Mesure de la consommation énergétique matériel et logiciel

Numérique et consommation énergétique

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Télécom SudParis

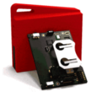
September 2023

Various devices







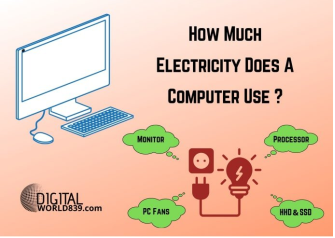



Various software

Questions and objectives

New questions for numerical engineers

- How much energy is consuming a computer?
- How much energy is consuming a given software?
- How much energy is consuming a given algorithm, method etc.?



Tools to answer those questions

- How can I measure computer and software energy consumption?
- What are the tools, what do they measure and what are their advantages/drawbacks

Outline

Orders of magnitude of power

Computer	≈ Power (W)	Equivalent
Sensor	0,000036	
Smartphone	1	LED bulb (eq. 40W incandescant)
Wifi Router	6	
Box internet	17	Electric shaver
Screen LCD 17"	35	1 Human brain
Printer	40	Medium Incandescant bulb
Laptop	80	1 cyclist
TV LCD	100	Solar panel $1m^2$
Game computer [1]	1 200	Electric kettel
Fugaku [2]	30 000 000	31ha solar parc

Table – Order of magnitude: Power consumed and produced

1. avec 4 GPU6
2. Fugaku : supercomputer 7 millions of cores, 415 petaFLOPS (10^{15})

Order of magnitude of number of equipments

Computer	≈ Power (W)	Number	Energy (MWh/year 24/24)
Connected object	1	19 000 000 000	599 184 000 000
Smartphone	1	7 000 000 000	220 752 000 000
TV	100	3 000 000 000	9 460 800 000 000
Laptop	80	2 000 000 000	5 045 760 000 000
Box internet	17	1 100 000 000	589 723 200 000
Servers in cloud	200	67 000 000	422 582 400 000
Super Computers	30 000 000	50	47 304 000 000

Outline

Outline

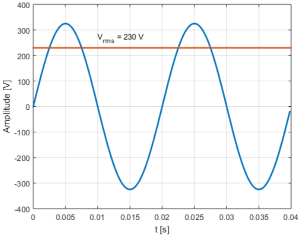
Electrical sources

Alternating sine signal

(AC = Alternating Current) 

- In Europe: 230 V_{RMS}, 50 Hz, 16 A (more or less, depending on cables, ...)

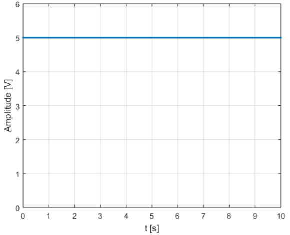
V_{RMS} Volt Root Mean Square



Continuous signal

(DC = Direct Current)

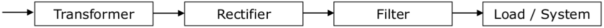
- 3.3 V, 5 V, 12 V, ...
- Battery Capacity [Ah]: ex. 200 AH correspond to 200 A for 1h or 2 A for 10h, ...

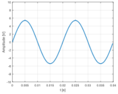


Electrical sources (cont.)

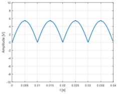
- Electronic components need continuous power supply signal(s).
  - $\Longrightarrow$ If an AC source is used, the AC voltage is converted to DC voltage thanks to an AC / DC converter.

Sine signal
V_{RMS} = 230 V
V_{avg} = 0 V

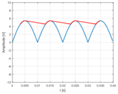




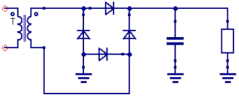
Attenuated signal



Rectified signal



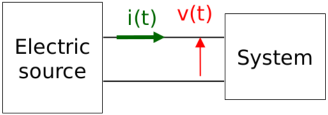
Almost constant signal



Remark: stabilization and regulation functions are also required.

Outline

Current and Voltage



- Power and energy consumption can be measured at the AC or DC electric source output.

