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Reducing power conversion losses in modern PSUs

Bachelor Thesis

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Abstract

The global demand for data and energy continues to surge, necessitating efficient power utilization in data transmission networks. This thesis investigates methods to reduce power conversion losses in modern network routers by optimizing their Power Supply Units (PSUs). The study evaluates energy savings achieved through deploying higher-efficiency PSUs and reducing redundancy by operating routers on a single PSU. Utilizing empirical data from a Cisco Nexus 9336C-FX2 switch and large-scale datasets from ETH's SWITCH network, the analysis reveals substantial underutilization of PSUs, leading to inefficiencies. The findings highlight the critical role of PSUs in sustainable network energy management, advocating for improved standards and practices to achieve greener digital infrastructures.

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Chapter 1

Introduction

1.1 Motivation

The global process of digitalization is rapidly progressing with no ending in sight. The number of internet users is steadily increasing and along with it, the amounts of data that traverse our network have grown 20-fold since 2010 [5]. The recent 'AI-boom' boosts the debate on whether our energy infrastructure is even able to handle such ever-increasing energy demands.

Today, data transmission networks and data centers account for 1-1.5% each in global electricity consumption and are projected to increase significantly in the next couple of years. The environmental impacts of the directly correlated increase of carbon emissions are life-threatening to generations that follow. To ensure a sustainable digital future, we must critically examine how to reduce and optimize energy consumption across all areas of technology. The infrastructural backbone of our internet must not be overlooked in this regard.

While past efforts have largely focused on optimizing cooling systems of routers and servers in large data centers, it is now time to take a closer look at the Power Supply Units (PSUs) of these routers as these account for significant energy losses that could possibly be reduced [6].

1.2 Task and Goals

Network routers are currently powered by two PSUs. We, firstly, wanted to compute an estimate of how much energy a network provider could save by simply deploying more efficient PSUs or powering its routers on a single PSU. This required an initial study of the current efficiency state of routers in our network to evaluate if said methods would even be beneficial.

Secondly, the power data that we analyzed in this regard revealed discrepancies in PSU power measurements, which initiated a deeper study of measurement precision of modern power supplies, using a Cisco router in our lab.

The two research questions can be summarized as follows:

1. How much energy could we save by deploying better PSUs or switching to one PSU per device?

2. How trustworthy are PSU internal power measurements?

1.3 Overview

Section 2 provides the necessary background on PSUs, including their structure, efficiency, challenges and standards such as *80Plus*. The role of redundancy in network devices and its implications for energy consumption are also briefly discussed. In Section 3, the computation of energy savings is introduced, including approaches to extend the *80Plus* benchmarks. Details of the analyzed SWITCH dataset and the experimental setup with a Cisco Nexus 9336C-FX2 switch are presented to support empirical evaluation. Section 4 evaluates the current state of PSU utilization, presents the results from the energy modelings and addresses the underlying assumptions of these modelings, while critiquing the data reliability. This section also includes a verification of power data using internal and external measurements to highlight discrepancies in PSU sensor readings. Section 5 outlines future directions, including refining measurement accuracy and exploring hybrid redundancy solutions to maintain reliability while saving energy. Finally, Section 6 summarizes the findings, emphasizing the importance of PSU efficiency and its potential to significantly reduce energy consumption in data transmission networks.

Chapter 2

Background

2.1 Power Supply Units

A power supply unit (PSU) supplies the needed power to whatever device it is connected to. Whether it be an electrical kitchen appliance, a TV or a network router, most electrical devices require direct current (DC) at a certain voltage to function correctly. PSUs convert the electricity from the power outlet – typically 230V AC – to the device-specific electricity, which is 12V DC for typical network routers. A PSU is typically designed for a specific maximum output capacity, which is the maximum energy that it is able to supply to the device that it is connected to. The ratio of the energy that a PSU outputs at a specific moment, P_{out}, and its capacity is defined as the *load*.

2.1.1 Power Conversion Losses

When energy is transformed from one form to another, energy losses can not be avoided completely. Consequently, energy losses occur in the form of heat when PSUs convert alternating current to direct current. Although these losses are inevitable, the scale of loss correlates to the load of a power supply. They are mostly minimal at roughly 50-60% load, varying from model to model. Hence, we characterize PSUs by their *efficiency*, which is the ratio of output power, P_{out}, to input power, P_{in}.

To precisely define and visualize the correlation of load and efficiency we have to look at the efficiency curve of a PSU, which can be found in some PSU's datasheets, although many PSU manufacturers do not publicly disclose the entire efficiency behavior of their PSUs. Figure 2.1 shows such a dependency, taken from the datasheet of a *PFE600-12-054xA* PSU (*"PFE"*). Due to the availability of an abundance of detailed data on this PSU [2], I will refer back to it fairly often throughout this report to explain certain phenomena and observations regarding PSU functionality and design.

2.1.2 80Plus

The efficiency of PSUs has improved with advancements in technology which can be observed in the evolution of the "80Plus" standard [3]. The 80Plus standard is an initiative that was started in 2004 to set a global standard for PSU efficiencies. Back then, every PSU that was certified as *80Plus* had to have a minimum efficiency of at least 80% at 20%, 50% and 100% loads. Since then, the standard has been extended with higher certificates ranging from *Bronze* to *Titanium* of which the requirements can be seen in table 2.1.

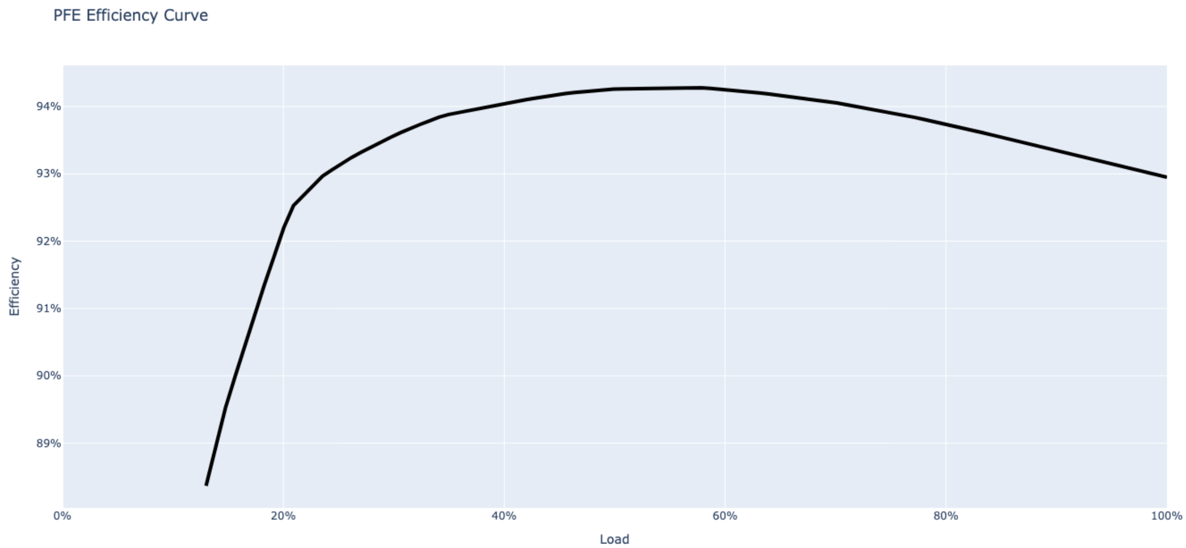

Figure 2.1: The efficiency curve of the *PFE600-12-054xA* starts at 13% load suggesting that the PSU should not run at lower loads.

Certification	**10% Load**	**20% Load**	**50% Load**	**100% Load**
80Plus Titanium	90%	94%	96%	91%
80Plus Platinum	-	90%	94%	91%
80Plus Gold	-	88%	92%	88%
80Plus Silver	-	85%	89%	85%
80Plus Bronze	-	81%	85%	81%

Table 2.1: 80Plus Certification Benchmarks for 230V Redundant Power Supplies [3]

The necessity for the addition of a benchmark at 10% load with the introduction of the *Titanium* standard suggests a severe drop in power conversion efficiency for loads below 20%.

