

Dirty Electrons: On the Carbon Intensity of Stored Energy

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⚡ Electricity Grid



11 gCO₂e/kWh



35 gCO₂e/kWh



1079 gCO₂e/kWh

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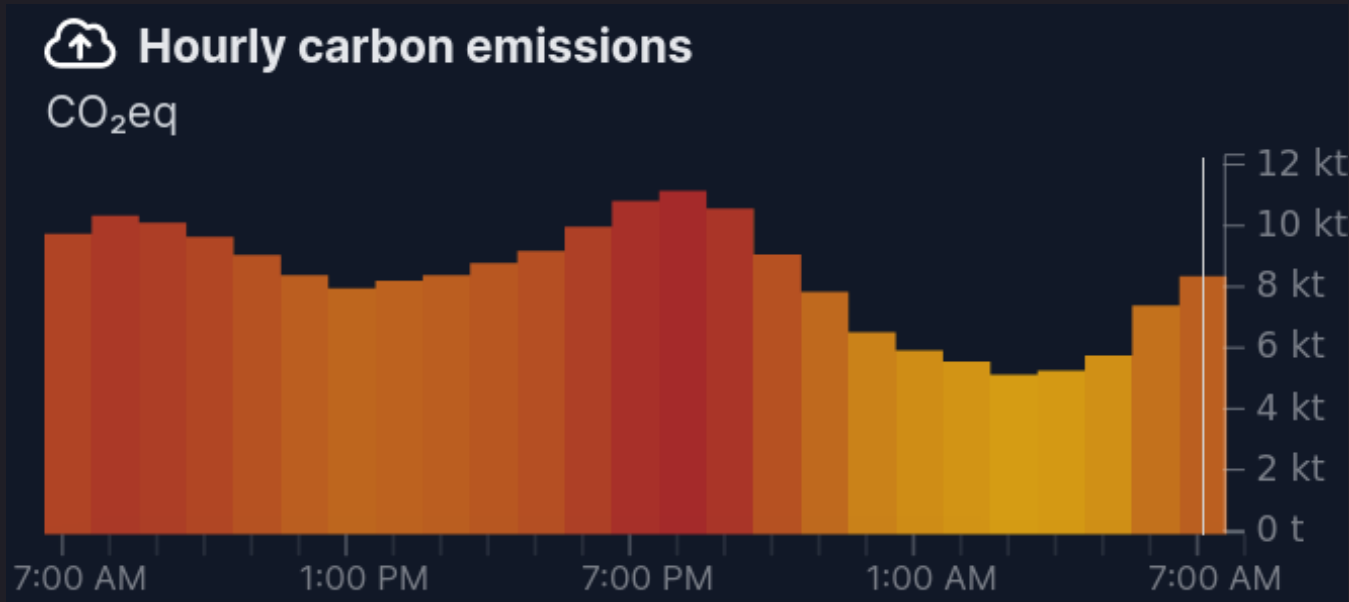
1079 gCO₂e/kWh

- Mix of renewable and fossil power plants determines the *carbon intensity* of the grid.
- Energy can be stored in batteries for later usage.

→ RQ: What is the *carbon intensity* of stored energy?

⚡ Carbon Intensity – Use Cases

What can a *carbon intensity* be used for?
(carbon per energy)



- Spatial & temporal shifting of workloads
- Carbon-accounting for apps
- Carbon-accounting for systems
- Carbon-benchmarking

Typically given in [gCO₂e/kWh]

