

Estimating the Carbon Footprint of Personal Computing

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Brief Introduction

Graduate student at ETH Zürich, Switzerland

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Focus on research at the intersection of computer architecture and operating systems

Outline

Background

Problem

Goal

Relevant Work

- Windows

- macOS

- Android

- iOS

- PowerTOP

System Design

End Product

Conclusion

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Carbon Footprint = Energy Consumption $\times$ Composition

Energy Consumption = Power $\times$ Latency

Composition depends on multiple factors, including geography, availability, and cost

Energy Consumption

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Latency is determined by hardware and software

Typically, only latency is optimized by programmers

*because it is **measurable**¹, and **observable by end-users***

¹CPU clock cycles

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Software power attribution

State of consumer operating systems

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Windows: : Kernel-supported tracing (**Windows E3**)

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Software power attribution

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iOS: Kernel-supported tracing (**Battery usage**)

Linux: ??

Problem

Why software power attribution matters?

Consumers wish they had *infinite* battery capacity

Problem

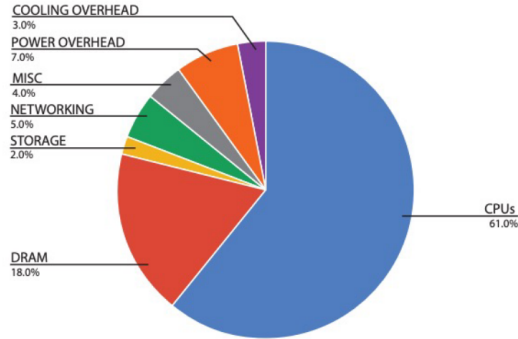
Why software power attribution matters?

Consumers wish they had *infinite* battery capacity

Battery capacity is a major design constraint and *UX factor* for any consumer device: mobiles, laptops, VR headsets [1]

[1] Cole, Wesley, A. Will Frazier, and Chad Augustine. Cost projections for utility-scale battery storage: 2021 update. No. NREL/TP-6A20-79236. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2021.

Hardware power attribution



Representative breakdown for per-component power dissipation.

Source: Barroso, Luiz André, Urs Hölzle, and Parthasarathy Ranganathan. "The datacenter as a computer: Designing warehouse-scale machines." Synthesis Lectures on Computer Architecture 13.3 (2018): i-189.

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Develop a framework to *reliably* determine the **energy consumption** of any process executing on a Linux system

Report the statistics to the

- ▶ **End-users**: In an easy-to-understand and useful format
- ▶ **Developers**: Via APIs that improve programmer actionability

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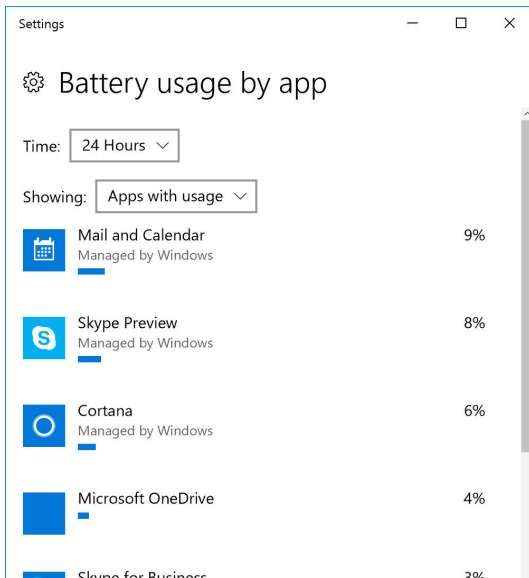
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System Design