2.1.3 Redundancy

Network routers in modern data transmission networks rely on *redundant* power supplies, which entails the usage of two (or more) individual PSUs working in parallel to maintain functionality of the router in case of a PSU failure. Loads are almost equally split over all PSUs in most routers.

Chapter 3

Foundation

In this chapter, I will introduce the foundation of this thesis by going over the evaluated dataset, the mathematical theory to compute the savings and the test bench used to verify the theory.

3.1 SWITCH Dataset

The subsequent analysis of power consumption in modern networks is subject to power data from ETH's network provider *SWITCH*. The total data consists of two datasets:

- the input power P_{in} of 107 routers deployed by *SWITCH* collected via SNMP over 10 months,
- a snapshot of environment sensor readings from 82 of the above mentioned 107 routers that, in addition to P_{in}, also provided data on P_{out} and temperature readings.

The data was combined for the computation of potential energy savings within *SWITCH's* network topology.

The environment sensor readings had different formats varying from PSU to PSU making it challenging to extract the relevant data.

Furthermore, the exact accuracy of measurements is unknown as sensor miscalibration and/or wear and tear of the PSUs could not be accounted for in the modelings. This question will be discussed further down in chapter 4.

3.2 Extending the 80Plus Benchmarks

We rely on the 80Plus benchmarks and the general efficiency behavior of a PSU to model the energy savings. Therefore, I had to assume all PSUs to generally adhere to the *PFE*'s efficiency curve, presented in Figure 2.1.

We can make use of knowing how efficiency correlates to load and extend the 80Plus benchmarks over the entire load spectrum by fitting the *PFE*'s efficiency curve to each rating. Specifically, the *PFE*'s efficiency curve almost exactly hits the 50% load efficiency benchmark for the *Platinum* standard. So we set this curve to be the extended boundary of the *Platinum* standard and use it as a reference to fit the same curve to all other ratings accordingly. We make use of the fact that the ratings are near to identical in shape and only set apart by a constant offset. This offset is calculated at the 50% load benchmark and added or subtracted to the curve to set the boundaries for each individual 80Plus standard up to the *Platinum* standard. For the *Titanium* rating, an additional offset had to be added on top of the 50% benchmark to ensure that the curve met the respective benchmark at 10% load.

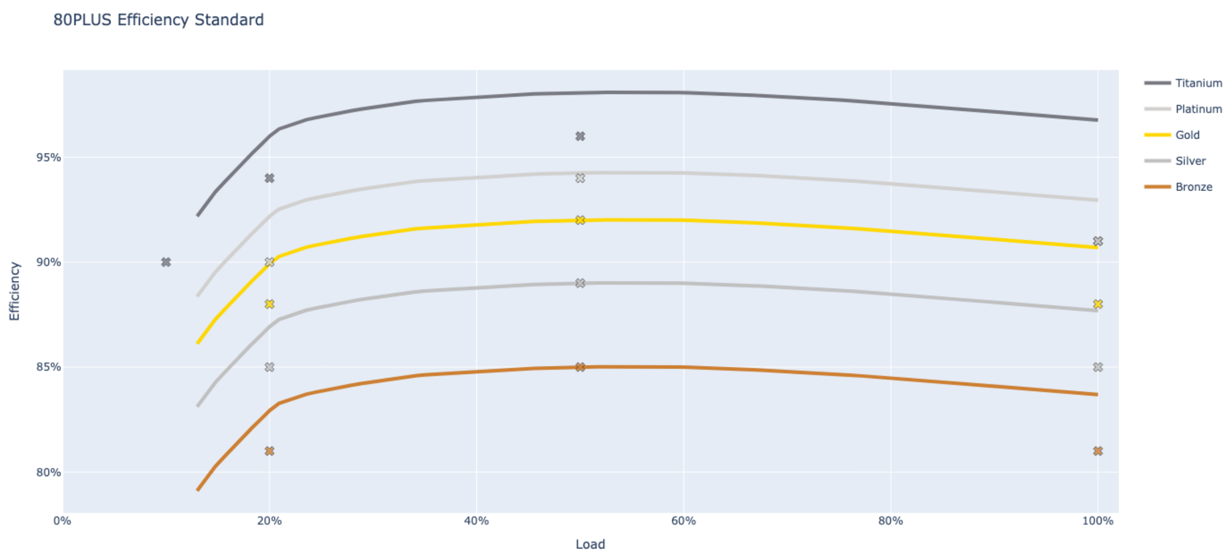

Figure 3.1: Fitting the *PFE600-054xA*'s efficiency curve to each individual 80Plus standard's benchmarks enables us to evaluate PSU's across the whole load spectrum and model changes in efficiency with varying load. Note that this model is an approximation as efficiency behavior generally varies from PSU to PSU. Nevertheless, the curves are fitted in a way that fulfills all respective efficiency requirements.

3.3 Modeling Energy Savings

The following three subsections describe the mathematical formalisms that I used to compute the energy savings by either deploying PSUs with higher 80Plus ratings, deploying a single PSU or doing both.

3.3.1 Deploying Better PSUs

Let us denote:

- P_{in}: The median *input* power (in W) of a PSU.
- E: The PSU's efficiency.
- C: The PSU's capacity.

The load of the PSU is defined as

$$L = \frac{P_{in}E}{C}. \quad (3.1)$$

The efficiency at that load for a given 80Plus rating is fixed by the respective efficiency curve, $f(L)$, as seen in Figure 3.1. This yields:

$$E_{80Plus} = f(L). \quad (3.2)$$

For every router in the dataset, the maximum value of E_{80Plus} and E is then chosen as E_{max} to recompute the PSU's *input* power

$$P_{in,new} = \frac{P_{in}E}{E_{max}} \tag{3.3}$$

The savings can thus be computed as

$$S_{absolute} = P_{in} - P_{in,new}, \quad S_{relative} = \frac{S_{absolute}}{P_{in}}. \tag{3.4}$$

The respective Python code used to compute these savings can be found in appendix A.2.

3.3.2 Switching to One PSU

Let us denote:

- P^1_{in}, P^2_{in}: The median *input* power (in W) of PSU1 and PSU2, respectively.
- P^1_{out}, P^2_{out}: The median *output* power (in W) of PSU1 and PSU2, respectively.
- E_1, E_2: The efficiency of PSU1 and PSU2, respectively.
- C: The capacity (in W) of each PSU.

The total *output* power of both PSUs (*i.e.* the power that the router required) is given by:

$$P_{total} = P^1_{in}E_1 + P^2_{in}E_2. \tag{3.5}$$

The loads are defined as

$$L_1 = \frac{P^1_{in}E_1}{C}, L_2 = \frac{P^2_{in}E_2}{C}. \tag{3.6}$$

If we decide to remove one PSU, the remaining PSU must deliver the same total output power P_{total} (from (3.5)). We thus define the new load of the single PSU as

$$L^{single} = \frac{P_{total}}{C} \tag{3.7}$$

Defining $f(L)$ as the efficiency curve function, we compute the new efficiency of the single PSU, E^{single}, as

$$E^{single} = f(L^{single}) + \delta \tag{3.8}$$

where δ is the offset of the PSU's efficiency to the *PFE*'s efficiency curve.

The *input* power of the single PSU is now simply calculated as

$$P^{single}_{in} = \frac{P_{total}}{E^{single}}. \tag{3.9}$$

The savings can thereby be computed as

$$S_{absolute} = P^1_{in} + P^2_{in} - P^{single}_{in}, \quad S_{relative} = \frac{S_{absolute}}{P^1_{in} + P^2_{in}}. \tag{3.10}$$

The respective Python code used to compute these savings can be found in appendix A.1.

3.3.3 Combining Methods 3.3.1 and 3.3.2

Taking L^{single} and E^{single} from section 3.3.2, we use $f_{80Plus}(L)$ to compute the efficiency of a PSU with a specific 80Plus rating:

$$E^{single}_{80Plus} = f_{80Plus}(L^{single}). \tag{3.11}$$

The maximum value of E^{single}_{80Plus} and E^{single} is taken as new efficiency to compute

$$P^{single}_{in} = \frac{P_{in}E^{single}}{E_{max}}. \tag{3.12}$$

The savings can thereby be computed as

$$S_{absolute} = P^1_{in} + P^2_{in} - P^{single}_{in}, \quad S_{relative} = \frac{S_{absolute}}{P^1_{in} + P^2_{in}}. \tag{3.13}$$

The respective Python code used to compute these savings can be found in appendix A.3.