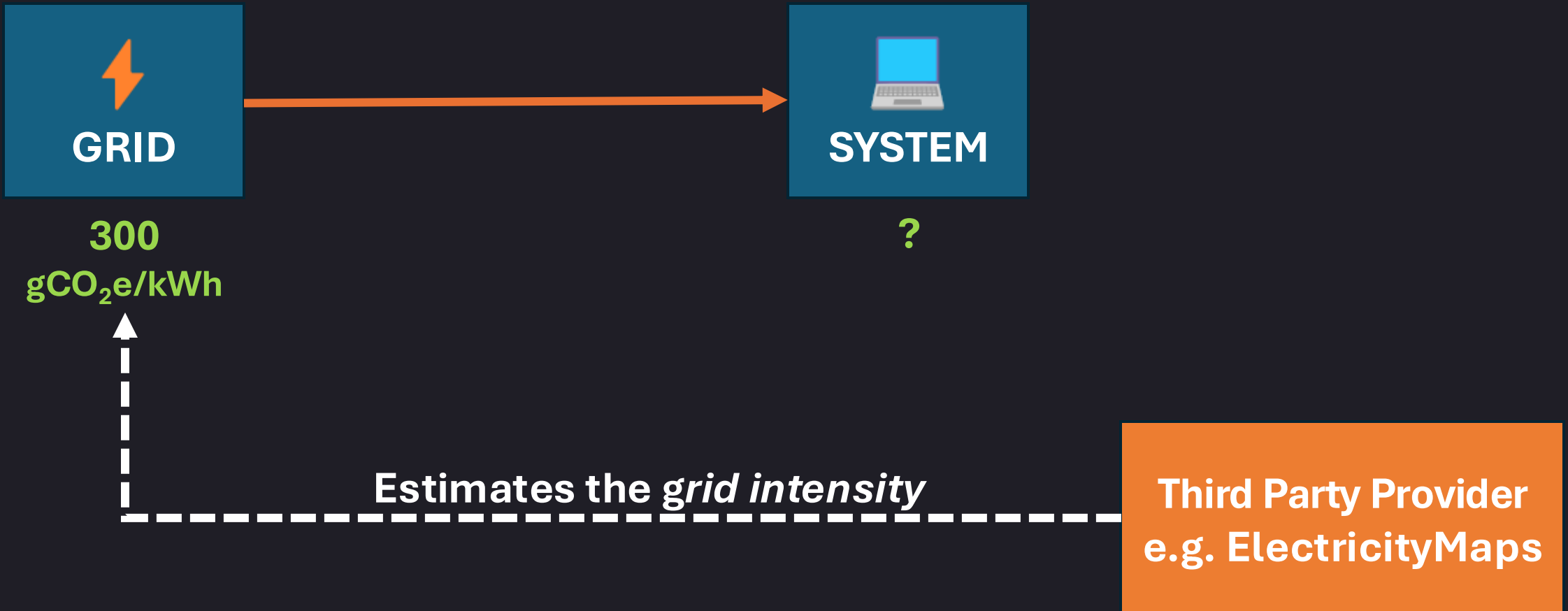


Typical View



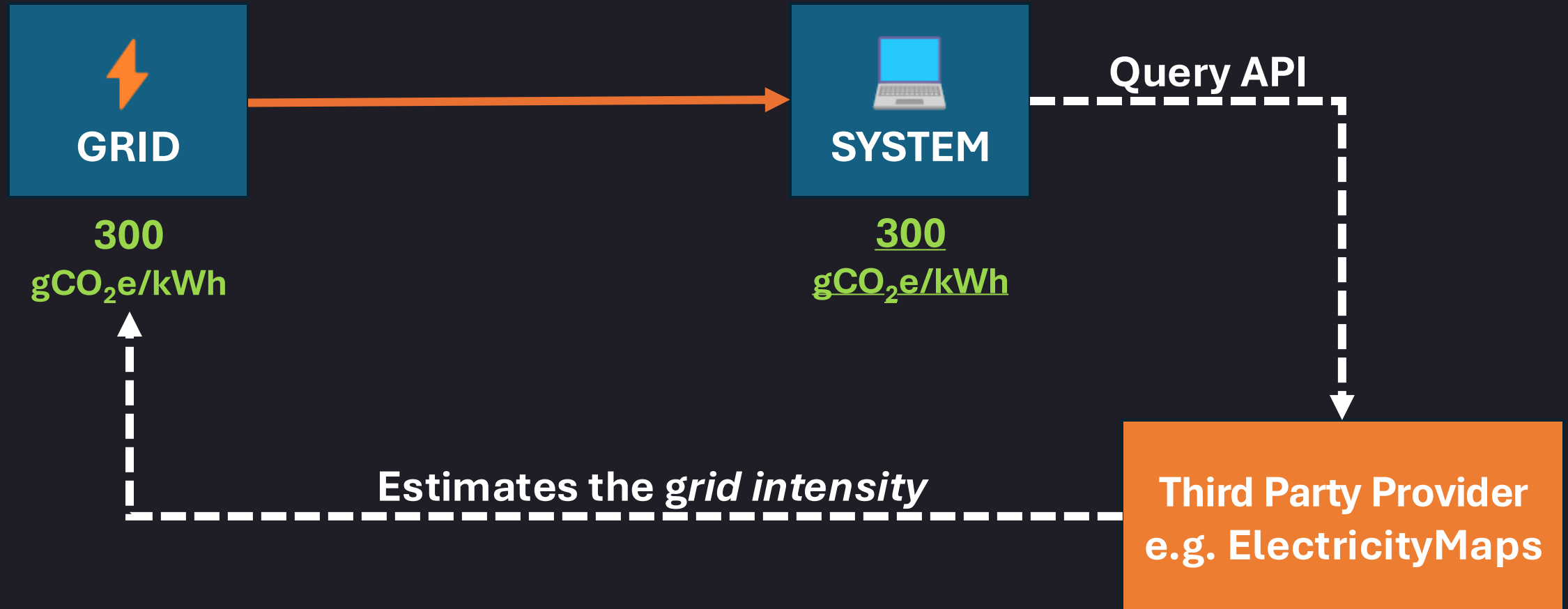


Typical View





Typical View





Typical View

PROBLEM:

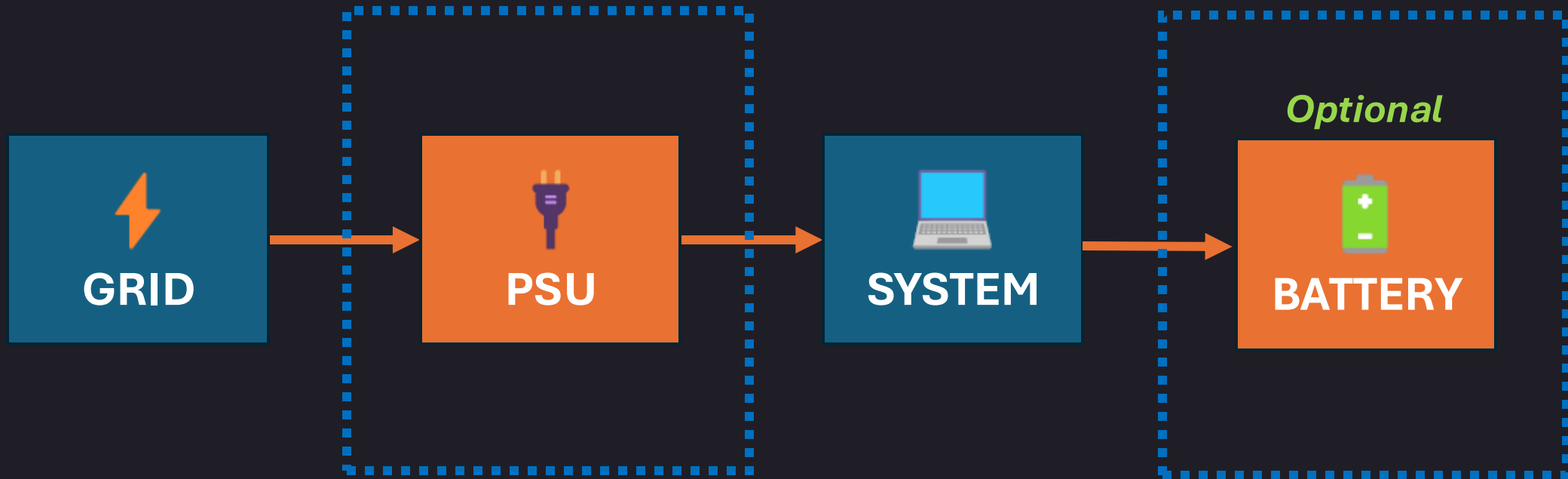
View ignores important components.

Estimates the *grid intensity*

Third Party Provider
e.g. ElectricityMaps

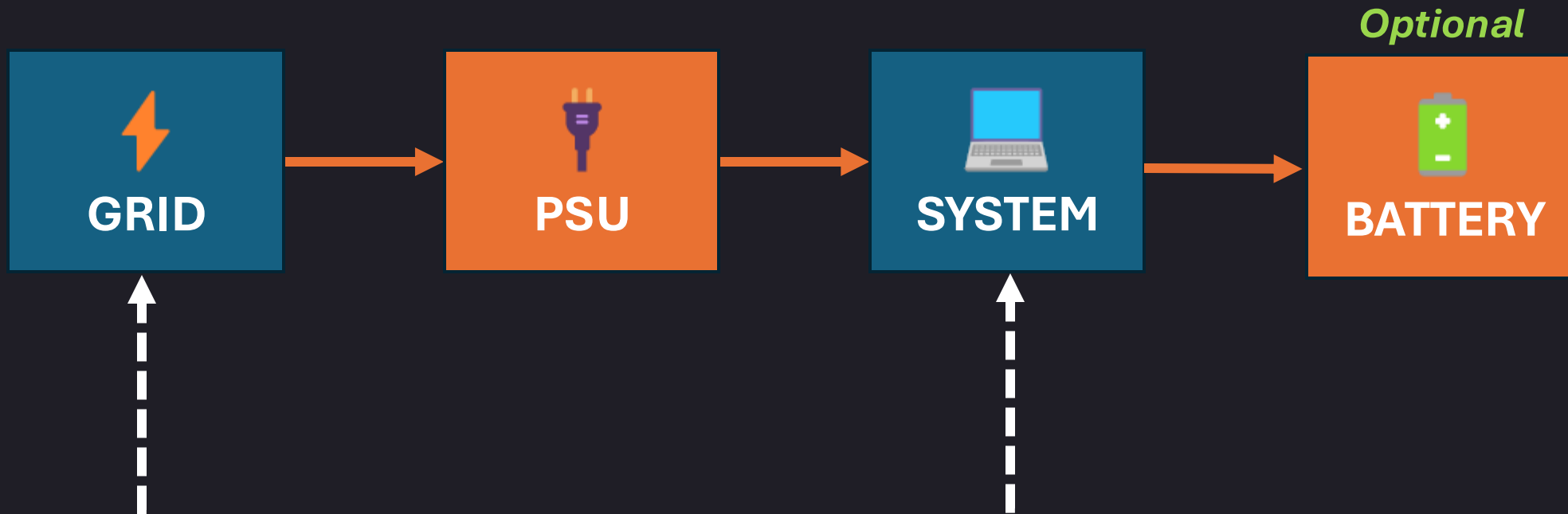


The More Realistic View (charging)





