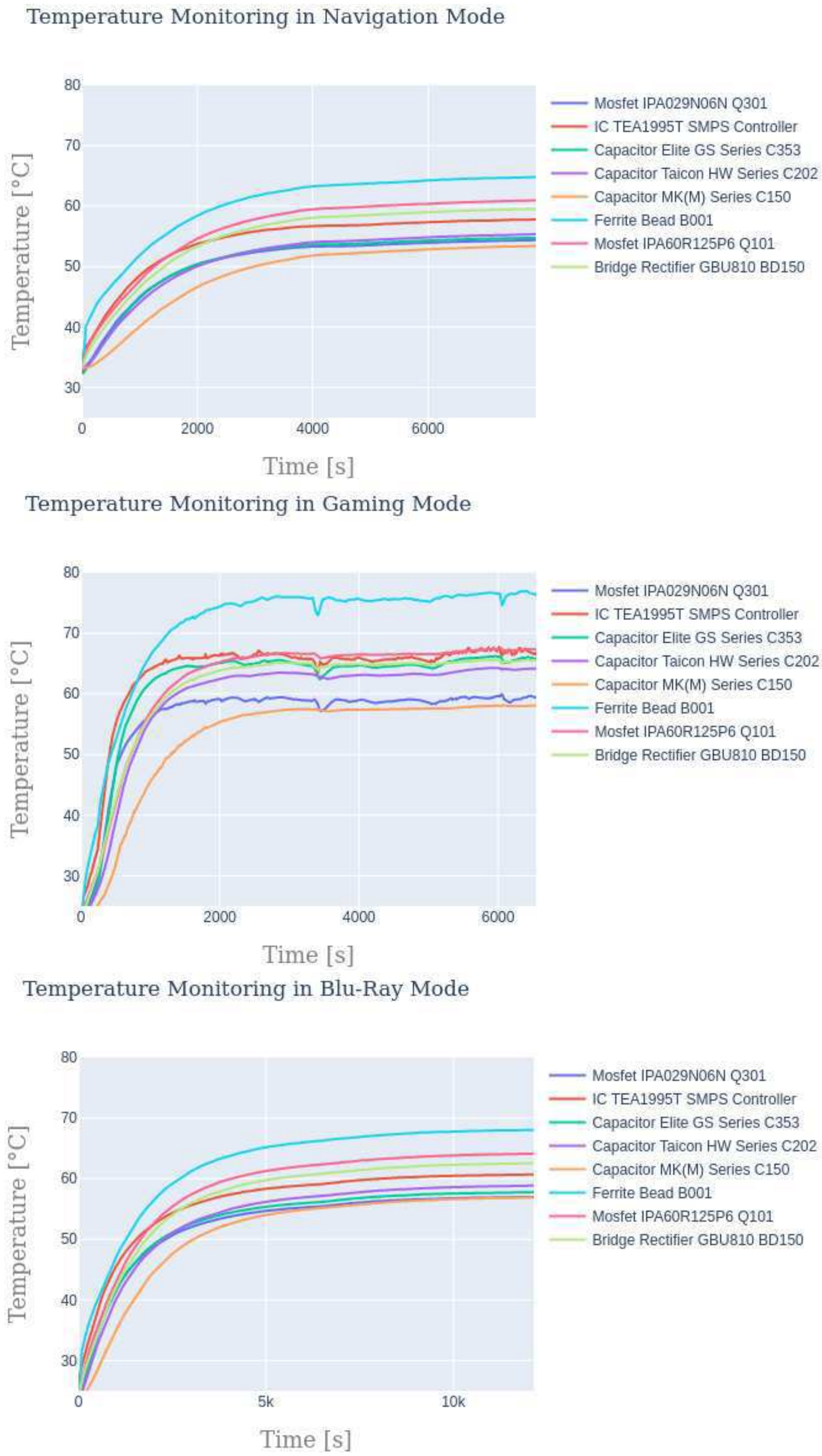


Figure 5.27: Temperature curves for the Xbox One X power supply monitoring for a) navigation mode b) gaming mode c) blu-ray mode

6 Results and Analysis

The measurements conducted in the last sections deliver promising results. This section provides an overview of the results with explanations of the numbers and conclusions of the measurements. Furthermore, to illustrate the outcome, some calculations help with the evaluation.