3.4 Cisco Nexus 9336C-FX2 Switch

To verify and empirically study the effects of running a router on a single PSU, I used a *Cisco Nexus 9336C-FX2 NX-OS Mode Switch* [1]. The Nexus 9336C is a typical 36-port router that is deployed in big-scale data centers and automated cloud environments. It features all modern functionalities (*e.g.* hot-swappable PSUs, programmability through *Cisco NX-OS*, etc.).

The whole setup additionally consisted of an external power measurement device and a workstation to dynamically simulate a load on the router by generating and sending network traffic. The external power measurement device was routed in between the power outlet and the router's PSUs.

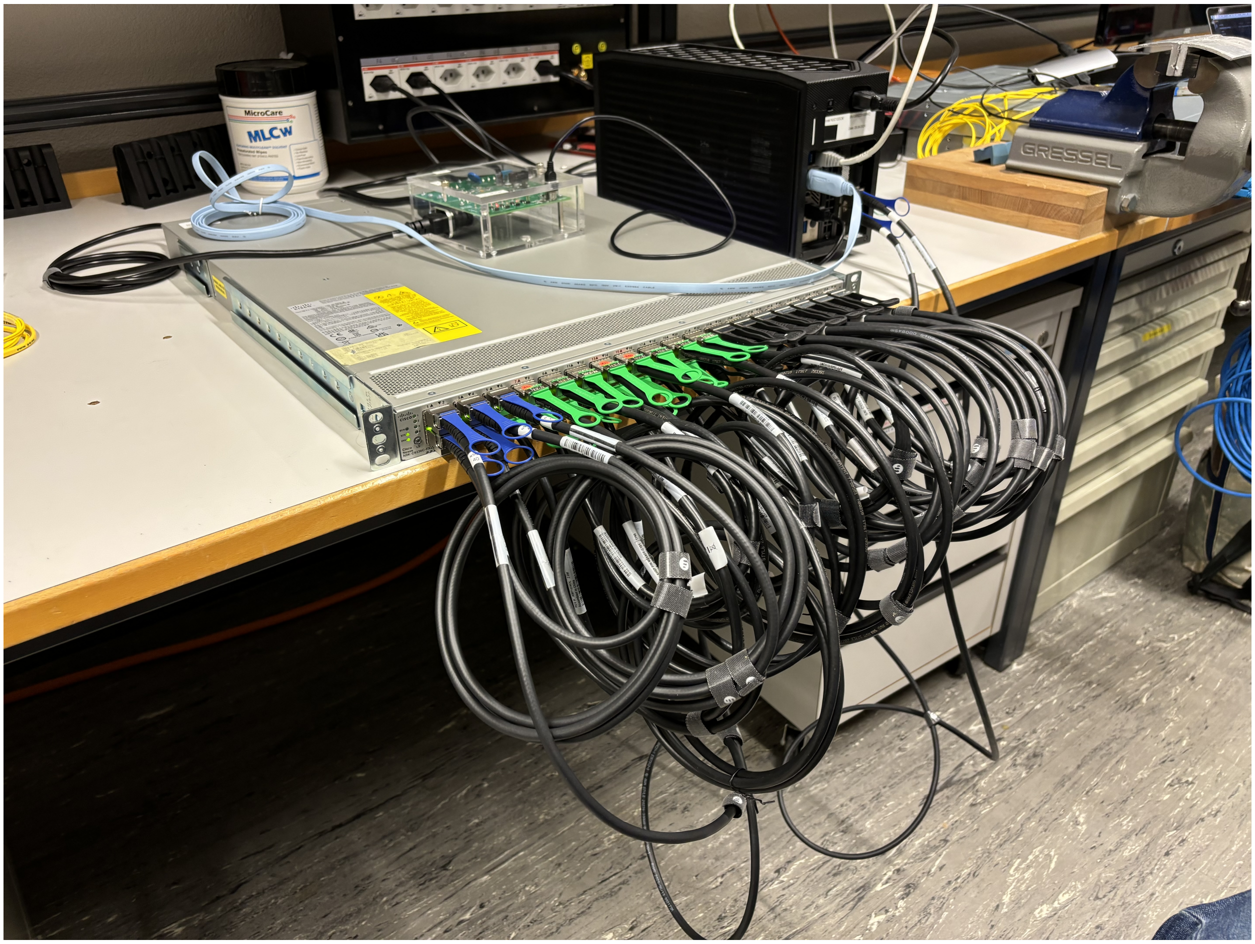

Figure 3.2: To generate as much load on the PSU as possible, traffic was looped through all 36 ports of the router.

Chapter 4

Evaluation

4.1 Current State of PSU Utilization

The foundational ground on which I argued for the potential of energy savings is a current under-utilization of PSUs in data transmission networks.

Load

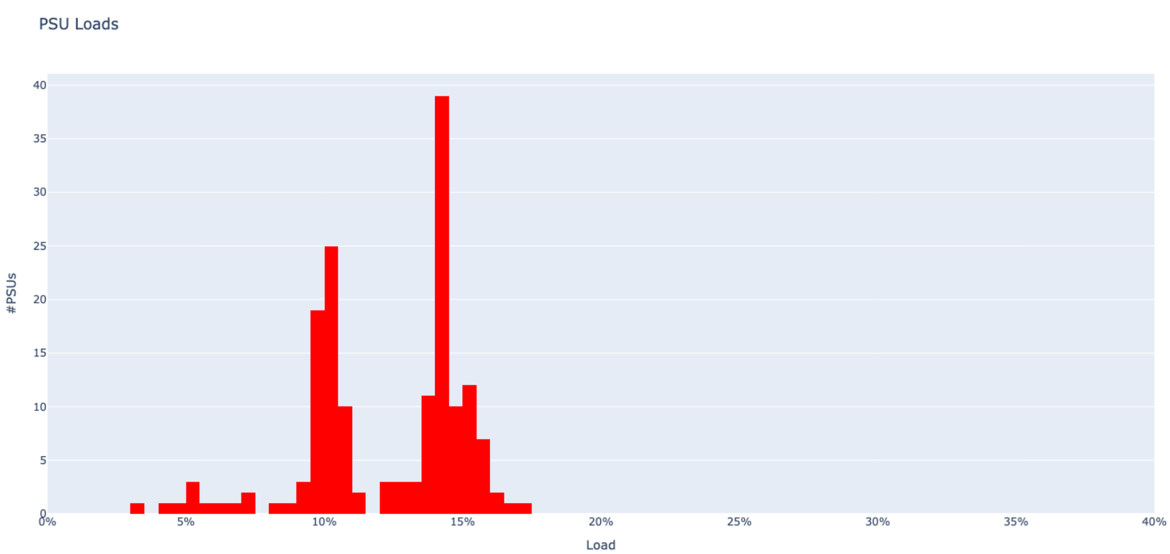

Figure 4.1: The load distribution of 82 routers inside SWITCH's network topology. A maximum efficiency of 17% shows how severely underutilized PSUs are.

Figure 4.1 proves the claim above to be valid.

The loads mainly concentrate around two points; these being 10% and 14%. The cause of this observation is can be found in table 4.1 where we observe most routers to either draw around 38W or 175W through their PSUs with capacities of 250W or 1100W, respectively, depending on the router model.

Router Model	Mean Power Consumption per PSU	PSU Capacity	Count
ASR-920-24SZ-M	38W	250W	52
N540-24Z8Q2C-M	80W	400W	1
8201-24H8FH	188W	2000W	2
8201-32FH	188W	2000W	4
NCS-55A1-24H	175W	1100W	10
NCS-55A1-24Q6H-SS	175W	1100W	6
NCS-55A1-48Q6H	175W	1100W	7

Table 4.1: Rounded mean input power consumption and PSU capacity of all analyzed router models taken from the SNMP-dataset. We see that most routers either draw 175W-188W or 40W from their PSUs.

