

# Life-cycle **carbon** assessment of an **intermittent Fog** service fully powered by **renewable energy** sources



PROGRAMME  
DE RECHERCHE  

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CLOUD

Matteo Chancerel, Anne-Cécile Orgerie – March 11th, 2026 – GreenDays, Sophia, FR

# Data centers and carbon emissions

- Cloud data centers tried to use 100% renewables, but
- they did not consider the whole Life-Cycle emissions
  - 24/7 availability is incompatible with solar and wind power.

## Research questions

- How to power a distributed fog with 100% renewable energy (accepting intermittency)?
- How to size the powering infrastructure, to maximize the uptime, while minimizing the carbon footprint?

# By-design intermittent

We take the example of a company email service, which is **only available during work hours.**

Servers are OFF during the night, only ON between 7AM and 7PM (7-19h).

Why this choice ?

- 1) Because solar panels do not produce power during the night,
- 2) We receive few professional emails during the night.
- 3) Because of *the right to disconnect*<sup>1</sup> from work.

<sup>1</sup> European Parliament. 2021. European Parliament resolution of 21 January 2021 with recommendations to the Commission on the right to disconnect (2019/2181(INL)).

[https://www.europarl.europa.eu/doceo/document/TA-9-2021-0021\\_EN.html](https://www.europarl.europa.eu/doceo/document/TA-9-2021-0021_EN.html)

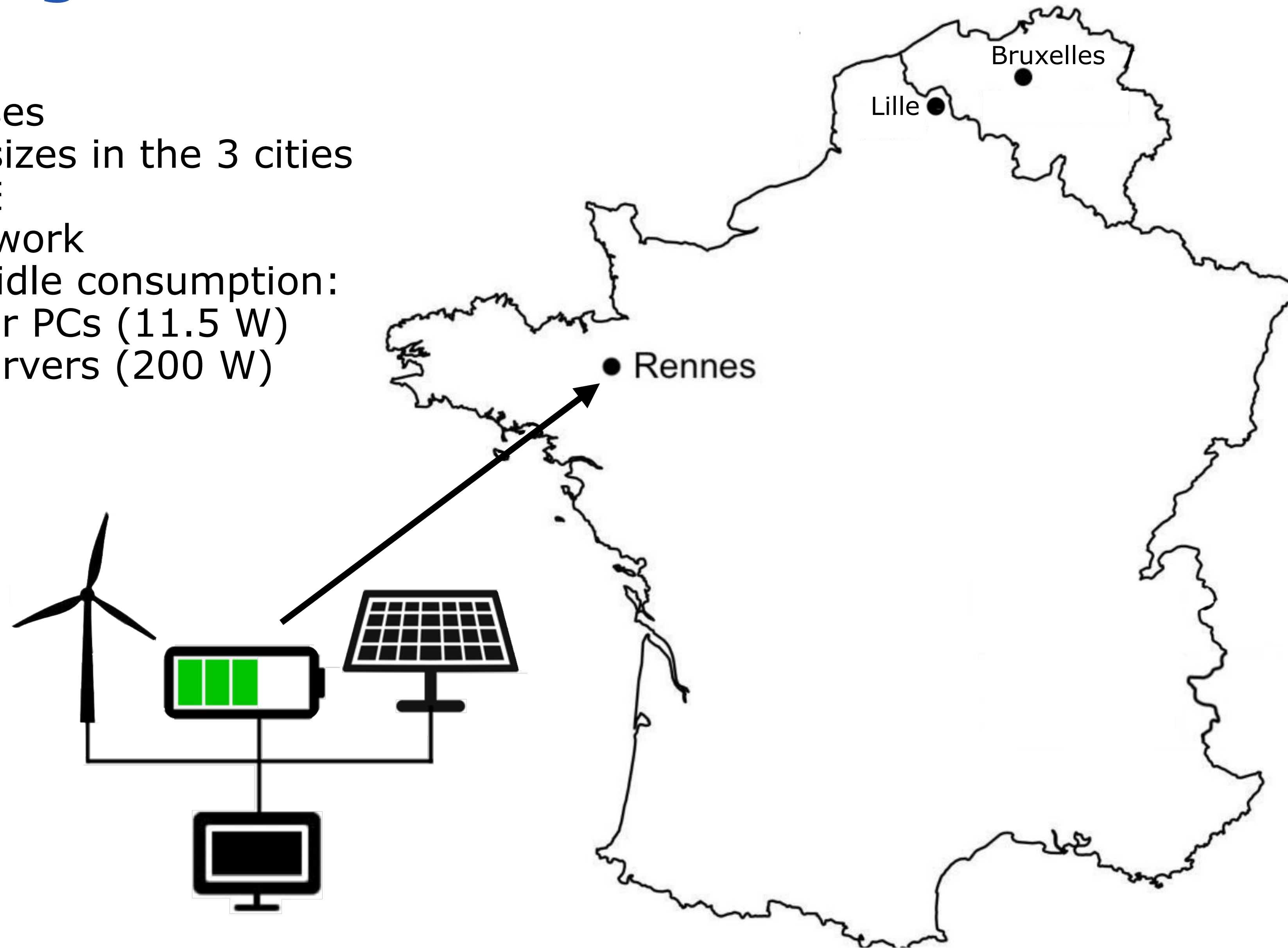
# Contributions

- method to size the powering infrastructure
- model to compute the carbon footprint and the uptime of the service
- evaluation with real workload traces