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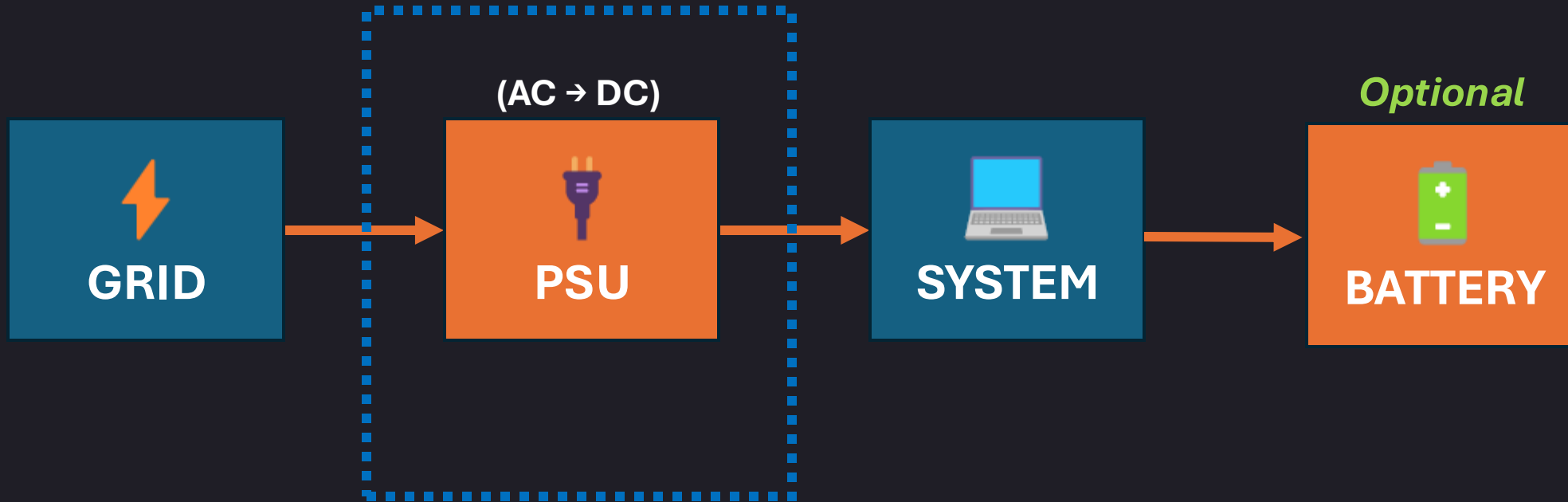


1. ElectricityMaps / WattTime
estimate *carbon intensity*
before the Power Supply Unit.

2. Typical approaches (RAPL)
measure
energy at the system.



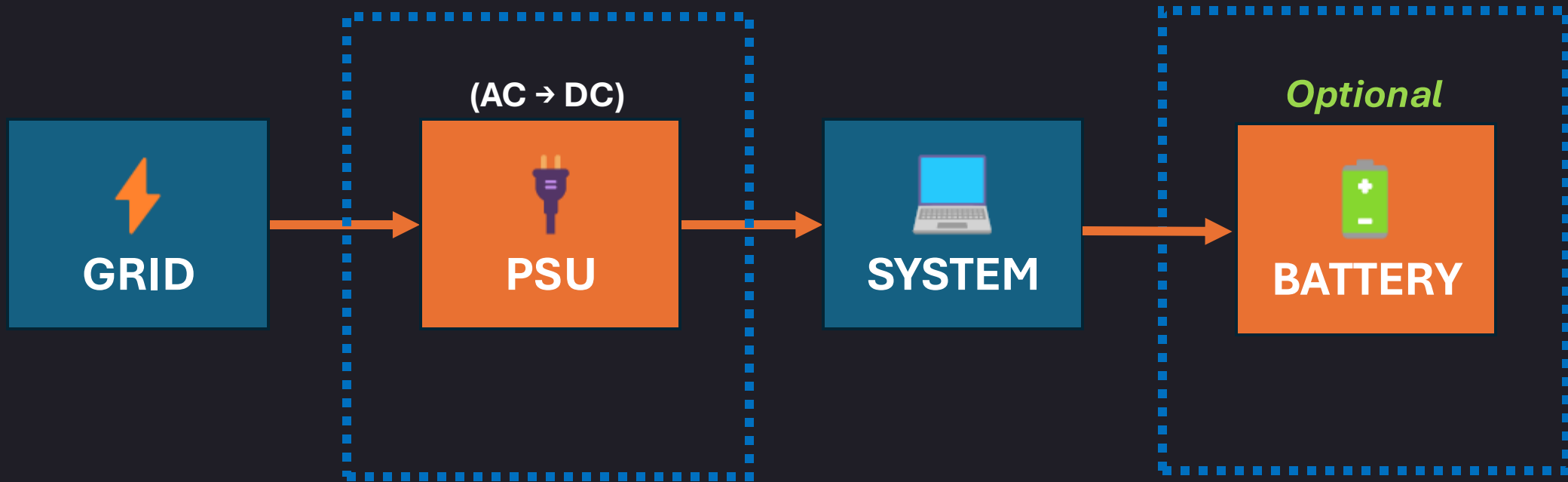
The More Realistic View (charging)