Voltage

- Instantaneous supply voltage $[volt, V]$: $v(t)$
- If the power supply voltage is constant: $v(t) = V_{dd}$

Current

- Instantaneous current $[ampere, A]$: $i(t)$
- Average current during $\Delta_t [ampere, A]$: $I_{avg} = \frac{1}{\Delta_t} \int_0^{\Delta_t} i(t)dt$

Power

- Amount of work being done per unit of time
- Measured in watts (W)

Electric Power

- $Power = Current * Voltage$
- Instantaneous power $[watt, W]$: $P_{inst}(t) = v(t)i(t)$
- If the power supply voltage is constant (DC signal): $P_{inst}(t) = V_{dd}i(t)$
- Average power during $\Delta_t[watt, W]$:
  $P_{avg} = \frac{1}{\Delta_t}\int_0^{\Delta_t} P_{inst}(t)dt = \frac{1}{\Delta_t}\int_0^{\Delta_t} v(t)i(t)dt$
- If the power supply voltage is constant (DC signal): $P_{avg} = V_{dd}I_{avg}$

Energy

Kinds of energy

- Moving energy, thermal energy, radiant energy, electrical energy

Calculation and units

- Joule $(1J = 1Watt * 1s)$
  - *Energy transferred to an object by the work of moving it a distance of one metre against a force of one newton*
- Energy during $\Delta_t[joule, J]$: $E = \int_0^{\Delta_t} P_{inst}(t)dt = P_{avg}\Delta_t$
- Other unit: watt hour $[Wh]$
  - $1Wh = 1Wx3600s = 3600J \implies 1J \approx 0.000278Wh$

Power and Energy (sampling)

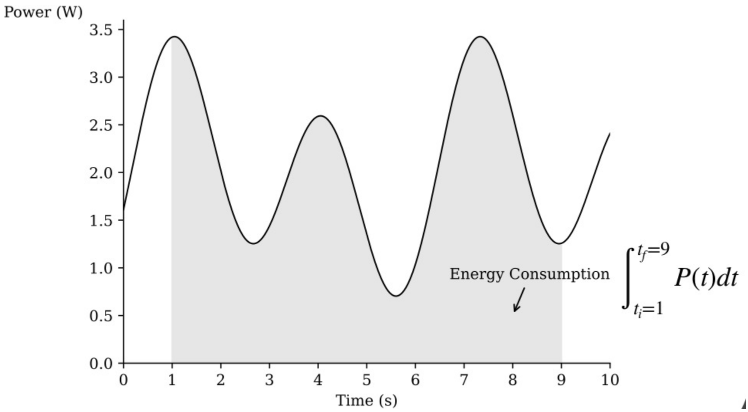


Figure – From power to energy

Images from the class of Luis Cruz on Sustainable Software Engineering

https://surfdrive.surf.nl/files/index.php/s/p2jqcN2tBpDBWKD

Power and Energy

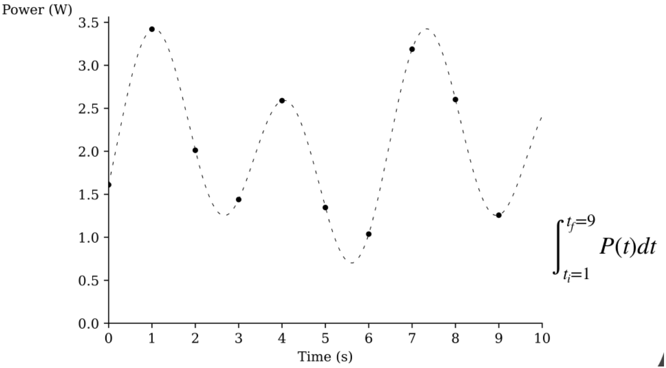


Figure – From power to energy

Power and Energy (cont.)

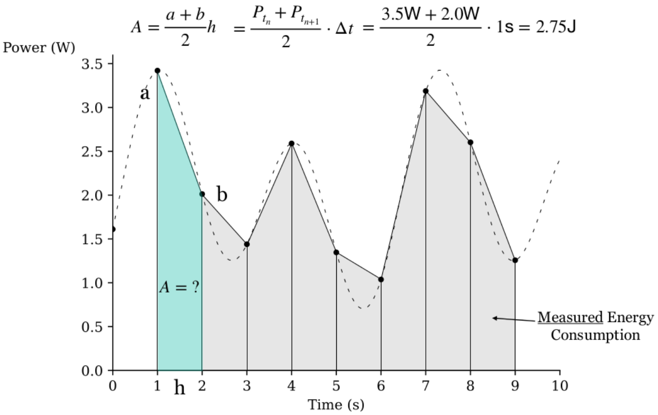


Figure – From power to energy

Power and Energy (cont.)