6.1 Efficiency Results

Figure 6.1 shows the results of the efficiency measurements for the main voltage of the consoles. The PS4 Pro has the best efficiency for low load values, whereas the Xbox One X has the best efficiency at higher load levels. The Nintendo Switch has the lowest efficiency over the whole range. The small form factor and the low overall power consumption might play a role in this. To better compare the results, a comparison sorted by the absolute load in Watts instead of load in % can also be found in the mentioned Figure. This graph changes the view on the consoles completely. The Xbox One S, for example, is very efficient at low power levels, which is beneficial for operation in low power modes and standby because no secondary voltage for low power is integrated. On the other side, the Xbox One X still has a very high efficiency at higher power levels but is not as efficient as the smaller variant at low power levels. Unfortunately, it does not incorporate a secondary voltage and thus consumes more energy when at lower modes of power. The Nintendo Switch power supply does not have the best efficiency values but in this Figure, we can see that the efficiency is high for such low levels of power. Only the Xbox One S has better values for that range.

Figure 6.2 shows the efficiency of the secondary voltages. The Nintendo Switch power supply uses either the 15 V or the 5 V, not both. The power supply switches between these voltages. When the console is in use, the voltage is always at 15 V. For the rest of the consoles, only the Sony models have a secondary voltage which is always present when they are connected to the grid. Turning on the console with the power button or the controller activates the primary voltage output. Additionally, due to changes in the system behavior, the primary voltage is also active if the USB ports are configured to charge when the console is in rest mode. Thus the secondary voltage is mainly responsible for supplying the console when in different low power modes. The efficiencies for the PS4 Slim and Nintendo Switch are very similar. Only the PS4 Pro manages to achieve higher Efficiencies, especially at very low loads, although the PS4 Slim and Pro were released almost simultaneously and incorporated similar designs for the PoS with identical ratings for the 5 V output.