1. Grid electricity is converted by the Power Supply Unit (PSU).



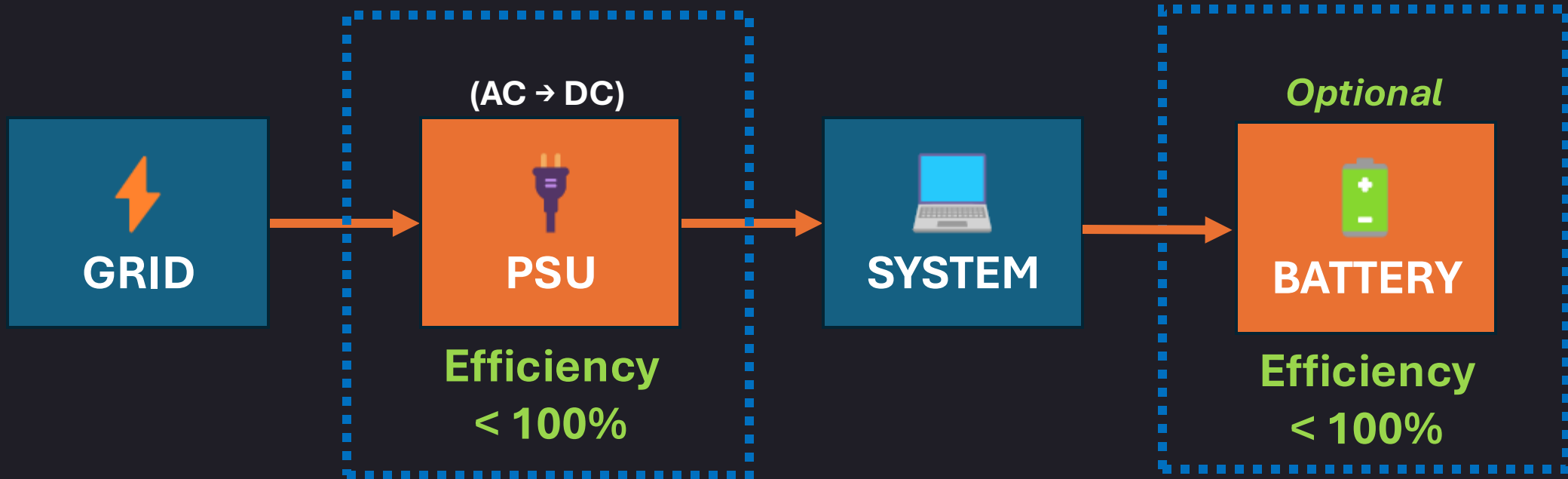
The More Realistic View (charging)



1. Grid electricity is converted by the Power Supply Unit (PSU).
2. Energy might be stored inside a battery and later discharged.



The More Realistic View (charging)

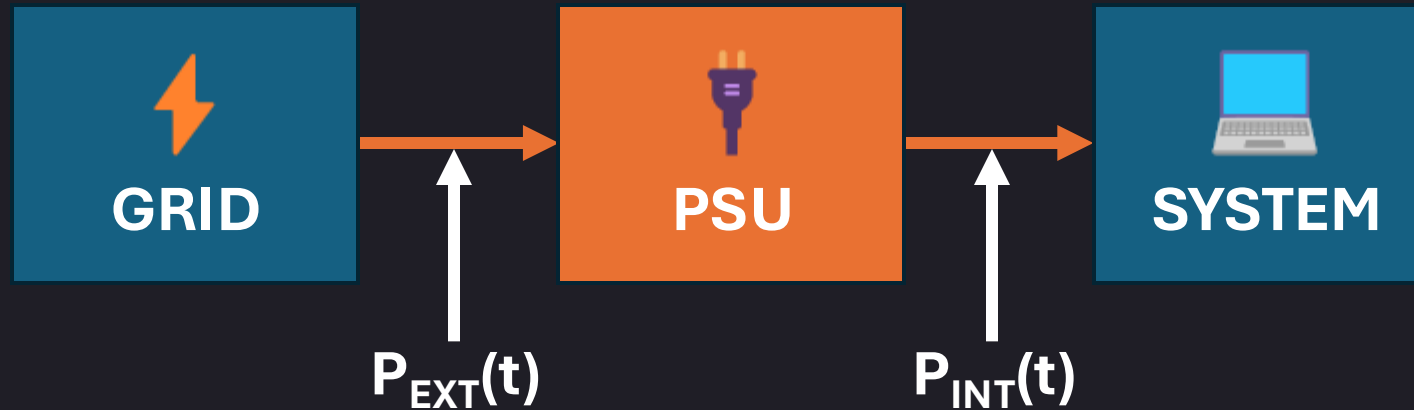


1. Grid electricity is converted by the Power Supply Unit (PSU).
2. Energy might be stored inside a battery and later discharged.
3. Both converting and (dis)charging is inefficient (Loss of usable energy).



The Power Supply Unit (PSU)

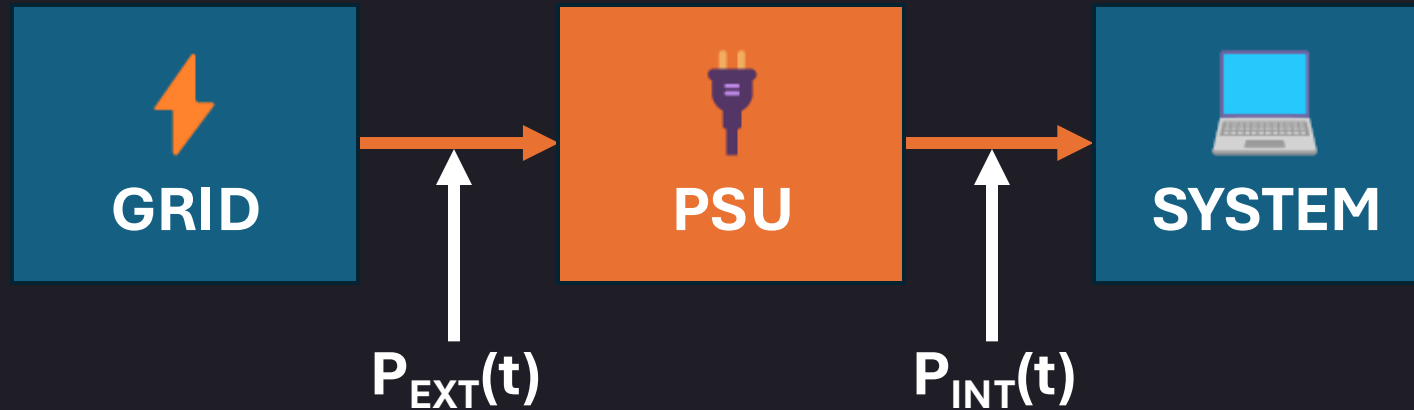
1. Measure the efficiency of the Power Supply Unit:





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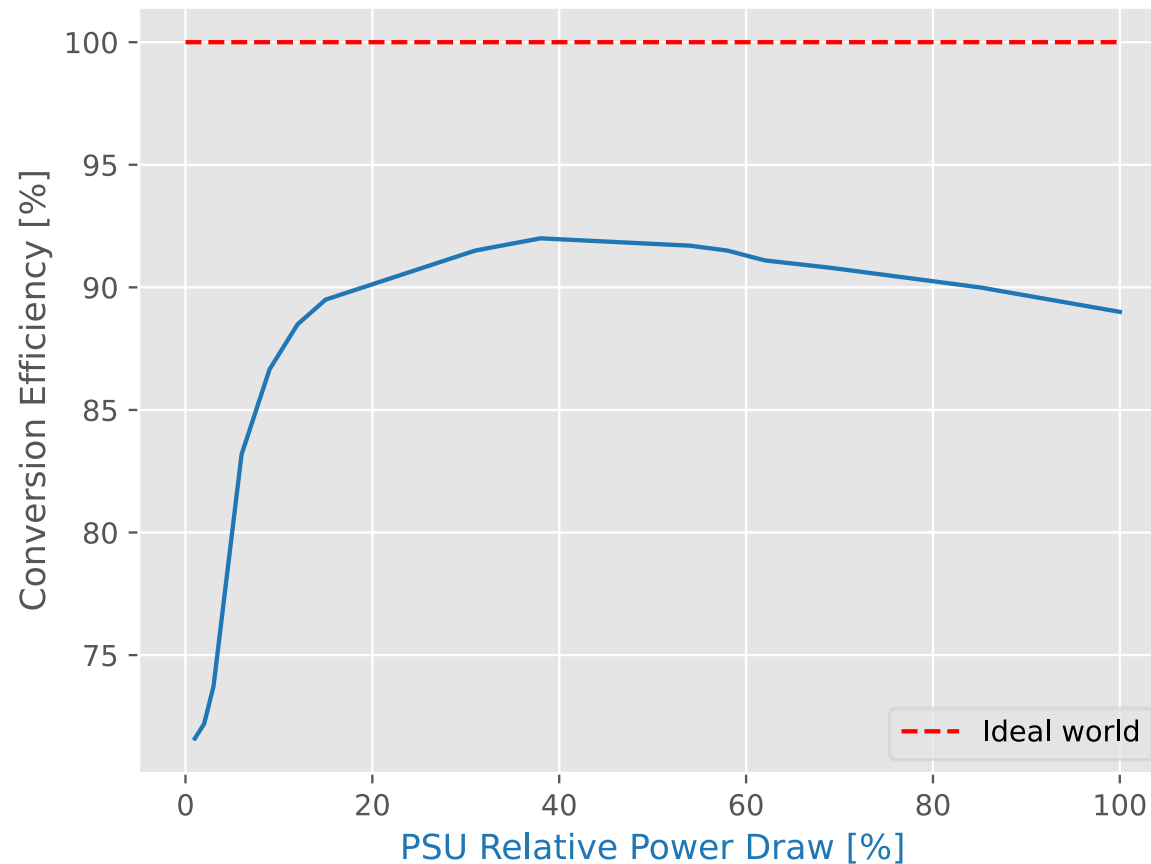


2. Calculate the PSU efficiency and *system intensity*:

$$\text{Eff}_{PSU}(t) = \frac{P_{INT}(t)}{P_{EXT}(t)} < 1 \quad \text{Int}_{PSU}(t) = \frac{\text{Int}_{GRID}(t)}{\text{Eff}_{PSU}(t)}$$



The PSU Efficiency Curve

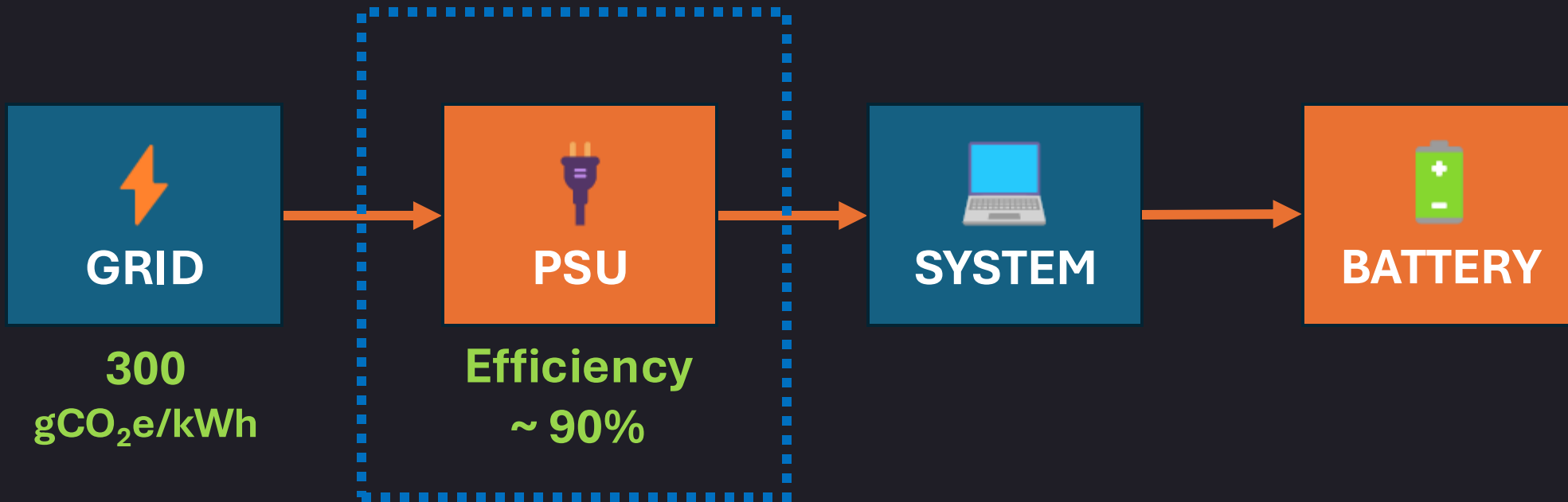


Load-dependent (in)efficiency

1. Efficiency of the PSU depends on the relative power draw.
2. There is an optimal point with best efficiency.
3. Optimum is in the middle of the relative draw.
4. Low relative loads have poor efficiency.

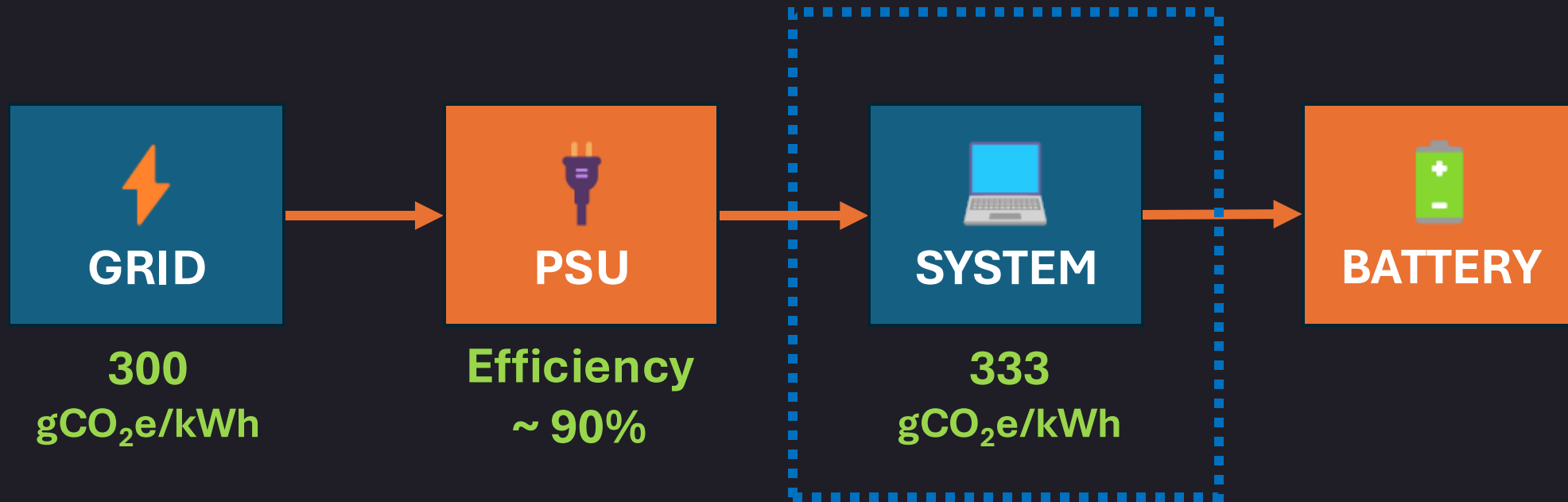


The More Realistic View (charging)