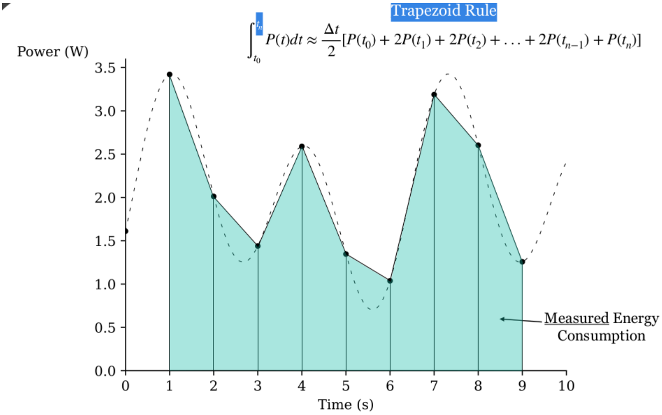


Figure – From power to energy

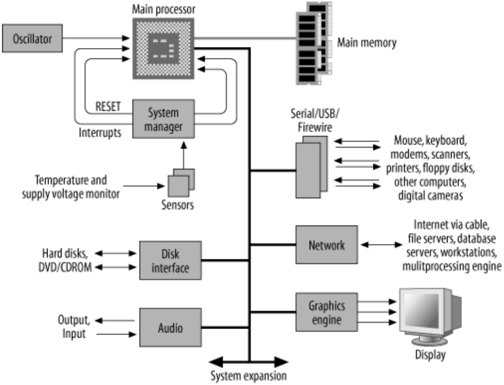
Average power to energy

- Average power consumption may be used for a stable activity
  $Energy = P_{avg} * \Delta t$
- It may also be useful to measure energy between two timestamps

Outline

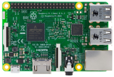
Energy consumption of a computer

- Consumption of all its components
  - Processor, Memory, disk, I/O, network interfaces, GPU . . .

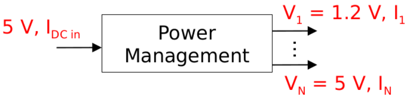


https://www.oreilly.com/ Designing Embedded Hardware,by John Catsoulis

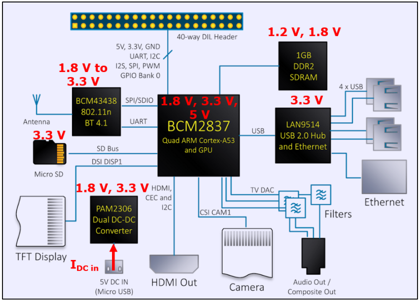
Raspberry Pi example



- Only one 5 V DC power supply source (micro-USB)
- A DC-DC converter (and onboard regulators) generate other DC voltages required by the circuits.
- Currents consumed by the circuits are supplied by the DC source.
  - V_i : i^{th} voltage supply (1.2 V, 1.8 V, 3.3 V, 5 V, ...)
  - I_i : current supplied by V_i

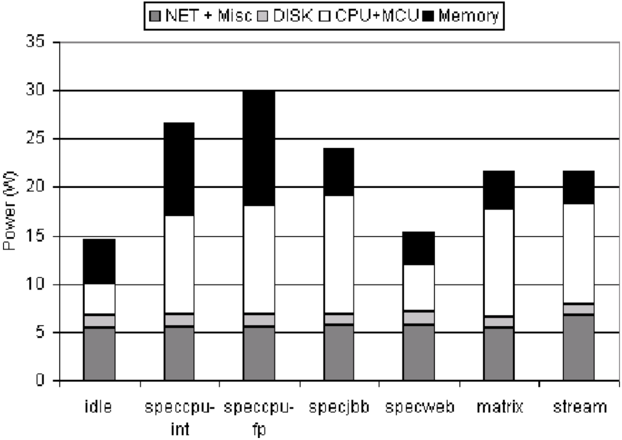


Main components of the Raspberry Pi 3 B (Single Board Computer)



https://xdevs.com/article/rpi3_oc/

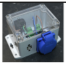
Computer components and energy



Component breakdown of measured power consumption with 7 benchmarks
D. Economou & all, Full-system power analysis and modeling for server environments, in: In Workshop on Modeling Benchmarking and Simulation, 2006