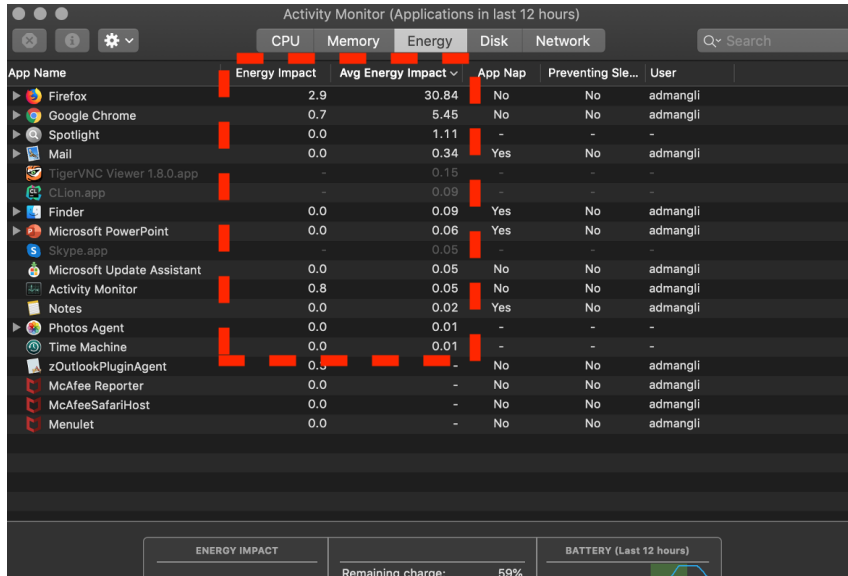
End Product

Conclusion

Windows Energy Estimation Engine (E3)



macOS



Android





PowerTOP

testuser@raquel-eth:~

File Edit View Search Terminal Help

PowerTOP 2.7 Overview Idle stats Frequency stats Device stats Tunables

Summary: 1541.8 wakeups/second, 42.9 GPU ops/seconds, 0.0 VFS ops/sec and 18.9% CPU use

Power est.	Usage	Events/s	Category	Description
4.45 W	0.0 pkts/s	Device	nic:virbr0	
1.45 W	38.7 ms/s	315.3	Process	/usr/bin/gnome-shell
353 mW	54.7%		Device	Display backlight
292 mW	36.7 ms/s	103.1	Process	/usr/libexec/Xorg vt4 -displayfd 3
200 mW	0.0 pkts/s		Device	Network interface: wlp2s0 (iwlwifi)
146 mW	7.4 ms/s	57.6	Process	/usr/libexec/gnome-terminal-server
110 mW	4.9 pkts/s		Device	Network interface: enp3s0 (r8169)
7.31 mW	1.3 ms/s	92.4	Process	/usr/libexec/at-spi2-registryd --u
0 mW	8.7 ms/s	62.0	Process	/opt/google/chrome/chrome --type=r
0 mW	5.4 ms/s	385.4	Interrupt	PS/2 Touchpad / Keyboard / Mouse
0 mW	4.9 ms/s	79.0	Process	/opt/google/chrome/chrome
0 mW	4.4 ms/s	2.5	Process	/usr/bin/python /usr/bin/powerline
0 mW	4.3 ms/s	163.0	Process	powertop
0 mW	3.6 ms/s	18.6	Process	gnome-shell --mode=gdm --wayland -

PowerTOP: The solution?

It is possible to use Powertop to view the "power estimate" of a process/device/interrupt/timer.

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2. **Vendor-specific** implementation
3. **Actionability** of this data for end-users and programmers

Process X consumes 1.45 Watts. What should the programmer do to optimize it?

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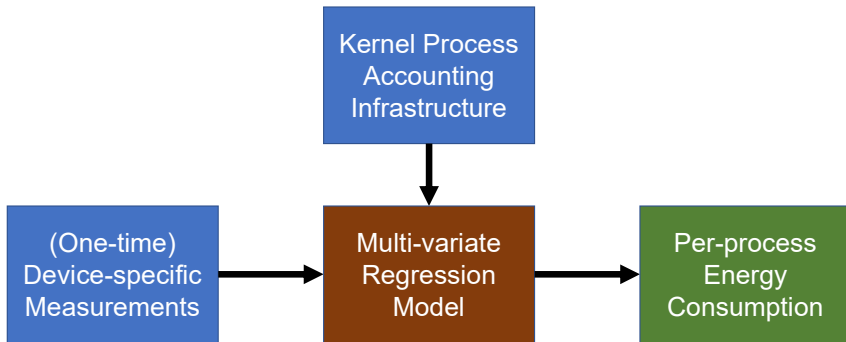
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System Design



Device-Specific Measurements

Goal: Determine regression parameters

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- ▶ Sweep target device parameters while measuring battery drain

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- ▶ Sweep target device parameters while measuring battery drain
- ▶ Train multivariate model
- ▶ Repeat for all target devices

Kernel Process Accounting Infrastructure

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- ▶ For each running process, poll the process accounting infrastructure to determine CPU time allocation, network activity, open file handles, memory usage, and screen wakeups.