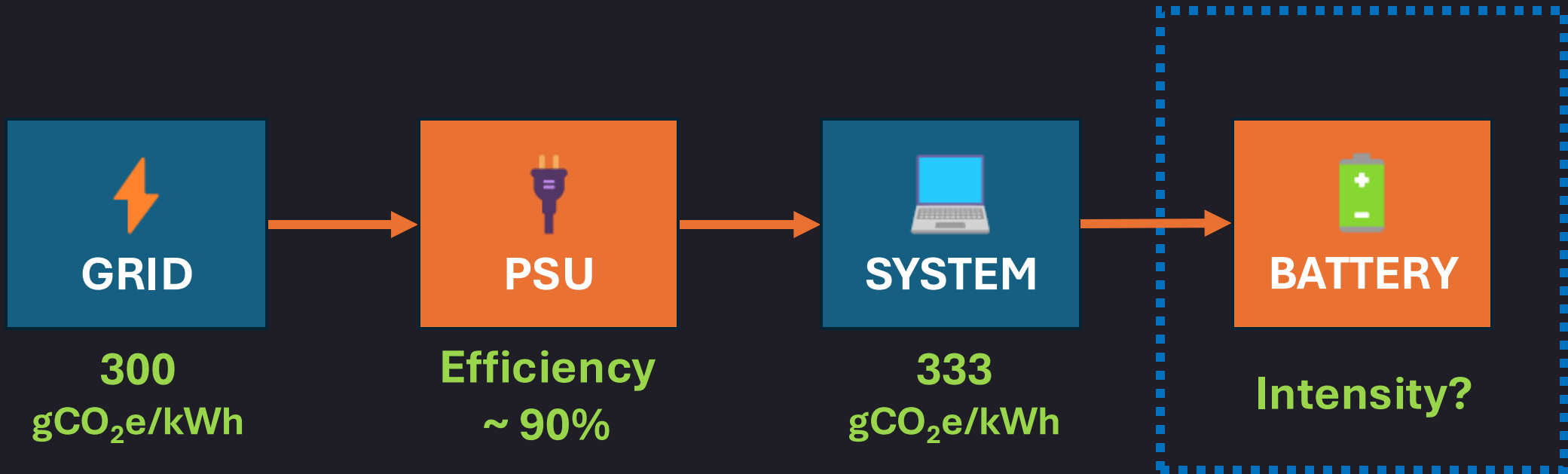


The More Realistic View (charging)



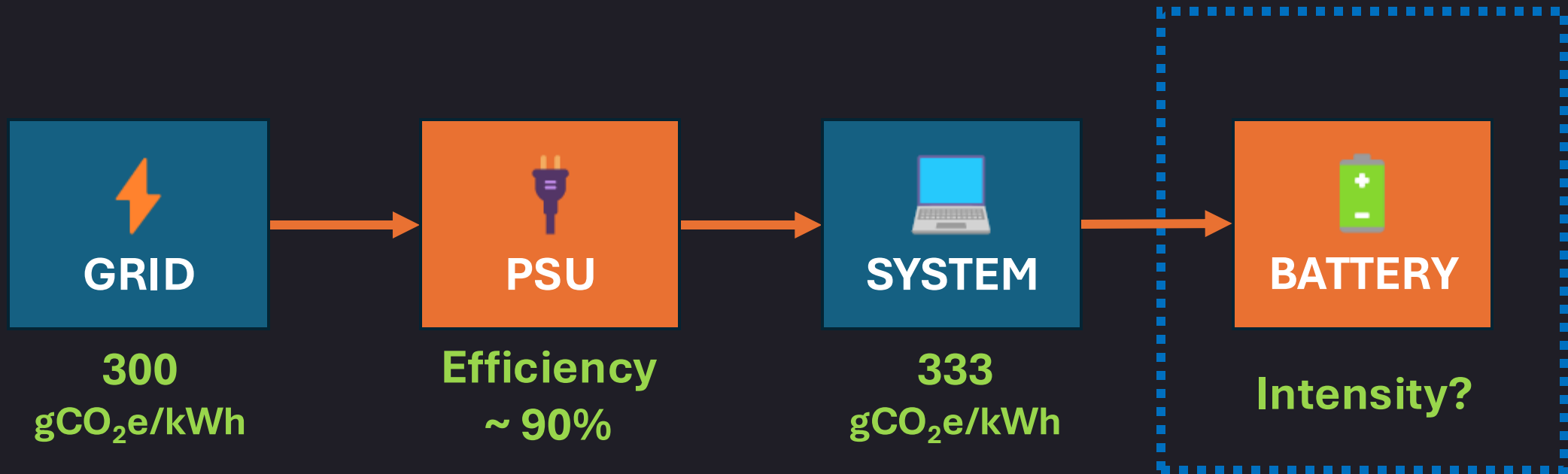


The More Realistic View (charging)





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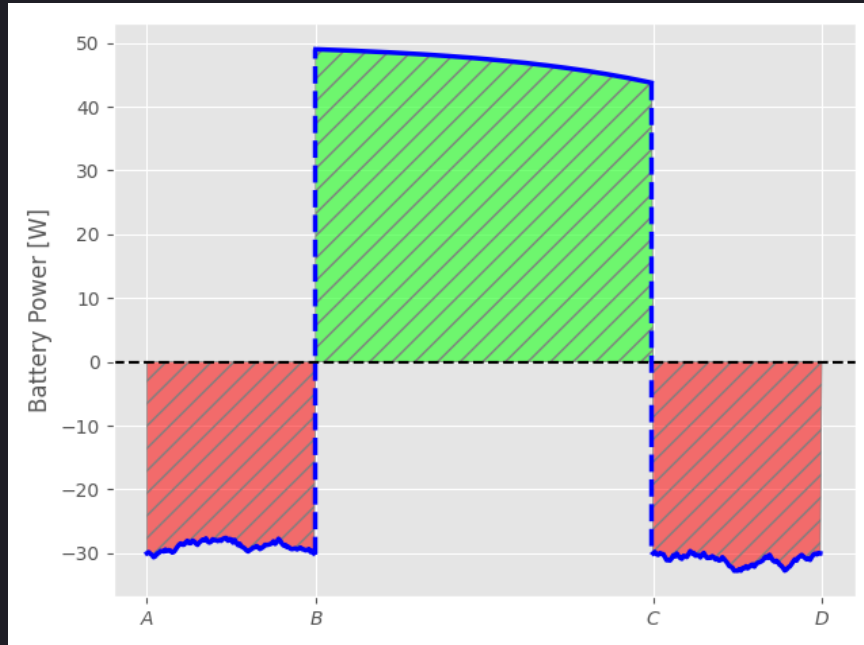
***Battery intensity* can be calculated with:**

1. Amount of *energy* stored in the battery.
2. Amount of *carbon* emitted for producing the *energy*.
3. Part of the of the *embodied carbon* from battery production.