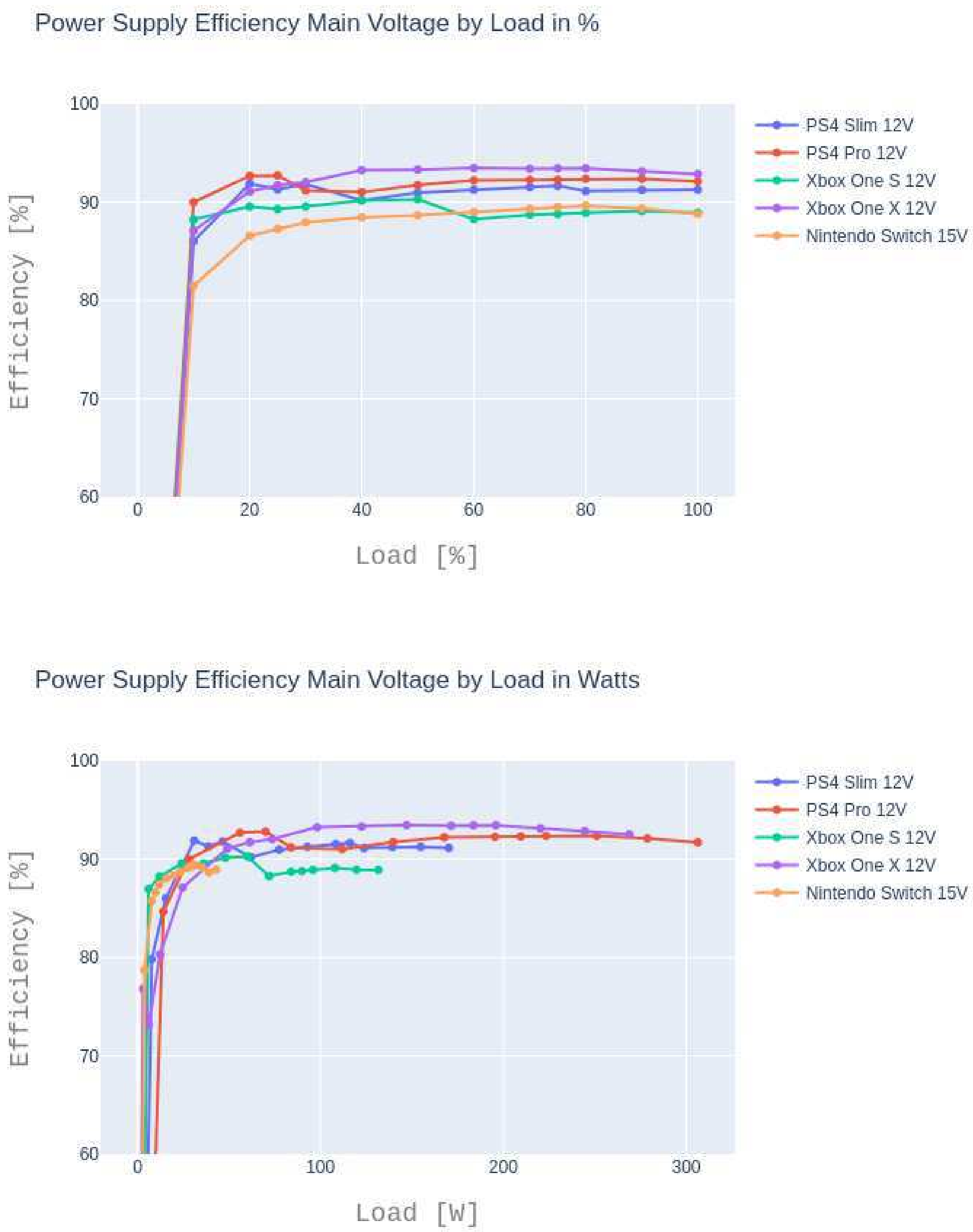


Figure 6.1: Efficiency comparison for all consoles tested (main voltage) depending on load in % and Watts