Efficiency

Putting the data into the context of the extended boundaries of the 80Plus standards introduced in Section 3.2 strengthens the case of a margin for efficiency improvements.[1]

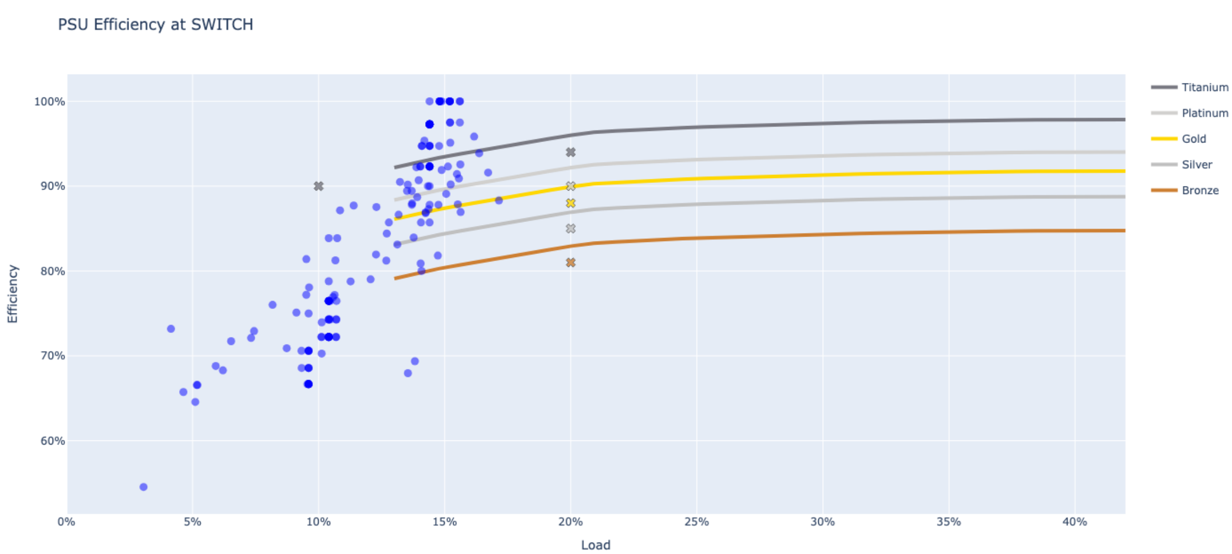

Figure 4.2: Underutilization leads to inefficiency as seen by the blue marked data points each representing one of 164 PSUs from the *SWITCH* data.

4.2 Results of Power Modelings

Applying the power modelings described in Sections 3.3.1 and 3.3.2 produced promising results in energy savings. In the following, I will individually present the results for each of the three energy saving methods:

1. Improving efficiency by deploying better PSUs of a universally fixed minimum 80Plus rating.

[1]PSUs with efficiencies of 100% are an indication for inaccurate power data and are discussed further down in Section 4.4.

2. Improving efficiency through increasing utilization by running each router on a single PSU (instead of two).

3. Combing methods 1 and 2 to run each router on a single PSU with an improved 80Plus rating.

Deploying better PSUs

80Plus Rating	Absolute Savings	Relative Savings
Bronze	445 W	3.2 %
Silver	687 W	5 %
Gold	888 W	6.5 %
Platinum	1076 W	7.8 %
Titanium	1469 W	10.7 %

Table 4.2: Deploying better PSUs could generate energy savings anywhere between 3-11% of energy savings depending on the universally fixed minimum 80Plus rating.

Switching to one PSU

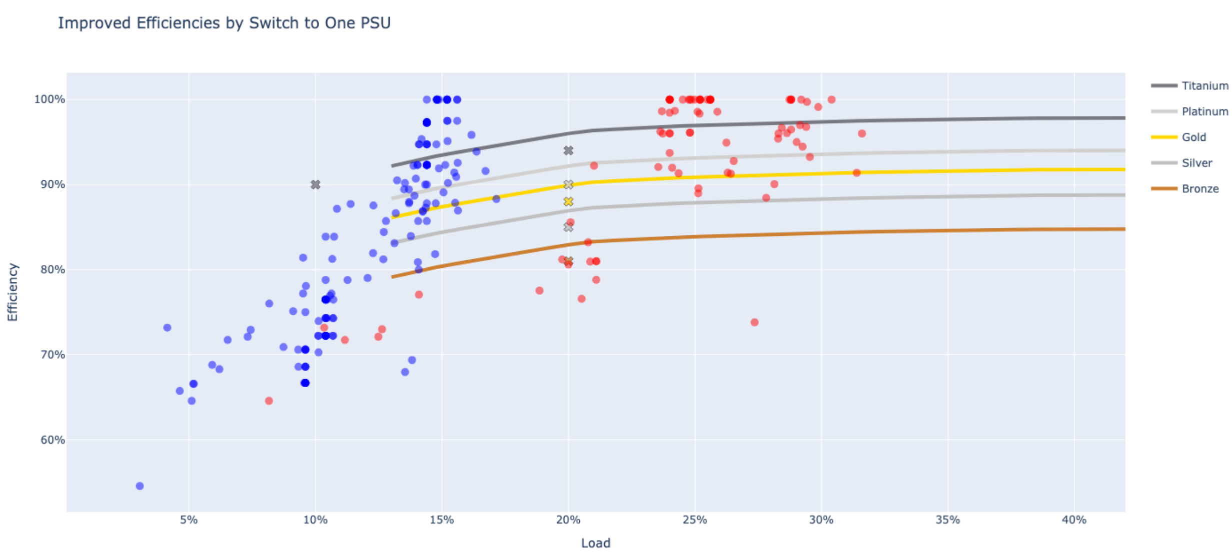

Figure 4.3: Marked blue are the original PSUs whereas the red markers represent the PSUs after switching to a single PSU per router. The energy savings would amount to 7% or 1001W.

Combining both methods

80PLUS Rating	**Absolute Savings**	**Relative Savings**
Bronze	1266 W	9.2 %
Silver	1413 W	10.3 %
Gold	1534 W	11.2 %
Platinum	1654 W	12 %
Titanium	1940 W	14.1 %

Table 4.3: Combining both energy saving methods to run each router on a single PSU of a minimum 80Plus rating generates the highest savings being between 9-14%.

Summary of results

Although the generated numbers above are fully reliant on the underlying data, all presented measures are expected to lead to significantly high savings.

4.3 Critical Assessment

Despite the promising results of Section 4.2, we cannot deny that the modelings rely on multiple critical assumptions. Some flaws have to be addressed.

Violation of 80Plus Ratings

PSUs are not necessarily as efficient as their 80Plus certifications suggest. Figure 4.4 provides an example of a PSU that does not comply with its respective rating. We can, therefore, not (with absolute certainty) assume all PSUs to have a minimum efficiency when we compute the savings of deploying PSUs with higher 80Plus ratings. Consequently, the real savings could possibly fall below the calculated values.