Outline

Comparison of measure instruments

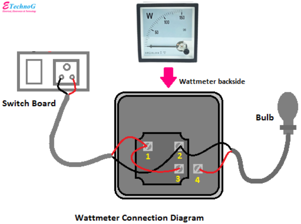
Tool					
Type	Low cost handheld multimeter	Power meter USB instrument	Power meter USB instrument	Power analyzer Standalone / USB	Plug-in socket power meter
Model	-	ST X-NUCLEO-LPM01A	Yocto-Watt	R&S HMC8015	-
AC, DC	AC, DC	DC	AC, DC	AC, DC	AC
Instantaneous, average	Average	Instantaneous, average	Average	Instantaneous, average	Average
Parameter	Voltage, current	Current, power, energy	Voltage, current, power, energy, cos φ	Voltage, current, power, energy, cos φ	Voltage, current, power, energy
Range	10 A DC / RMS max 500 V DC / RMS max	1 nA to 200 mA static 100 nA to 50 mA dynamic Supply voltage 1.8 V to 3.3 V	-16 to 16 A DC / RMS -250 to 250 V DC / RMS	50 µW to 12 kW	Up to 3680 W
Resolution / Precision	~ mV, ~ 10 µA	-	Max (0.02 W, 1,5%) AC Max (0.002 W, 1,5%) DC	-	-
Sampling rate or integration bandwidth	Few Hz integration bandwidth	3.2 Msps	600sps	500 ksps	-
Price	~ 25 €	~ 80 €	~ 85 €	~ 2800 €	~ 30 €
Application	Measure the average AC / DC current of a system	Measure the instantaneous power of a connected object	Measure the average AC / DC power of a system with a high precision	Measure the instantaneous or average AC / DC power of a system with a high precision	Measure the average AC power of a system

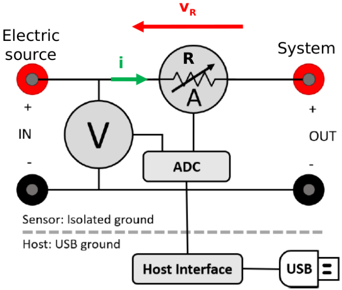
Multimeter

- Measures voltage and current

Wattmeter Measurement principle

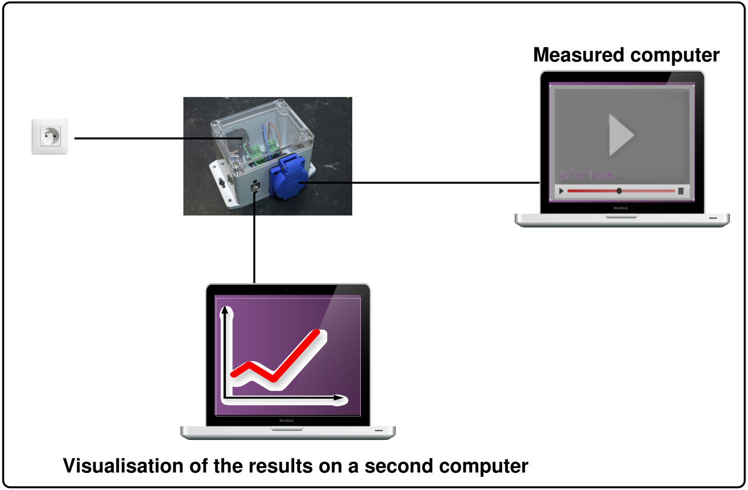
- To measure power and energy
  - Voltage and current must be measured first
- A voltmeter measures the voltage v
  - DC signal: depending on the tool, the voltage supply can be provided by the tool itself, so it is known.
- A shunt resistor R in an ammeter (ampere meter) measures the current: $i = v_R/R$
- The 2-channel ADC samples the voltages v and $v_R \implies$ I is determined and so the power, the energy, ...
- Remark if the signal to be sampled is too low, an amplifier is added before the ADC.