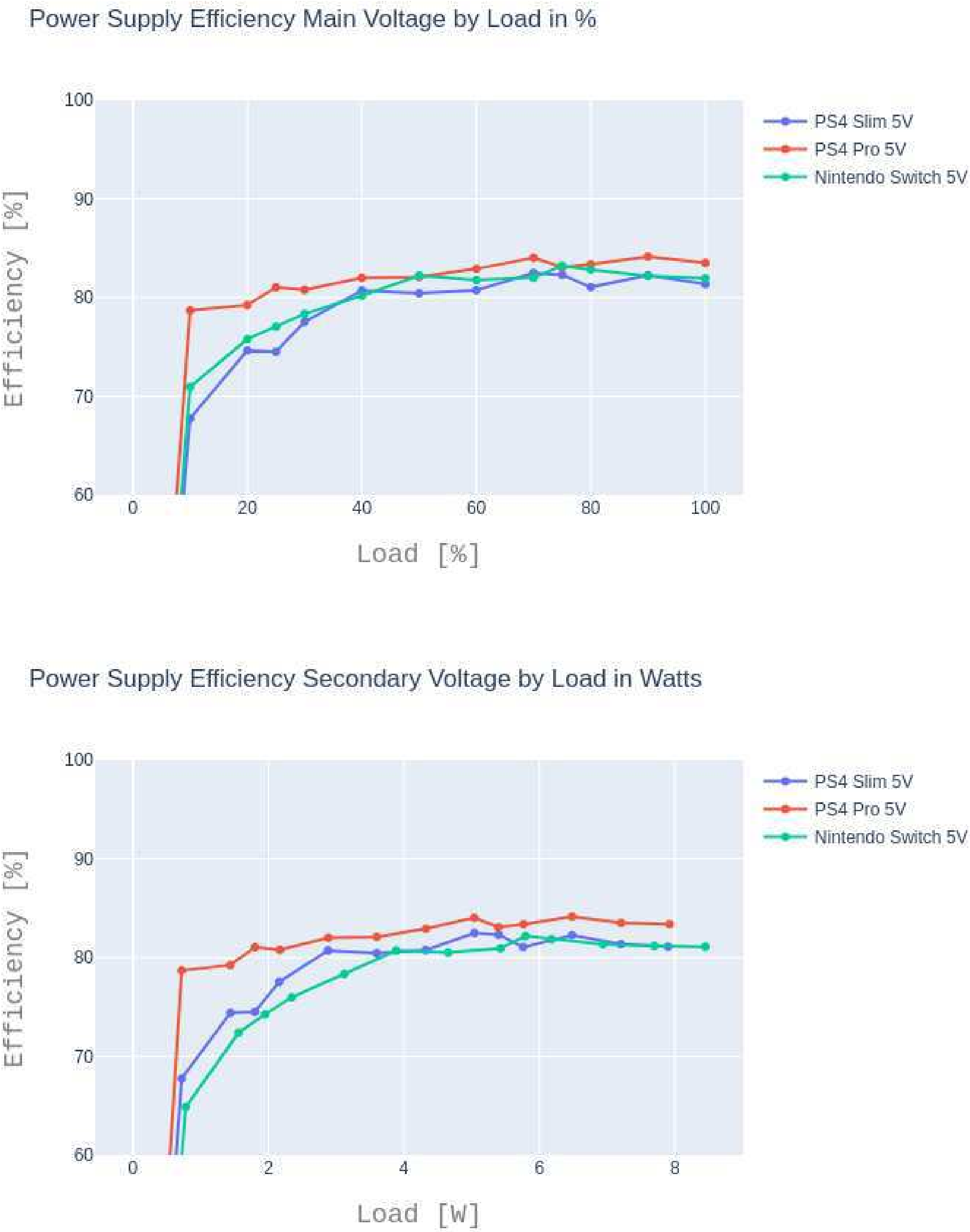


Figure 6.2: Efficiency comparison for all consoles tested (main voltage) depending on load in % and Watts

Knowing the efficiency of the PoS allows calculating a new TEC. Figure 6.3 shows the measured consoles with a value for the TEC calculated in Section 3.3 and a hypothetical one for improved average efficiency of about 96,2 % according to the best available efficiency in the EU regulation 2019/1782 [Com19]. In total, this would save about 1,17 TWh of TEC. This is approximately the energy a Danube power plant with an average output power of 163 MW [1]. These savings only include improvements for the reviewed consoles and not for the older models. Therefore the savings could be significantly higher if all the consoles power supplies were improved.

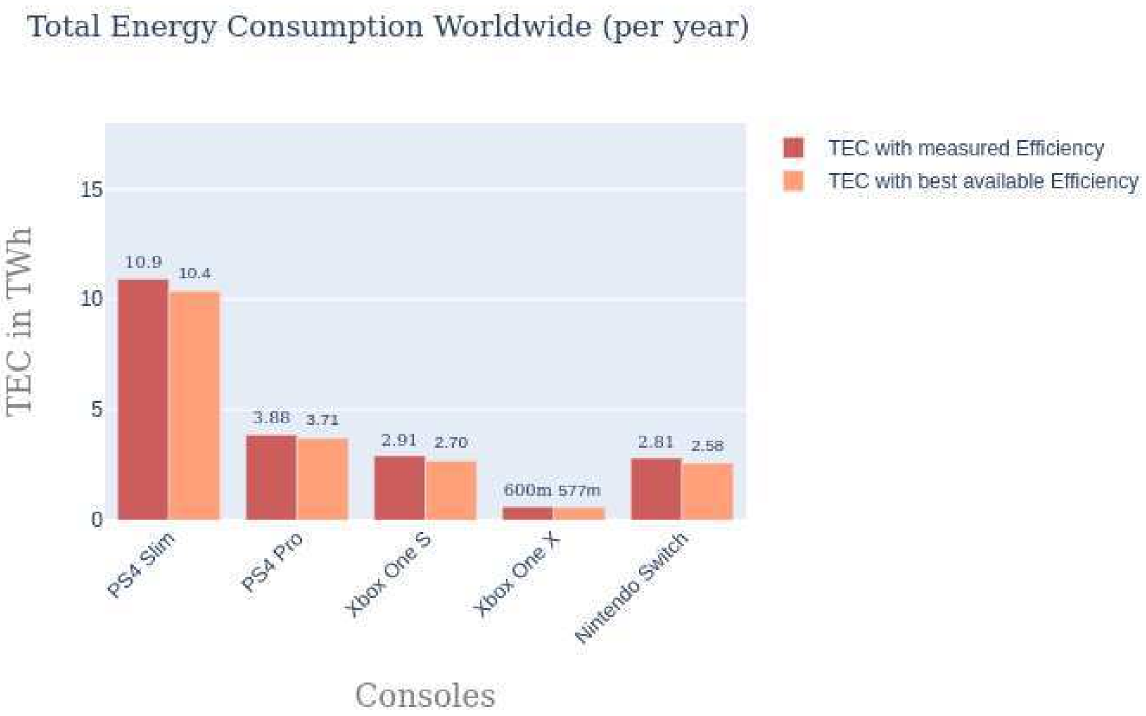


Figure 6.3: Comparison for the Total Energy Consumption based on the measured efficiency and the best available efficiency from the EU regulation [Com19] for external power supplies

The results from the efficiency measurements show high overall efficiencies for all the consoles with the more powerful consoles achieving slightly better results. This could be due to constant loss having less impound when consuming higher amounts of energy.