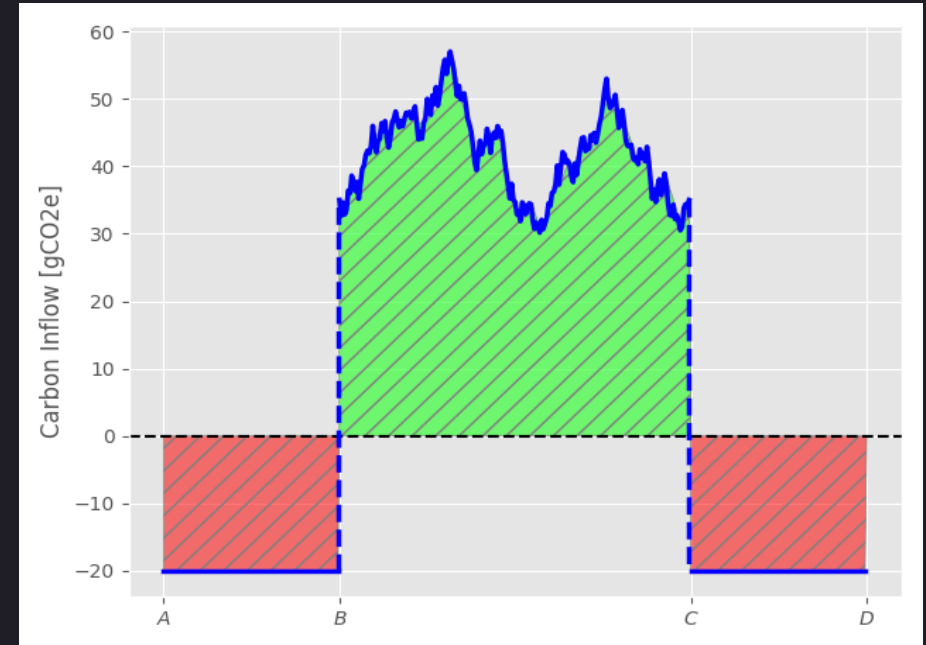
Tracking the Battery (Energy + Carbon)

Battery Energy
(Integral of Power · Efficiency)



$$E_{BAT}(t) = E_0 + \int_0^t P_{BAT}(t) \cdot \text{Eff}_{BAT}(t) dt$$

Tracking Carbon
(Integral of Power · System Intensity)



$$C_{BAT}(t) = C_0 + \int_0^t P_{BAT}(t) \cdot \text{Int}_{PSU}(t) dt$$



Battery Lifetime Model (Embodied)

1. Batteries have a minimum number of cycles before degradation.
(Maximum capacity falls below 80%)
2. Production costs for batteries can be approximated (~100 kgCO₂e/kWh).
3. By dividing the production cost by number of possible cycles, it is possible to derive an amount of embodied carbon per kWh.

Battery Info:

Cycles: 1000 before degradation

Production: 100 kgCO₂e/kWh

$$\begin{aligned} M_{kWh} &= \frac{100 \frac{kgCO_2e}{kWh}}{1000} = 0.1 \frac{kgCO_2e}{kWh} \\ &= 100 \frac{gCO_2e}{kWh} \end{aligned}$$

Tracking the Battery



Continuous tracking of:

- Energy
- Carbon

1. Calculate the *energy intensity*:

$$\text{Int}_E(t) = \frac{C_{BAT}(t)}{E_{BAT}(t)} \left[\frac{gCO_2e}{kWh} \right]$$

2. Calculate the *embodied carbon*:

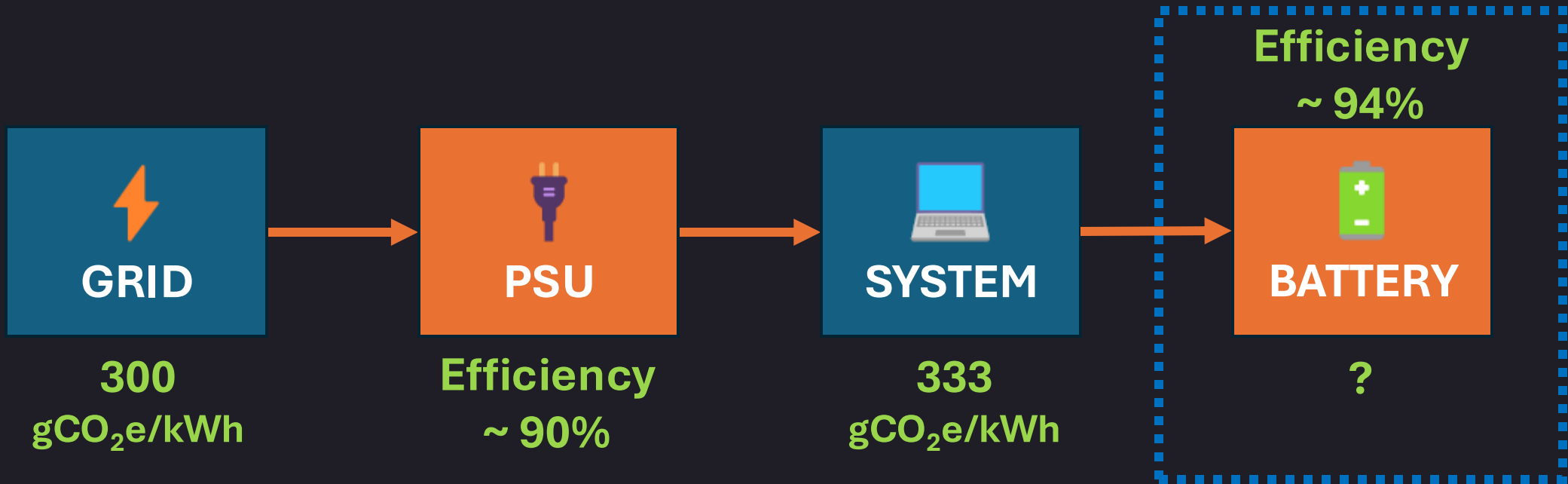
$$M_{BAT} = \frac{\text{ProductionCost}}{\text{Cycles}} \left[\frac{gCO_2e}{kWh} \right]$$

3. Calculate the *battery intensity*:

$$\text{Int}_{BAT}(t) = \text{Int}_E(t) + M_{BAT} \left[\frac{gCO_2e}{kWh} \right]$$



The More Realistic View (charging)



Battery Info:

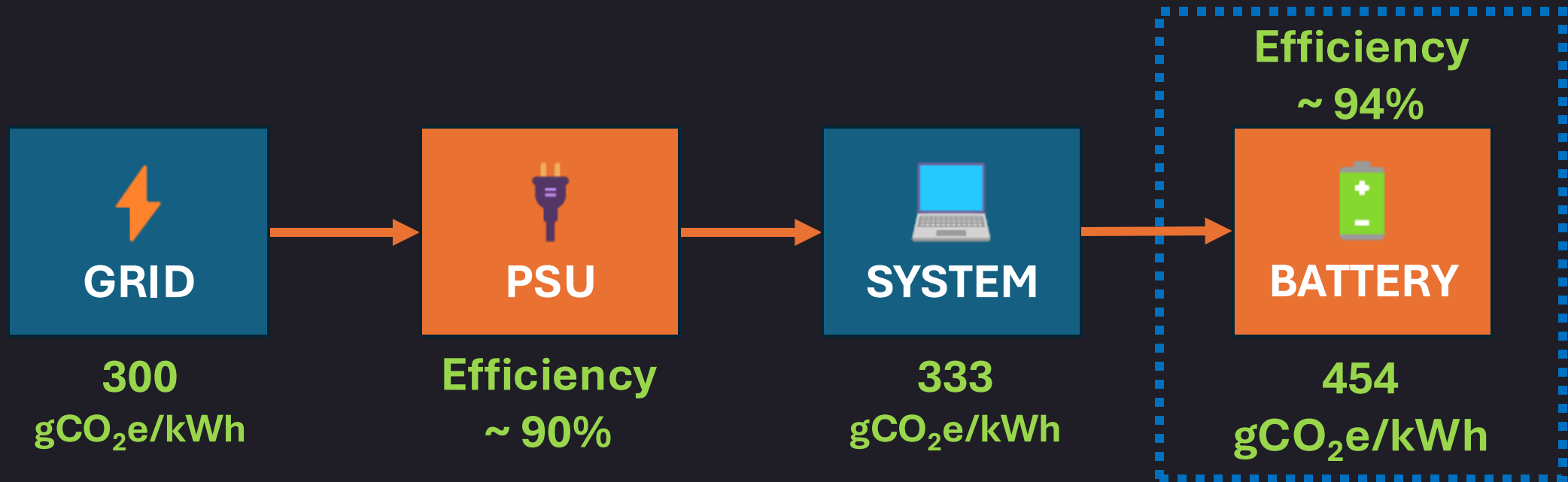
Cycles: 1000 before degradation

Production: 100 kgCO₂e/kWh

$$M_{BAT} = \frac{100 \frac{kgCO_2e}{kWh}}{1000} = 100 \frac{gCO_2e}{kWh}$$
$$Int_{BAT} = \frac{333 \frac{gCO_2e}{kWh}}{0.94} + 100 \frac{gCO_2e}{kWh} = 454 \frac{gCO_2e}{kWh}$$



The More Realistic View (charging)



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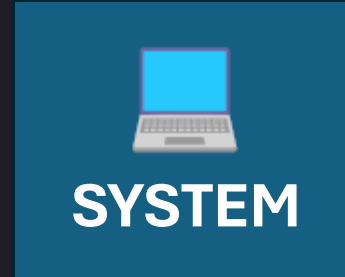
$$Int_{BAT} = \frac{333 \frac{gCO_2e}{kWh}}{0.94} + 100 \frac{gCO_2e}{kWh} = 454 \frac{gCO_2e}{kWh}$$



The More Realistic View (discharging)



300
gCO₂e/kWh



454
gCO₂e/kWh



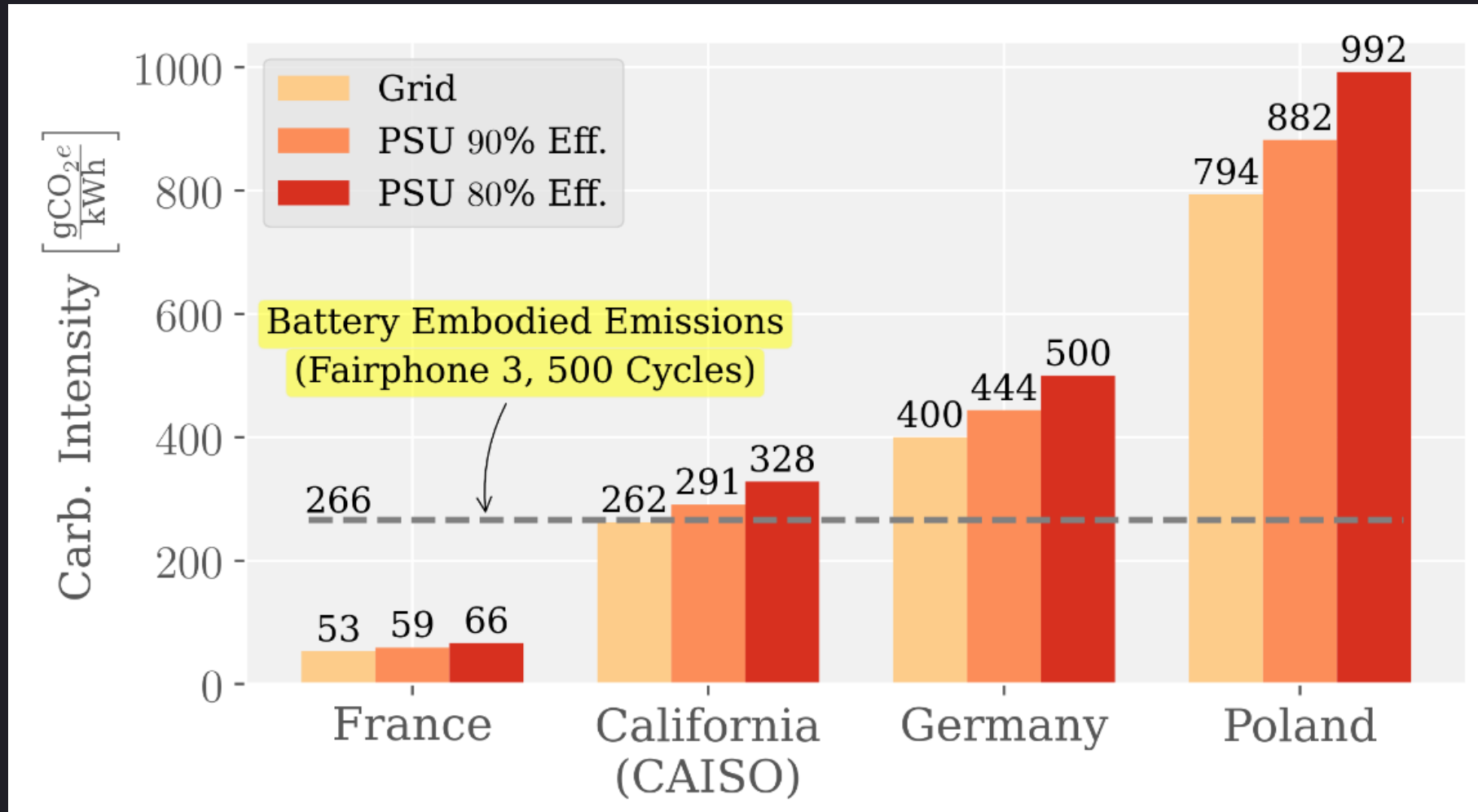
454
gCO₂e/kWh

Battery intensity is 154 gCO₂e/kWh higher than the grid intensity.

→ Amplification by more than 50% in this example.



The Bigger Picture



Summary

- Usage of the *grid intensity* in combination with e.g., RAPL only gives a lower limit of the actual *carbon intensity*.
- Power Supply Units and batteries are inefficient components.
- Batteries are degrading and have a non-negligible embodied carbon footprint.
- By tracking the PSU and battery, it is possible to derive a more realistic *system intensity*.
- Depending on the location, the embodied carbon of the battery can outweigh the operational emissions.

Thank you for your attention!

Questions?



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