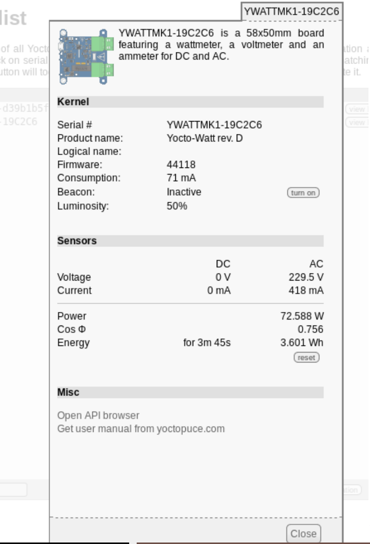


https://www.joulescope.com/

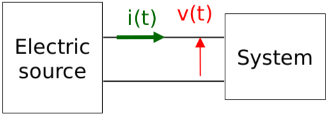
Yocto-Watt Wattmeter connexion

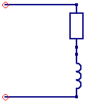


Yocto Wattmeter interface



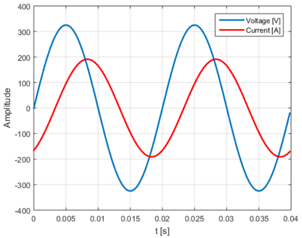
Power factor (Cos Φ) - In short





- Let's consider an AC sine signal $v(t) = V_{max} cos(2\pi Ft)$ and a linear system impedance.
- If the system impedance is resistive (Z = R) like a heater, a lamp light, . . . :
  - $i(t) = \frac{v(t)}{R} = \frac{V_{max}}{R} cos(2\pi Ft) = I_{max} cos(2\pi Ft) \implies$ v(t) and i(t) are in phase
  - System effectively consumed (or active) power: $P_{avg} = \frac{1}{T} \int 0^T v(t)i(t)dt = \frac{V_{max} I_{max}}{2} = V_{RMS} I_{RMS}$
  - Apparent power provided by the energy supplier: $S = V_{RMS} I_{RMS}$

Power factor (Cos Φ) - In short (cont.)



- If the system impedance is complex ($Z = R + jX = |Z|e^{j\Phi}$) like a motor
  - $i(t) = \frac{V_{max}}{|Z|} cos(2\pi Ft - \Phi) = I_{max} cos(2\pi Ft - \Phi) \implies$ v(t) and i(t) are phase-shifted.
  - System effectively consumed (or active) power: $P_{avg} = \frac{1}{T} \int 0^T v(t)i(t)dt = V_{RMS} I_{RMS} cos\Phi$
  - Power Factor $= cos\Phi =$ ratio between the effectively consumed power P_{avg} and the apparent power S

Power factor (Cos Φ) - In short (cont.)

Examples

- Resistive system
  - A heater ($cos\Phi = 1$) needs a power $P_{avg} = 100W$
  - The energy supplier will have to provide a power S = 100 VA (volt-ampere).
  - Verification: $P_{avg} = Scos\Phi = 100x1 = 100W$
- Inductive system
  - A motor with $cos\Phi = 0.7$ needs a power $P_{avg} = 100W$
  - The energy supplier will have to provide a power $S = 142.8VA$
  - Verification: $P_{avg} = Scos\Phi = 142.8x0.7 = 100W$

Software power meters

- We don't always have a wattmeter
- We would like to measure more precisely the cost of a given software/process/method

$\Longrightarrow$ Use of a **Software meter**

☹ Each computer comes with different tools

Intel RAPL Running Average Power Limit

- Introduced by INTEL to limit heating
  As transistors have shrunk in size and increased in speed, they have begun to heat up; this led to manufacturers putting a speed limit on processing in 2004.[Freitag et al., 2021]

- Estimates energy usage by using onboard power meters and I/O models
- Updates the energy counters approximately once every 1ms
- Estimations available through **Operating System registers**

Limitations

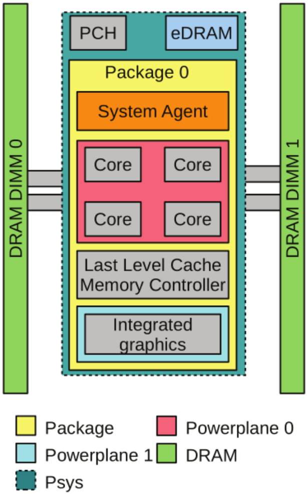
- Only some processors (Intel)
- Only CPU, DRAM and GPU components

Intel RAPL package registers

PACKAGE_ENERGY 176.450363J
(Average Power 42.9W)

DRAM_ENERGY 11.899246J
(Average Power 2.9W)

PP0_ENERGY 118.029236J
(Average Power 28.7W)



Tools to access RAPL registers

Windows Intel Power Gadget

Linux Intel Power Top, **Likwid**, perf, Scaphandre, Power Joular

Likwid [3]

To measure the energy consumed of one given command :
`$ likwid-powermeter "yourcommande"`

CPU name: Intel(R) Core(TM) i7-8650U CPU @ 1.90GHz
CPU type: Intel Kabylake processor
CPU clock: 2.11 GHz
———————————————-
Runtime: 41.0879 s
Measure for socket 0 on CPU 0
Domain PKG:
Energy consumed: 71.8161 Joules
Power consumed: 1.74787 Watt
Domain PP0:
Energy consumed: 12.0212 Joules
Power consumed: 0.292574 Watt
Domain DRAM:
Energy consumed: 12.6542 Joules
Power consumed: 0.30798 Watt

Drawback: other processes may share the same processor

3. https://github.com/RRZE-HPC/likwid

Energy consumption of one process

How do you isolate the consumption of one process ?