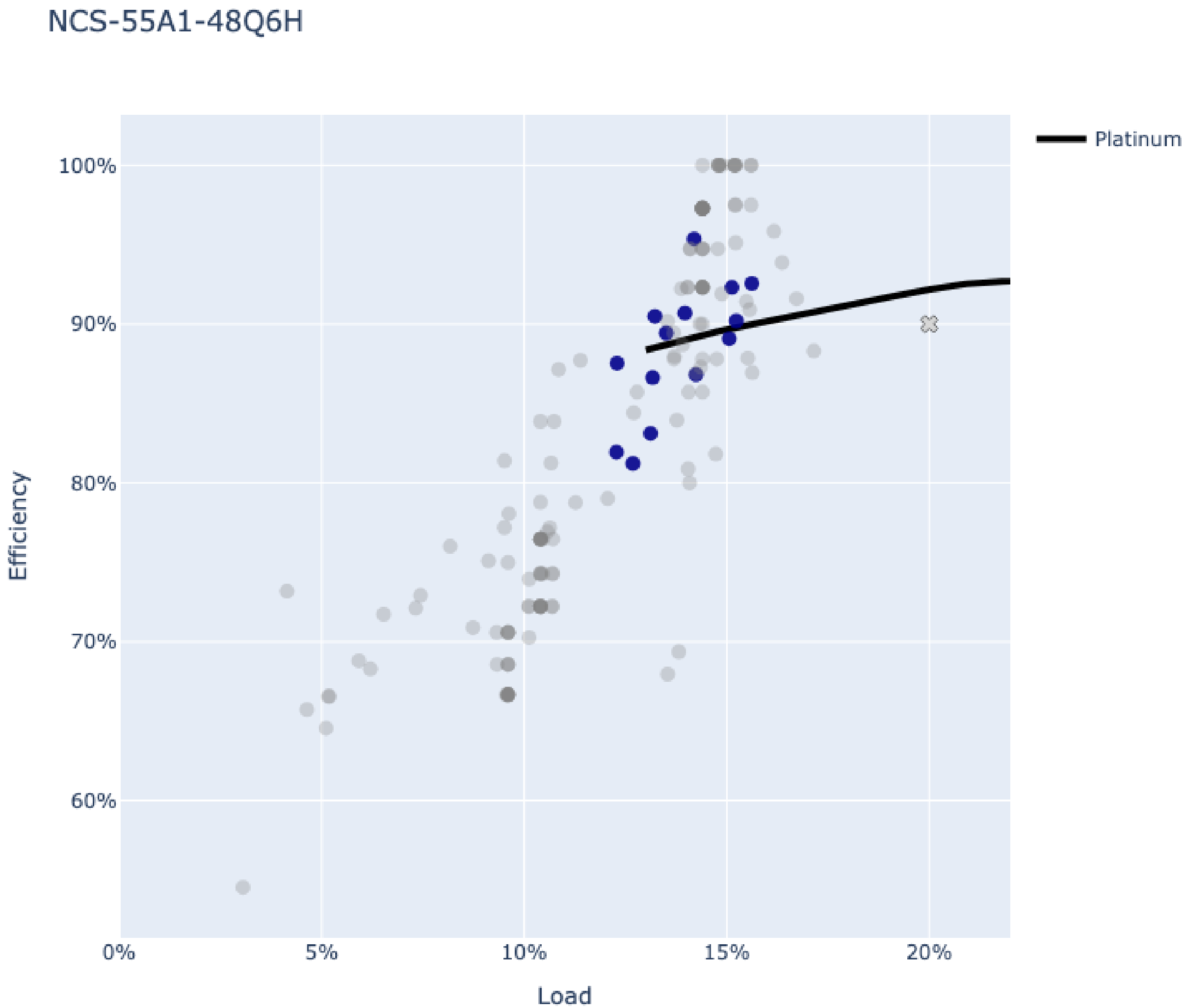

Figure 4.4: According to the inventory files from *SWITCH*, the PSU inside the *NCS-55A1-48Q6H* router is an *NCS-1100W-ACFW* PSU (marked blue here) which is *Platinum*-certified. However, some of the PSUs fail to meet the relevant efficiency requirement.

Other Factors Influencing Efficiency

The modelings consider load as the only parameter to influence PSU efficiency. An easy guess as to what other factor could have an effect on efficiency is the temperature of the router or, more specifically, the PSUs.

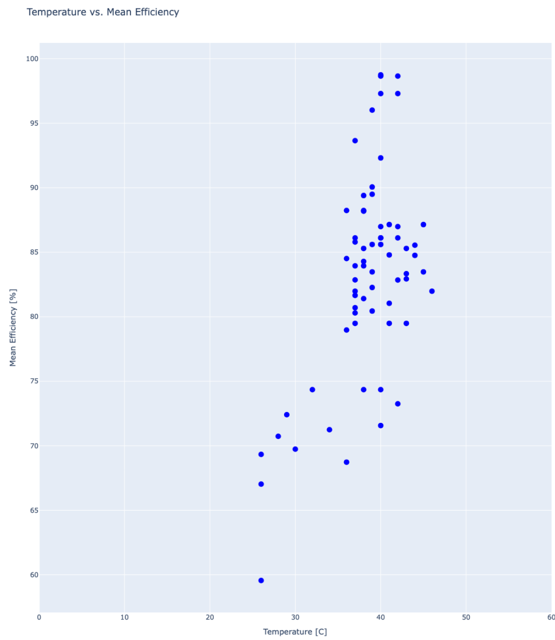

Figure 4.5: The dataset provided data on the router's inlet temperature, which is a metric that should influence both PSU's equally.

Plotting the inlet temperature of the router against the PSU's efficiencies did not lead to any clear conclusions. However, we might be able to see a very slight linear correlation between both parameters. The influence of temperature on efficiency should hence be investigated more closely, which in our case was not possible to a lack of data.

Should the router's temperature indeed affect PSU efficiency, it should be included into the modelings of energy savings.

Unreliability of Power Data

Figure 4.2 displays some PSUs at 100% conversion efficiency. Generally, this is almost near to impossible, but in fact, these values have already been capped to 100% to maintain somewhat realistic results in the computation of energy savings. In the original unprocessed data (Figure 4.6), these efficiency values go beyond 100% which undeniably indicates errors in the PSU-internal power sensor's measurements.

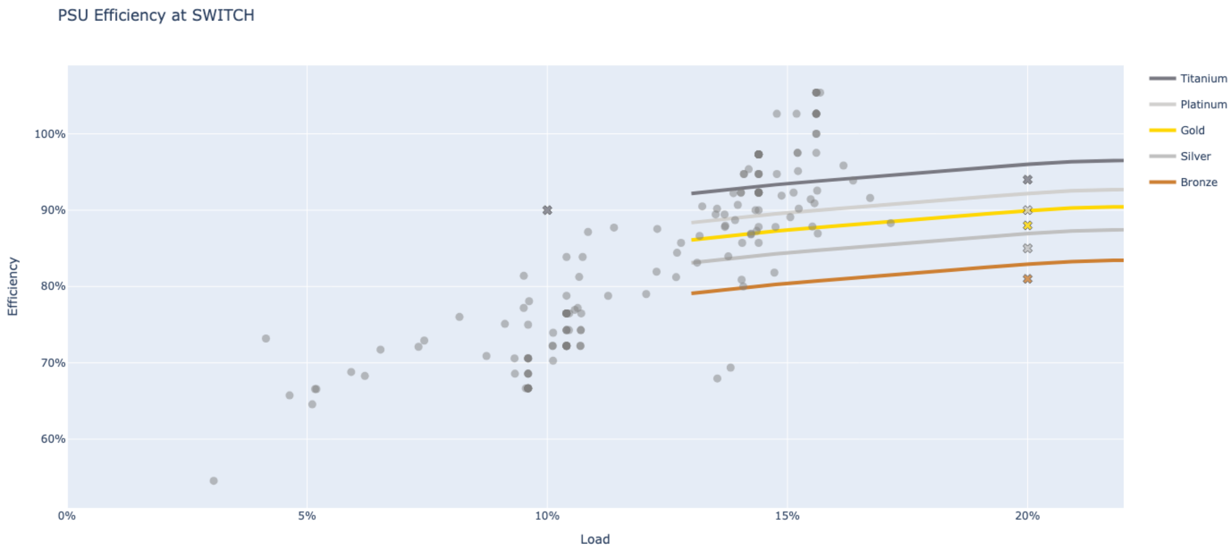

Figure 4.6: Some PSUs in the one-time-snapshot of the environment sensor readings had values for input and output power that led to computed efficiencies of over 100%.

If the PSU-internal power data includes values that are evidently wrong, how can we be sure that the modelings of power savings, which are entirely based on this data, produce reasonable savings estimates?

4.4 Verifying the Power Data

As we have now evidently seen in Section 4.3, the PSU-internal measurements seem to be flawed, if not completely incorrect. This threatens the power modelings to be imprecise as a whole, since the computation of energy savings exclusively relies on PSU-internal power data.

To assess the precision of a typical router's power sensor readings, I compared the Cisco router's internal measurements to those of an external measurement device that was set up as described in Section 3.4.

4.4.1 Comparing internally and externally measured input power data

First, I will merely state observations regarding the differences in external and internal power measurements.