6.2 Component Temperature Results

The thermal measurements carried out in Section 5 show no critical temperatures at the first look. Unfortunately, the measured temperature corresponds only to the case temperature if the sensors are appropriately attached. Therefore no direct conclusion about the values can be made. To do that, either the value inside the component has to be calculated (e.g., junction temperature for semiconductors) or a max value for the case temperature has to be provided. In Table 6.1, the measured components are listed with the measured case temperature, the thermal junction to case resistance, the maximum dissipation power for a defined temperature, and the maximum allowed temperature for the component are given.

Console	Component	Type	T_{c_meas}	$R_{th\text{-}jc}$	P_{tot}	I_{max} @ T_{case}	T_{max}
PS4 Pro	Rubycon ZLJ	Capacitor C116	~ 58°C	-	n.A	n.A	105°C
	STTH10LCD06	Diode D11	~ 73°C	6°C/W	~13W@55°C	10A@55°C	175°C
	GS1M	Diode D21	~ 73°C	-	11W@100°C	1A@100°C	150°C
	Nippon KMQ	Capacitor C2	~ 62°C	-	n.A	n.A	105°C
	STF40N60M2	Mosfet Q3	~ 65°C	3,13°C/W	40W@25°C	7A@100°C	150°C
	STU3N65M6	Mosfet Q9	~ 65°C	2,78°C/W	45W@25°C	2,2A@100°C	150°C
	STFH13N60M2	Mosfet Q102	~ 69°C	5°C/W	25W@25°C	52A@100°C	150°C
	GBU10V08	Bridge Rectifier	~ 47°C	4,3°C/W	~ 9W@85°C	10A@100°C	150°C
	8QB77 D9WDH	VRAM GDDR5	~ 75°C	-	n.A	n.A	100°C
PS4 Slim	GBL408A	Bridge Rectifier	~ 54°C	10°C/W	~ 4W@50°C	4A@50°C	150°C
	Rubycon CXW	Capacitor C2	~ 68°C	-	n.A	n.A	105°C
	STF24N60M2	Mosfet Q6	~ 81°C	4,2°C/W	30W@25°C	12A@100°C	150°C
	Samsung SEC 834	VRAM GDDR5	~ 75°C	-	n.A	n.A	95°C
Xbox One S	IPA60R280P6	Mosfet	~ 90°C	1.2°C/W	~ 32W@25°C	8,8A@100°C	105°C
	Taicon AR (AQ)	Capacitor C120	~ 63°C	-	n.A	n.A	105°C
	Elite UPE	Capacitor C203	~ 81°C	-	n.A	n.A	105°C
	Samsung SEC 831	DDR3 VRAM	~ 51°C	-	n.A	n.A	95°C
Xbox One X	IPA029N06N	Mosfet Q301	~ 57°C	3°C/W	~ 38W@25°C	59A@100°C	175°C
	TEA1995T	Controller	~ 57°C	90°C/W	~ 0,5W	-	150°C
	Elite GS Series	Capacitor C353	~ 58°C	n.A	-	-	105°C
	Taicon HW Series	Capacitor C202	~ 58°C	n.A	-	-	105°C
	Elite MK Series	Capacitor C150	~ 57°C	n.A	-	-	105°C
	IPA60R125P6	Mosfet Q101	~ 64°C	3,65°C/W	~ 34W@25°C	19A@100°C	150°C
	GBU810	Rectifier BD150	~ 63°C	2,2°C/W	-	8A@100°C	150°C

Table 6.1: Analyzed components with their operating conditions and limits concerning component lifetime

Unfortunately, the data is not sufficient for determining the temperature at the junction or core. In addition to the values provided, the total loss calculates as a function of efficiency and input power. Due to the high efficiency of the PoS, this power is low even while gaming. Table 6.2 lists the values for each console in the three modes that were used for temperature monitoring.