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- ▶ For each running process, poll the process accounting infrastructure to determine CPU time allocation, network activity, open file handles, memory usage, and screen wakeups.
- ▶ Input the measured values in the regression model to predict energy consumption estimate for each process.

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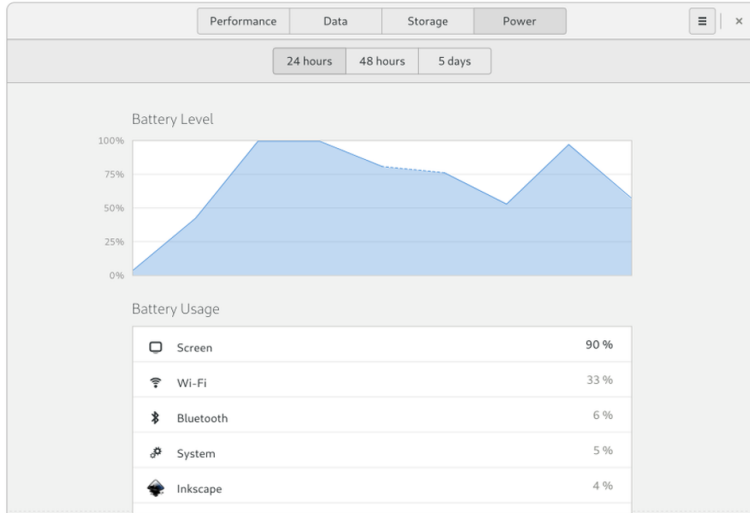
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End-users



Programmers

Upstream the **kernel module**

Expose API for programmers

Example use-case: Energy-based optimization suggestions in IDE

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A useful feature is missing from the Linux kernel

This module empowers both end-users and programmers with **realistic carbon footprint** of their applications

Questions/Suggestions ?

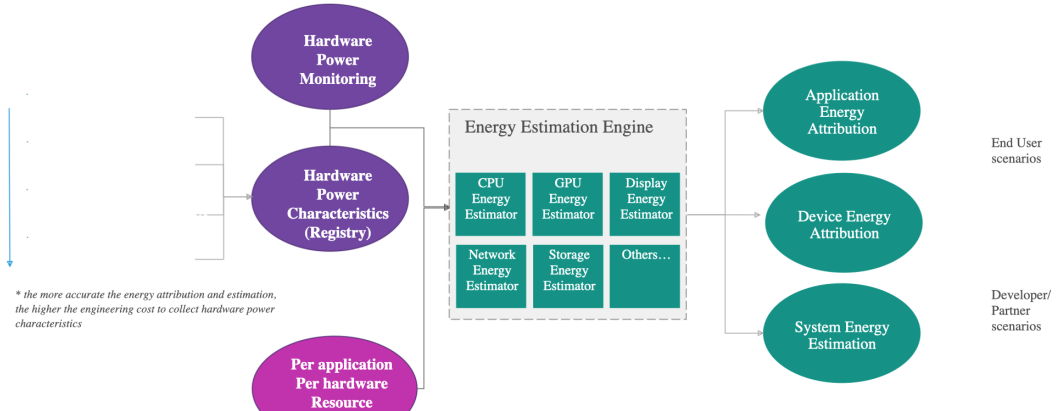
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Extended Discussion

Windows Energy Estimation Engine (E3) System Design

How Does Energy Estimation Engine Work?



Reverse Engineering Windows'

Energy Estimation Engine: back-end

- ▶ The Energy Estimation Engine (E3) service runs on all Windows devices and attributes energy consumption to individual hardware components and applications.