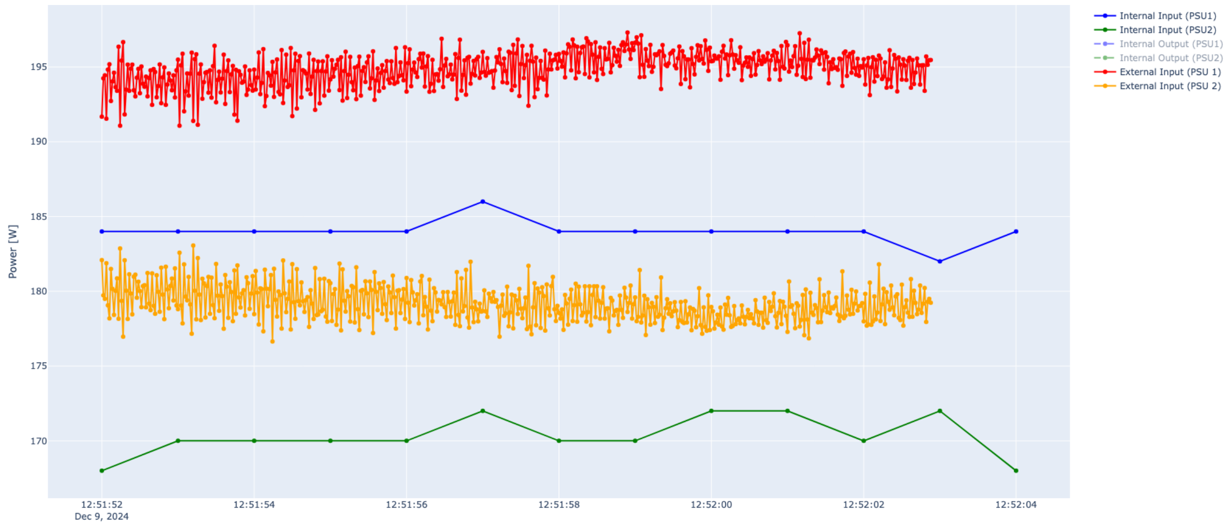

Figure 4.7: The figure contains four plots equaling an external and internal input power measurement per one of the two PSUs over a time interval of 12 seconds. External measurements were taken in 20ms intervals whereas the internal measurement was only able to record power data in one-second intervals. The internal measurements of input power are off by 9W or 11W compared to the external measurements, which we know to be from a correctly calibrated sensor.

Given the fact that the external measurements of power were sampled at a much higher frequency than the internal measurements, I cannot make any comments on differences in patterns between internal and external measurements. This, however, should not change the conclusions to be drawn from the measurements.

What is apparent, is that the mean values of the internal power measurements fell below the external mean values by 9-11W.

	Internal	**External**	**Offset**
PSU 1	184 W	195 W	11 W
PSU 2	170 W	179 W	9 W

Table 4.4: An overview of the mean power values in Figure 4.7.

Repeating the same experiment while the router was only supplied by a single PSU showed an equal offset between the measurements on PSU1.

	Internal	**External**	**Offset**
PSU 1	358 W	369 W	11 W

Table 4.5: An overview of the mean power values in Figure 4.8.

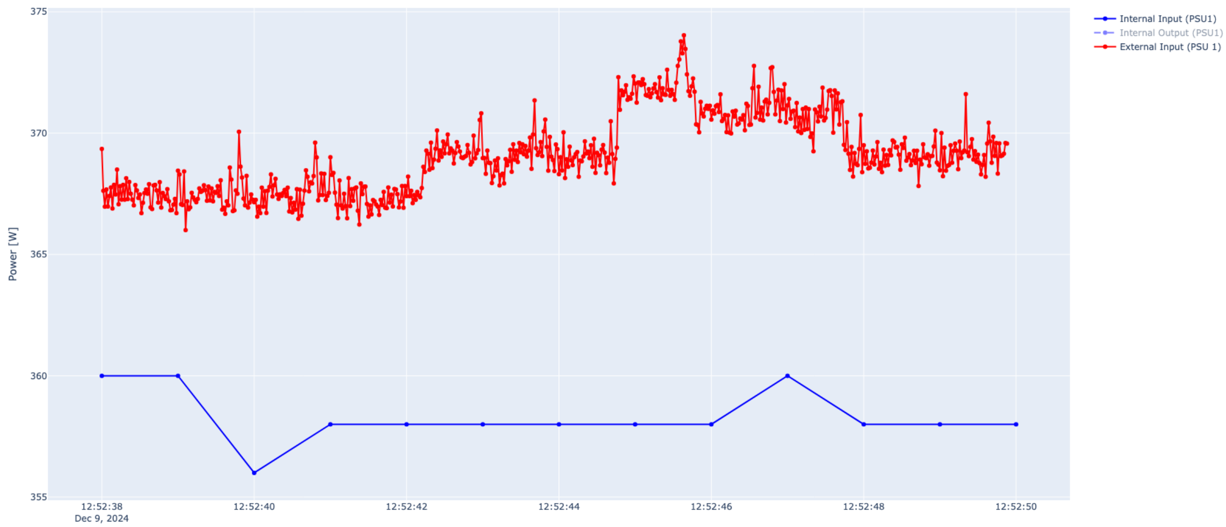

Figure 4.8: Again, we obtain an offset of 11W between the internal and external measurements of input power. Mind that this figure only contains two plots instead of four, because the router was only running on a single PSU in this experiment.

Considering that the difference in load on PSU1 between both measurements is approximately 25% [2], we can conclude the deviation of power values to be constant and independent of load.

4.4.2 Comparing internal input and output power data

Furthermore, the comparison of the internal input and output power measurement raises a few question marks.

[2]As we are dealing with a 750W-rated PSU, the load on PSU1 when running in parallel to PSU2 can not be higher than $\frac{195W}{750W} = 26\%$ according to the externally measured input power value whereas this upper load boundary increases to $\frac{369W}{750W} = 49.2\%$ when PSU1 runs alone. Considering that the PSU runs at better efficiency for loads closer to 50%, the difference in loads between both configurations should be slightly higher than 23.2%.

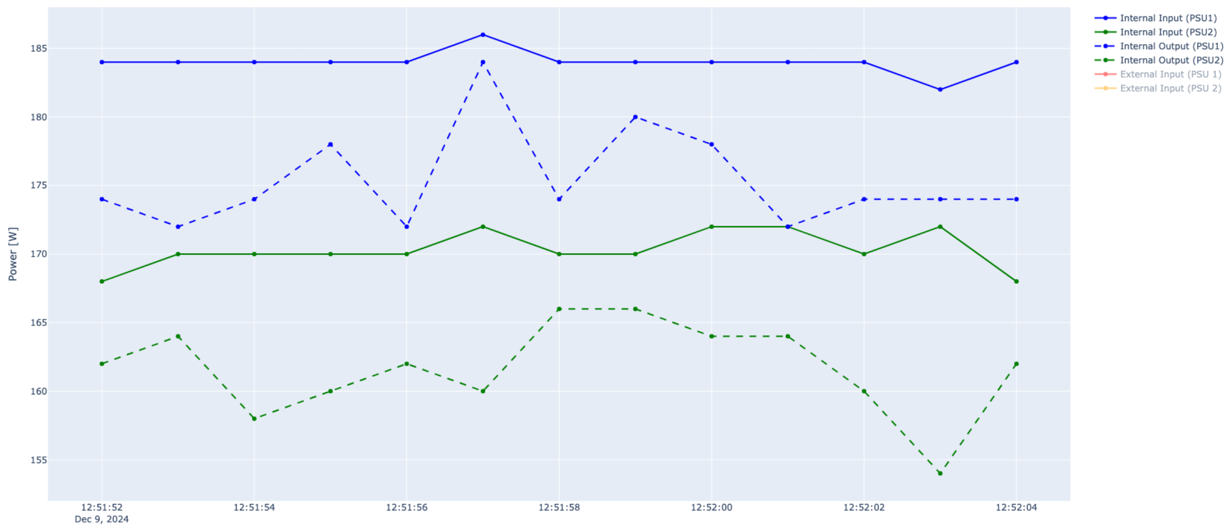

Figure 4.9: The evolutions of input and output power do not match each other. Notice how output power on PSU1 at timestamp 12:51:57 almost matches input power, which should not happen according to our understanding of PSUs where power losses do not arbitrarily in-/decrease.