Console	Navigation		Gaming		Blu-Ray	
PS4 Pro	P_{avg}=60 W	P_L~4 W	P_{avg}=160 W	P_L~12,5 W	P_{avg}=72 W	P_L~5 W
PS4 Slim	P_{avg}=44 W	P_L~3,5 W	P_{avg}=86 W	P_L~7,5 W	P_{avg}=48 W	P_L~4 W
Xbox One S	P_{avg}=30 W	P_L~3 W	P_{avg}=73 W	P_L~7,5 W	P_{avg}=38 W	P_L~4 W
Xbox One X	P_{avg}=51 W	P_L~4,5 W	P_{avg}=166 W	P_L~11 W	P_{avg}=54 W	P_L~5 W

Table 6.2: Average power and thermal power dissipation in navigation, gaming and Blu-ray mode

Determining the exact dissipation power without measuring each device on its own is rather difficult due to the unknown waveforms. Nevertheless, there are a couple of components in the circuits known to have higher losses than others. In SMPS, those are switching elements and rectifying elements. So for the PoS under investigation, there are several components responsible for most of the dissipation power listed in Table 6.3.

Component	**PS4 Slim**	**PS4 Pro**	**Xbox One S**	**Xbox One X**
Bridge Rectifier	yes	yes	yes	yes
PFC Mosfet (Switching Element)	yes	yes	yes	yes
PFC Diode (Rectifier)	yes	yes	yes	yes
12V Converter (Switching Element)	2x	2x	1x	2x
5V Converter (Switching Element)	yes	yes	no	no
Rectifier 12V (Diode or Mosfet)	2x	2x	1x	2x
Rectifier 5V (Diode or Mosfet)	yes	yes	no	no

Table 6.3: Components with assumed high power dissipation

As an estimation, 75% of the total dissipation power is assumed to be dissipated by those devices. Even if the total power left in this calculation is dissipated by a single component in the power chain, the maximum junction temperature would not be exceeded. However, the dissipation power distribution and the dynamic behavior of the thermal resistance and temperature gradient are neglected. The distribution of dissipation power depicted in Figure 6.4 shows that if a component is mounted on a heat-sink or PCB with good thermal properties and airflow, most of the dissipation power flows to the side that is adequately cooled [7]. The thermal resistance of a component is usually only valid for the stationary case, so deviations in the temperature gradient can occur.

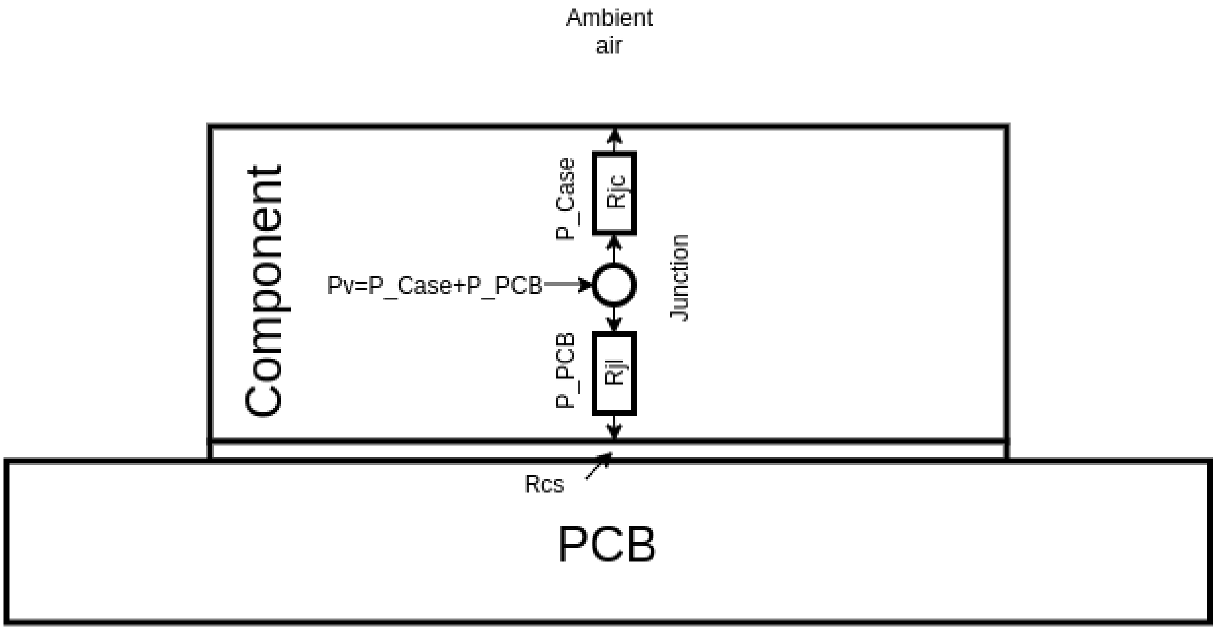


Figure 6.4: Illustration of power distribution of a component mounted to a PCB or heat-sink