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Reverse Engineering Windows'

Energy Estimation Engine: back-end

- ▶ The Energy Estimation Engine (E3) service runs on all Windows devices and attributes energy consumption to individual hardware components and applications.
- ▶ Why software-based attribution: Few PCs in the market have such dedicated chips: According to reports, 99% of current devices in market lack dedicated current and voltage monitors.
- ▶ Software-based power attribution provides about 85% accuracy compared to a 98% accuracy rate from systems equipped with dedicated current and voltage monitors (e.g., Microsoft Surface)
- ▶ Microsoft claims that they prioritize data from devices with dedicated chips while developing the software-based power

E3 System Design

- ▶ Power profiles: Windows has separate power profiles for individual hardware devices like network, disks etc. Further, profiles specialize for Laptops, Tablets, Phones devices etc.
- ▶ The following data columns can be observed in the E3 Service Report (shown below): ScreenOnEnergy, CPUEnergy, SoCEnergy, DisplayEnergy, DiskEnergy, MBBEnergy, NetworkEnergy, EmiEnergy, and many more.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
1	AppId	UserId	TimeStamp	MeasuredPower	OnBattery	Foreground	ScreenOn	BatterySrv	LowPower	Interactive	Committed	TimeInMS	MeasuredBtmup	EnergyLoss	CPUEnergyC	SoCEnergyC	DisplayEnergy	DiskEnergyC	NetworkE	MBBEnergy	OtherEnergy	EmiEnergyC	TotalEnergyConsumption
2	\Device\HarddiskVolume4\Windows\explorer.exe	5-1-5-21-0	2016-08-29 22:05:00	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	Focus	TRUE	119999	0000000000	0	1605	0	357627	548	140	0	0	0	360006
3	\Device\HarddiskVolume2\Windows\System32\csrss.exe	5-1-5-18	2016-08-29 22:05:00	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	NotUnique	TRUE	124638	0000000000	0	1983	0	51	49	0	0	0	0	2083
4	\Device\HarddiskVolume1\Windows\System32\LogonUI.exe	5-1-5-18	2016-08-29 22:05:00	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	NotUnique	TRUE	20000	0000000000	0	245	0	10000	0	0	0	0	0	10000
5	Microsoft.Windows.ShellExperienceHost_x-ww-14905-1000_neutral_neutral_zh-tw	5-1-5-21-851	2016-08-29 22:05:00	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	NotUnique	TRUE	119999	0000000000	0	722	0	0	523	0	0	0	0	1245
6	\Device\HarddiskVolume4\Windows\explorer.exe	5-1-5-21-851	2016-08-29 22:05:00	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	NotUnique	TRUE	600000	0000000000	0	6507	0	178946	901	47	0	0	0	186991

Figure: Data dump from E3 CLI

System design goals

The framework should be:

Accurate: Eliminate anomalous values

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Portable: Able to function across different hardware vendors²

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System design goals

The framework should be:

Accurate: Eliminate anomalous values

Portable: Able to function across different hardware vendors²

Independent of *extra* measurement devices

Transparent: Should not induce *any* load on the target system²

Reliable: Repeat experiments should yield *similar* results

²Stretch goal

Design Optimizations

Central information store to overcome randomness?

- ▶ Overcoming variation in values: Collect data across systems to create a database

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Central information store to overcome randomness?

- ▶ Overcoming variation in values: Collect data across systems to create a database
- ▶ Privacy challenges: can we do better?

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 - ▶ Hardware devices do not measure/expose individual power draw.
 - ▶ Significant variation in data-sheets across devices and vendors.
 - ▶ Reliable values: CPU perf counters (RAPL?) and current battery charge (ACPI?)

Different hardware devices

- ▶ CPU: Dominant factor, P-states vs C-states, interfaces (Intel RAPL)
- ▶ GPU: periodic bursts of large power draw
- ▶ RAM: Increasing DRAM capacity is challenging due to refresh power draw (Reference)
- ▶ I/O Peripherals: USB devices are polled every 5 ms
- ▶ Display: Often the most consistent drain
- ▶ Network Adaptors: Ethernet, WiFi ping frequency
- ▶ Disk: SSD, HDD writes are cached for bulk ops

Design Considerations

- ▶ Hardware requirements: Cannot rely on external power monitors
- ▶ Transparency: Polling for values induces load on the target system
- ▶ Able to function across different hardware vendor APIs
- ▶ Actionability of data: Reporting hardware power values is "futile" because hardware is difficult to change, but processes might be optimized.