We notice that the internal input power fluctuates much less than the internal output power, which are both sampled in 1 second intervals. In general, the difference in patterns between input and output power is surprising, since we would expect both plots to evolve synchronously due to efficiency staying rather constant. In that case, the plot of the output power should more or less have the same shape as the input power with an offset that occurs due to energy losses, which (due to constant efficiency) should be constant as well.[3]

4.4.3 Interpreting the measurements

The main observations from Sections 4.4.1 and 4.4.2 are:

1. The external and internal input power measurements of PSU1 and PSU2 are offset by 11W and 9W respectively.

2. The internal input power fluctuates much less than the internal output power data. Hence, the input and output power plots evolve differently, which is odd considering efficiency to remain rather constant here due to which the patterns of both plots should be similar in shape, if not synchronized.

As we know the external power measurement device to be precise, we need to investigate the exact origin of the PSU's power measurements, *i.e.* the location of the power sensors inside the PSU, to derive possible causes for the deviation of the PSU's internal power measurements.

PSU-internal power sensors

Since Cisco does not publicly provide details to their products, we have to look into the schematics of another PSU; the *PFE600-12-054xA* introduced in Section 2.1.1.

[3]Technically, the efficiency is not really constant as it depends on the load, but at such marginally small fluctuations of maximum 10W in a 750W PSU as shown in Figure 4.9 we can consider the efficiency to be approximately constant.

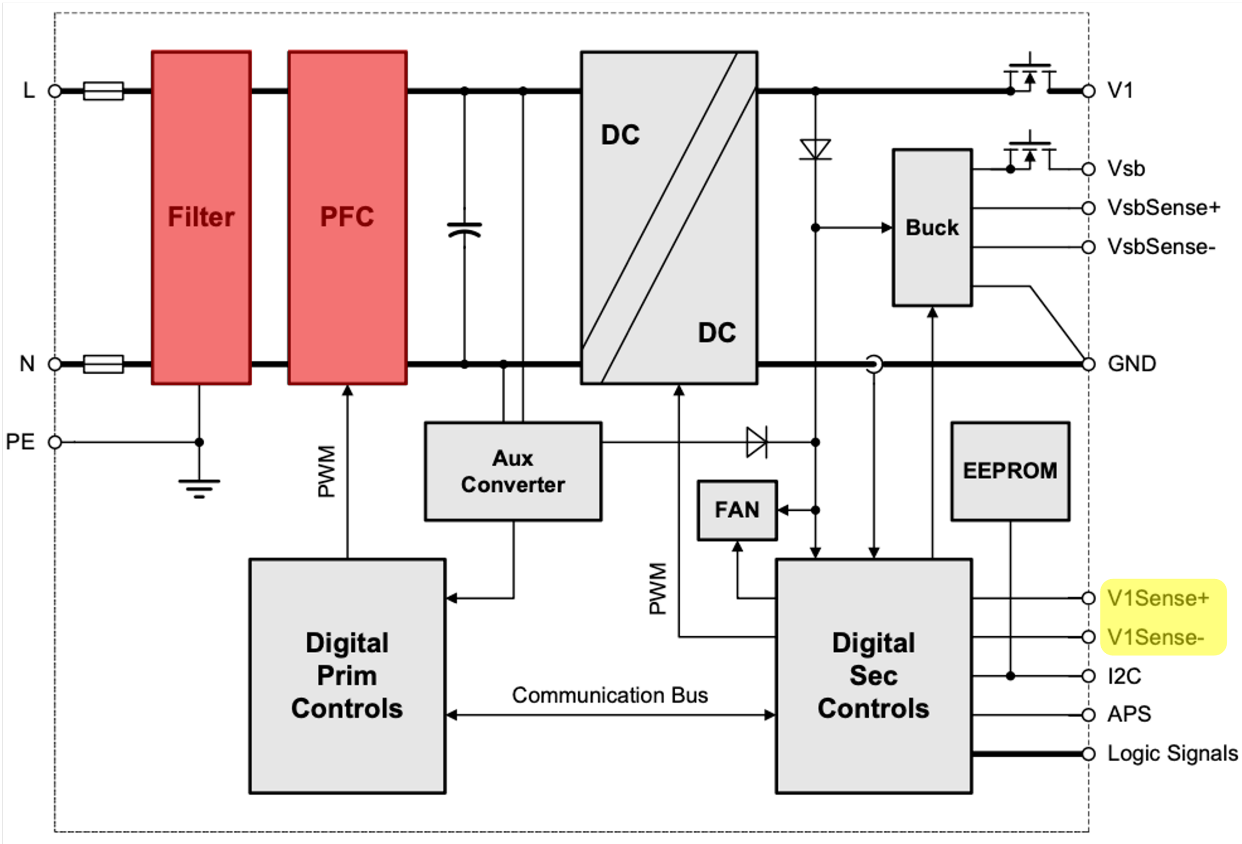

Figure 4.10: The power converting components (Filter and Power-Factor-Correction (PFC)) are marked in red while the sensor output are marked in yellow. All lines leading to the sensors originate from behind the Filter and PFC. [2]

According to the schematics and datasheet, only one power sensor is of interest and it is located behind the AC-DC conversion chain [2].

Why could this be an issue and what do I mean by 'AC-DC conversion chain'?

Looking at the outputs of the block diagram in Figure 4.10 we see that the PSU has two different sensors labeled as *Vsb* and *V1*. We can neglect *Vsb* as this sensor only has system-internal functionalities unrelated to power measurement according to the PSU's datasheet [2]. *V1*, on the other hand, is used to record the internal power data at the PSU's output. Let me emphasize that once again – there is only one power sensor which is at the output of the PSU, far behind the input, meaning that the PSU is actually only capable of measuring the output power.

Therefore, we can conclude the input power measurement of the PSU itself to be a value that is simply computed from the measured output power value.

Only placing a power sensor at the output of the PSU can have multiple reasons. Having a power sensor at the input of the PSU would expose it to any sudden current bursts that could harm the sensor. The sensor at the output is protected from any harmful currents coming from the energy source and further measures a cleanly filtered signal at 12V DC which is much easier than measuring power at 230V AC. Therefore, we can also assume this engineering decision to be cost-motivated as implementing sensors at the input of the PSU would require much more sophisticated components, ultimately increasing the cost of the PSU.

Internal computation of input power

The consequential sacrifice of saving production costs and computing power values internally is that all measurements rely on the precision of one single sensor. As soon as the output sensor is off in measurement due to miscalibration or inevitable aging-effects, the measurement error propagates through the internal calculation of input power, resulting in incorrect power values, as likely happened above in Section 4.4.1.

Although we do not know the exact formula that is used to compute the input power value, it is probably based on the PSU's efficiency curve and, potentially, other parameters that are precisely correlated to the PSUs efficiency so that $P_{in} = \frac{P_{out,measured}}{E(L,x)}$, where $E(L, x)$ is the PSU's efficiency depending on load, L, and other factors x.

Furthermore, the asynchronous evolution and lack of fluctuation of internal input power compared to output power gives reason to believe that the computation of input power does not happen 1-on-1 for every output power value in real-time, but that it is rather based on an average of the past N output power values. Of course, this may make the input power values of the PSU's more robust against outliers in output power measurements. I could also imagine understanding this approach under the circumstances that the power data of routers is usually not sampled in such small intervals as I did. Nevertheless, the goal should be to produce precise and accurate power data which, in this case, is clearly not given. Especially when studying PSU efficiency, this method of computing input power based on an average of output power values harms the accuracy of results.

For instance, imagining a scenario in which the power consumption of a router suddenly increases significantly just right before a power measurement is conducted. The output power value given by the PSU upon query may be correct as it is assumed to be a real-time value, but the input power data will be based on an average of output power data that might not yet reflect the surge in power consumption. Not only does this lead to measurements as seen at timestamp 12:51:57 on PSU1 in Figure 4.9, but to efficiencies over 100% as seen in the *SWITCH* data from Figure 4.6.

4.5 Application

Interestingly, summing up the power consumption of both PSUs for each measurement method (internal or external) and each configuration (1 or 2 PSUs) yields two different interpretations of the effects that switching to a single PSU per router has.