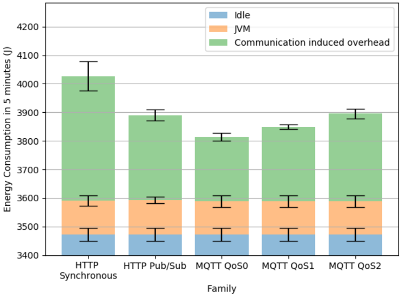


Figure – Example on impact of protocols and interaction patterns

Analysis of the impact of interaction patterns and IoT protocols on energy consumption of IoT consumer applicationsRodrigo Canek, Pedro Borges, Chantal TaconetDAIS 2022

Software energy

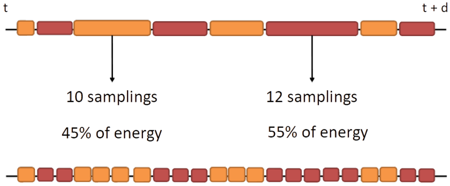
- Energy consumed by hardware components to execute software instructions
  - Example: a software instructs the processor to calculate the first 100 digits of Pi
- Energy is measured at runtime and depends on hardware configuration
- Limitations: measure may also be impacted by
  - External temperature
  - Other sofware running on the computer

Joular JX : energy consumption

Granularity: process and methods

- Goal: help developers to understand software power consumption
- With a Java-based agent
  Command: `$ java java -javaagent:joularjx.jar yourProgram`
  - Get power (through rapl registers) - *every s*
  - Get %CPU used by the process: ⇝ deduce the process consumption - *every s*
  - Get method name (through execution stack trace) - *every 10ms*

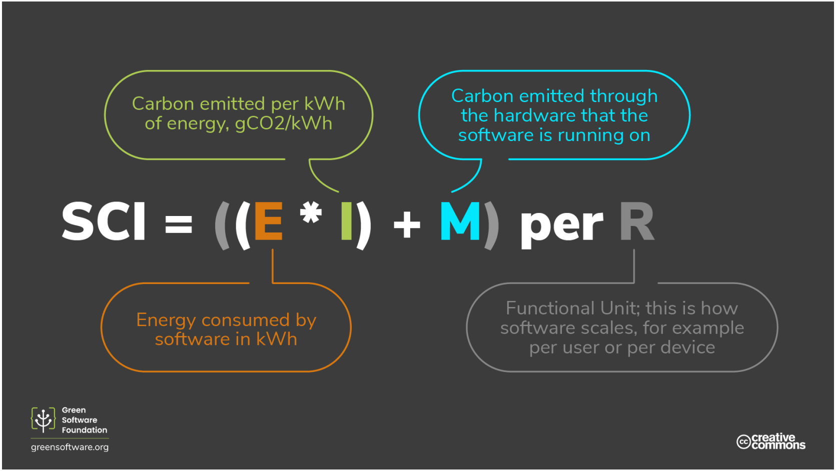
⇝ To estimate statistically power consumption of each method



- Drawback: Short methods are not detected

Outline

Software Carbon Intensity in $gCO_2 - eq$



https://learn.greensoftware.foundation/measurement

See the SCI specifications

Software Carbon Intensity in $gCO_2 - eq$ (cont.)

Difficulties

- Isolate a functional unit
- Choose the measuring method
  - The measured value is valid for one hardware
- Calculate M Embodied emissions of a software system
  - e.g. For: device's embodied carbon (refer to boavitza) 1000kg; lifespan four years; reserved for use for one hour for the functional unit; $M = 1000 * 1/(4 * 365 * 24) \approx 29g$
- The score should be calculated for each deployment (depends on region, hardware)

What next?

4 labs

1. Wattmeter lab: measure the energy consumption of a computer during an activity (1h30)
2. Likwid lab: measure the consumption of a processor during an activity (1h30)
3. Joular JX lab: measure the energy consumption of java methods (1h30)
4. Software energy efficiency: improve the energy efficiency of a software (3h00)

References

Freitag, C., Berners-Lee, M., Widdicks, K., Knowles, B., Blair, G. S., et al. (2021).

The real climate and transformative impact of ICT: A critique of estimates, trends, and regulations.

Patterns, 2(9):100340.