6.3 Capacitor Life Expectancy

As mentioned in Section 5.2 capacitor life expectancy depends on temperature especially for electrolytic types. They are also the components that have a rather low maximum allowed temperature. Table 6.4 lists the measured capacitors with their maximum temperature and specified lifetime for that temperature. Furthermore, the measured maximum temperature is given to estimate how the capacitor would survive with this temperature. For estimating the life expectancy, the measured temperature and an additional 5 °C are used due to the inner temperature in aluminum electrolytic capacitors being usually higher, according to [Par99]. The calculations are based on Equation 5.18 in Section 5.2

Capacitor	**Rated Temperature**	**Rated Endurance**	**Measured Temperature**	**Estimated Life Expectancy**
Rubycon ZLJ Series	105 °C	5000 hrs	58 °C	92000 hrs
Nippon KMQ Series	105 °C	2000 hrs	62 °C	28000 hrs
Rubycon CXW Series	105 °C	5000 hrs	68 °C	46000 hrs
Taicon AR (AQ) Series	105 °C	2000 hrs	63 °C	26000 hrs
Elite UPE Series	105 °C	5000 hrs	81 °C	19000 hrs
Elite GS Series	105 °C	2000 hrs	58 °C	92000 hrs
Taicon HW Series	105 °C	7000 hrs	58 °C	129000 hrs
Elite MK Series	105 °C	- hrs	57 °C	- hrs

Table 6.4: Capacitors with rated life expectancy and estimated real life expectancy due to rise in temperature

The capacitors used in the various consoles are of a different type. Although, the rated temperature is in all cases 105 °C, the rated endurance at this temperature is different in many cases. It ranges from 2000 hours to 7000 hours. For the Taicon AR (AQ) series capacitor, the expected lifetime is the lowest with 26000 hrs, which is still high and equals ∼ 11 hours of daily use for seven years, which is approximately the time from one console generation to the next. Even the extreme users of game consoles only use the console for 6 hours on average for gaming according to [WLG+19]. Therefore the capacitor would survive at least 12 years with that amount of playtime. Due to the lower temperature in media consumption and navigation, the capacitor would deteriorate in those modes too, but at a much slower pace.

A factor not taken into account until now is deterioration of the cooling caused by dust or constrained spaces. Due to the continuous flow of air through the console dust builds up inside the case. After some time this dust could restrict the airflow to an extend were the temperature starts to rise beyond the measured values. Another factor could be the placement of the console inside a cabinet where only parts of the air exchanges with the outside. Here the temperature could also rise to higher levels. If the temperature rises 10 °C due to these factors the life expectancy would drop to half of the estimated value and would be almost lower than one generation of games consoles.

7 Discussion

This thesis reveals that the game consoles investigated are designed with a focus on the state of the art technology. The components in the consoles deliver appropriate performance, especially for the price. The question is, whether the selection of the power supply technology is appropriate. If more effort and money would be invested, there could have been devices that need less energy and last longer in terms of thermal deterioration. Especially nowadays, where climate change is on the edge of changing our lifes, it would be better to invest more to gain higher efficiencies. Semiconductor technologies such silicon carbide or gallium nitrite could improve efficiency to even higher levels. Concerning the thermal management, temperature measurements at more points and fan control could avoid thermal stress. As there are millions of consoles active every day, they consume a considerable amount of energy. Also production has a significant share of energy consumption and should be kept at the necessary minimum. Therefore optimization of life longer than the average product cycle should be stressed. The highest possible efficiencies with state of the art cooling solutions help to reach that goal.

The efficiency measurements were carried out with an electronically adjustable load, several multimeters, and a power meter. In order to improve the accuracy and quality of the measurements, some changes could be advisable. The power source used for the measurements is the power grid itself without any adaptions. Therefore deviations, noise, and disturbances in the grid could alter the results. A particular power supply for this purpose would improve the conditions. This would also allow for proper measurements of the harmonics of the currents drawn by the power supply. Due to the distortion of the grid voltage, the measurements can fail.