	Two PSUs	**One PSU**	**Savings**
Total Internal Input	354 W	358 W	-11 W (-1.1%)
Total External Input	374 W	369 W	5 W (1.3%)

Table 4.6: The absolute savings are computed as $S_{Abs} = P_{2PSUs} - P_{1PSU}$, meaning positive values indicate energy savings by switching to one PSU and negative values indicate an increase in power consumption when switching to one PSU. The relative savings are the ratios of the absolute savings and power consumption, P_{in}, on two PSUs.

According to the internal power measurement, power consumption increases by switching from two PSUs to one PSU on the Cisco router. Conversely, the external measurements suggest a decrease of power consumption.

As discussed in Section 4.4.3 the power sensor readings of the PSU are prone to errors. Thanks to the externally measured power data, we know the PSU's internal power readings to deviate from the real values. Adding this deviation on top of the internal power measurements shown in 4.6 does confirm energy savings as seen in table 4.7. This perfectly illustrates how subtle measurement errors can lead to completely different interpretations of an experiment, highlighting the importance of accurate PSU internal power measurements.

We can thus conclude that switching to one PSU on underutilized routers saves energy.

	Two PSUs	**One PSU**	**Savings**
Total Internal Input	354 W	358 W	-11 W (-1.1%)
Corrected Internal Input	374 W	369 W	5 W (1.3%)
Total External Input	374 W	369 W	5 W (1.3%)

Table 4.7: Adding the offset on top of the internal power measurements yields a result that aligns with the external power measurements, confirming enegy savings

Chapter 5

Outlook

Investigating the correctness of router internal power measurements is definitely an exciting task that is left for future work. In order to properly understand the power consumption of network routers, it is necessary to have access to viable data that precisely reflects a router's PSU usage. Otherwise, the theoretical energy savings will not be anywhere close to what can be expected in reality.

Examining other possible factors that affect PSU efficiency aside from load would be essential to improving the modelings of energy savings.

Furthermore, we need to examine the feasibility of introducing some "hot-standby" into PSU technology for network routers [4]. The idea would be to have a configuration that enables a router to run on a single active PSU and another inactive PSU that could seamlessly take over the power supply in case the active PSU fails. This would be critical in handling router reliability and redundancy when reducing the number of PSUs inside a router to save energy. No one will want to give up redundancy to save "some" energy.

Chapter 6

Summary

This project has revealed multiple promising insights into ways of reducing the amount of wasted energy in a steadily growing network. The key takeaways are:

- PSUs in current networks seem severely underutilized at maximum loads of 17%, leading to poor power conversion efficiencies with a mean efficiency of 83.5% among all PSUs considered.
- Increasing PSU utilization by reducing the number of PSUs per router is projected to lead to significant savings in energy of 7%, whereas simply deploying higher-rated PSUs than the ones in operation currently could generate savings of almost up to 11%.
- Switching to a single PSU on a poorly utilized router is empirically proven to reduce its total power consumption.
- PSU internal power measurements are inaccurate. They might provide reasonable numbers that are in the ballpark of the real values, but small discrepancies can cause major differences in interpretation.

Although the computation of energy savings relied on evidently flawed and inaccurate data, the results of the modelings provide a great incentive to put more efforts into improving data collection in PSUs. The modelings may be precise but as long as the power data is not, we will not be able to commit to the produced results fully.

The modelings themselves should be further refined too. The computations presented in Chapter 3 may only be an optimistic approximation of the real energy savings which could be much lower. For instance, adapting the efficiency curve of the model to each PSU's actual efficiency curve would produce much more realistic models as well as having data on the output power of each PSU over a longer period of time instead of a snapshot would be beneficial to the computation.

Concluding, PSUs have so far been studied too little and should definitely be given more attention when looking for ways to optimize power consumption in our network as this could lead to substantial energy savings. We should improve modelings of PSU energy savings to provide much more precise estimates and attract the interest of network providers and others to implement suggested energy saving measures.

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Appendix A

My Appendix

A.1 Python code to compute savings of switching to a single PSU

```
def get_new_efficiency(row, PSU, load_label):
    offset = row['efficiency_PSU' + PSU] - eff_interp(row['load_PSU' + PSU])
    return custom_eff(row[load_label],offset) # row[load_label] is the new load of the one PSU

df['total_power_out'] = df['median_power_PSU1']*df['efficiency_PSU1'] + df['median_power_PSU2']*df['efficiency_PSU2']
df['total_load'] = df['total_power_out'].div(df['PSU_capacity'])

for PSU in ['1', '2']:
    df[f'efficiency_PSU{PSU}_total_load'] = df.apply(get_new_efficiency, args=(PSU, 'total_load'),axis=1)

if cap == True:
    df['max_efficiency'] = df[['efficiency_PSU1_total_load','efficiency_PSU2_total_load']].max(axis=1).clip(upper=1.0)
else:
    df['max_efficiency'] = df[['efficiency_PSU1_total_load','efficiency_PSU2_total_load']].max(axis=1)
df['total_power_in'] = df['total_power_out'].div(df['max_efficiency'])

# savings per router
df['savings_abs'] = (df['median_power_PSU1']+df['median_power_PSU2']) - df['total_power_in']
df['savings_rel'] = df['savings_abs'].div(df['median_power_PSU1']+df['median_power_PSU2'])

# global savings
savings_total_abs = df['savings_abs'].sum(axis=0)
savings_total_rel = savings_total_abs / (df['median_power_PSU1'].sum(axis=0) + df['median_power_PSU2'].sum(axis=0))
```

A.2 Python code to compute savings of deploying better PSUs

```
for cert in [br, si, gol, pl, ti]:
    for PSU in ['1', '2']:
        df['efficiency_PSU{}_as_{}'.format(PSU, cert.__name__)] = df[f'load_PSU{PSU}'].apply(cert)
        df['efficiency_PSU{}_as_{}'.format(PSU, cert.__name__)] = df[['efficiency_PSU{}_as_{}'.format(PSU, cert.__name__),
                                                                       f'efficiency_PSU{PSU}']].max(axis=1)

        df['power_in_PSU{}_as_{}'.format(PSU, cert.__name__)] = df['median_power_PSU' + PSU]
                                                                * df['efficiency_PSU' + PSU]
                                                                / df['efficiency_PSU{}_as_{}'.format(PSU, cert.__name__)]

        label_savings_abs = 'savings_abs_PSU{}_{}'.format(PSU, cert.__name__)
        label_savings_rel = 'savings_rel_PSU{}_{}'.format(PSU, cert.__name__)
        df[label_savings_abs] = df['median_power_PSU' + PSU] - df['power_in_PSU{}_as_{}'.format(PSU, cert.__name__)]
        df[label_savings_rel] = df[label_savings_abs] / df['median_power_PSU' + PSU]

# Compute the gains
savings_total_abs = df['savings_abs_PSU1_'+cert.__name__].sum(axis=0) +  df['savings_abs_PSU2_'+cert.__name__].sum(axis=0)
savings_total_rel = savings_total_abs / (df['median_power_PSU1'].sum(axis=0) + df['median_power_PSU2'].sum(axis=0))
```

A.3 Python code to compute savings of a single better PSU

```
for cert in [br, si, gol, pl, ti]:
    label_eff = 'efficiency_' + cert.__name__
    df[label_eff] = df['total_load'].apply(cert)
    df[label_eff] = df[[label_eff,'max_efficiency']].max(axis=1)

    df[f'median_power_{cert.__name__}'] = df['total_power_in'] * df['max_efficiency'] / df[label_eff]

    label_savings_abs = 'savings_abs_' + cert.__name__
    label_savings_rel = 'savings_rel_' + cert.__name__
    df[label_savings_abs] = df['total_power_in'] - df[f'median_power_{cert.__name__}']
    df[label_savings_rel] = df[label_savings_abs] / df['total_power_in']

    savings_total_abs = df['savings_abs_'+cert.__name__].sum(axis=0) + df['savings_abs'].sum(axis=0)
    savings_total_rel = savings_total_abs / (df['median_power_PSU1'].sum(axis=0) + df['median_power_PSU2'].sum(axis=0))
```