As already mentioned in Chapter 2, the European Commission created a regulation concerning external power supplies. This regulation puts up standards for minimum required efficiencies of external power supplies. Depending on the type and specifications of the power supply, it should achieve high average efficiency. Moreover, it provides numbers for the best available efficiencies at the moment. Unfortunately, this regulation applies only to external power supplies and not to any power supplies embedded into devices like game consoles. For game consoles, this is not that big of an issue as they are self-regulated separately, but this is not the case for other products. So the European Commission should consider establishing another framework for products that include internal power supplies as well.

Another option for measuring the efficiency and thermal properties would be to use a hotbox or climate box that allows adjusting the ambient temperature to evaluate the results under different conditions. For example, the temperature could be increased to the maximum or minimum allowed value. This would also allow for simulating different conditions at the end-user where shelves, walls, and other barriers restrict the airflow to or from the consoles.

The consoles reviewed in this thesis were all relatively new, so no effect from degradation has been taken into account. For example, dust that is present in every household builds up inside the videogames consoles and restricts airflow and heat removal. Also, other factors could change the behavior not visible at first.

Concerning the thermal measurements, it was not easy to evaluate the results properly. The measured temperatures do not always correlate sufficiently with the real value inside a component. Possible improvements would be to permanently attach the thermocouples to the DUT with epoxy glue or other materials. Additionally, attaching the thermocouple between heat-sink and device could also help to get better readings.

To evaluate every component on a deeper level, directly measuring dissipation allows a direct calculation of the junction temperature. However, this would require to measure the values under load while the PoS is in the videogames console. Inserting the cables and sensors necessary for the measurement could be difficult.

Usually, there exist different models of a product, which also applies to game consoles. Due to different reasons such as availability, costs, and effort, only one console model per type is investigated. Therefore, the results can differ from model to model, and the results may not be valid for the other ones. It is also possible that one of the devices has a malfunctioning component or component group that affects the behavior. Furthermore, the results are just a snapshot of the current situation, and a change in design happens frequently.

Additionally, there are many more ways to investigate the design of consoles. Still, as the possibilities are vast, one should not underestimate the time needed and is therefore out of scope in the course of this thesis.

8 Conclusion and Outlook

Investigating the consoles in this thesis revealed no critical issues concerning efficiency and lifetime. The efficiency for all the consoles is close to 90 %, with some of them reaching even better values. Nevertheless, there is still improvement potential to optimize this even more and reach the best available efficiencies laid out in the European Commission regulation.

Apart from the main voltage's efficiencies, the PS4 models provide a secondary voltage supply for low power. The PS4 Pro achieves higher values compared to the PS4 Slim. So it would be of interest to increase the efficiency also for the Slim model.

Due to the secondary voltage for low power, the PS4 models consume slightly less power while switched off. Nevertheless, the Xbox One models achieve almost similar values even without that.

If the second output voltage efficiency could be improved to even higher values, it would be advisable for the future to power the USB devices from this output. Moreover, if the attached device's power consumption (e.g., a controller) is very low, it would already be better to power the USB from the secondary output.

Concerning the thermal characteristics of the consoles, no critical readings gave the impression of bad design. The PS4 models were similar in mechanical design, the PS4 Pro having larger dimensions and more powerful hardware. The Xbox One models were somewhat different, with the Xbox One S sucking the air through the openings in the case and the power supply and transporting it through the APU heat-sink and out of the device. On the other hand, the Xbox One X works similarly to the PS4 models blowing the air through the heat-sink and afterward through the PoS. The main difference is that only part of the airflow is used for the power supply cooling compared to the PS4. This results in higher temperature values operating in navigation and blu-ray mode. Furthermore, the console needs more time to cool down and even turned off the temperature is higher than in the other consoles due to the nearly non-existing airflow. Apart from that, all the consoles operate at acceptably low temperatures.

If the efficiency improves in the future, this would also positively reduce the components' dissipation power. Therefore if the cooling design is kept the same, the life expectancy of at least the power supply components would rise even more.

To evaluate whether the manufacturers improved their designs, especially the efficiency of power supplies in the next generation, repeating the analysis at a later generation of consoles would provide a valuable insight delta.

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Erklärung

Hiermit erkläre ich, dass die vorliegende Arbeit ohne unzulässige Hilfe Dritter und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt wurde. Die aus anderen Quellen oder indirekt übernommenen Daten und Konzepte sind unter Angabe der Quelle gekennzeichnet.

Die Arbeit wurde bisher weder im In- noch im Ausland in gleicher oder in ähnlicher Form in anderen Prüfungsverfahren vorgelegt.

Wien, am

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