# Our Fog model (inspired by Deuxfleurs and the lowtech magazine)

## Hypotheses

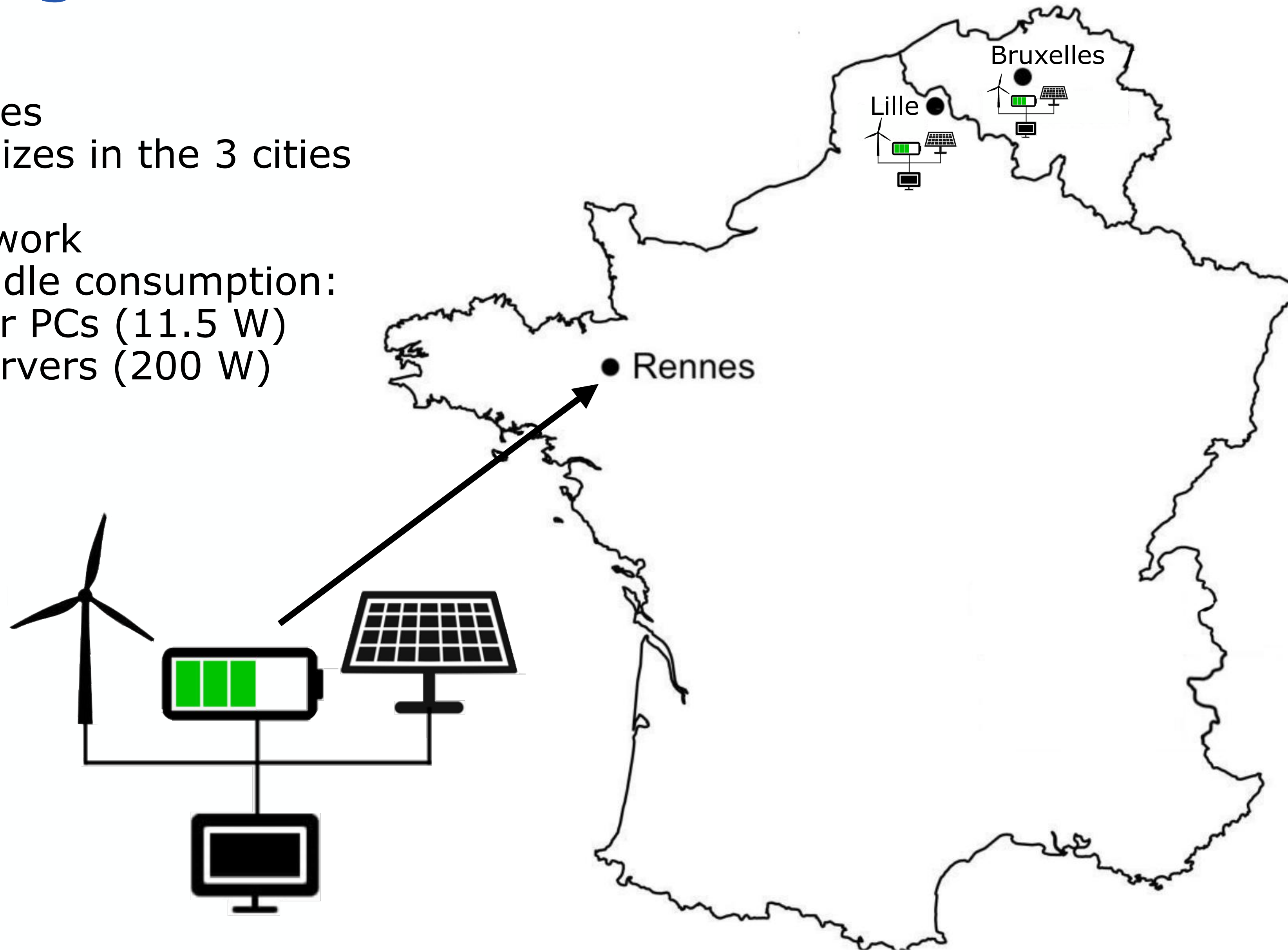
- same sizes in the 3 cities
- no PUE
- no network
- nodes idle consumption:
  - either PCs (11.5 W)
  - or servers (200 W)



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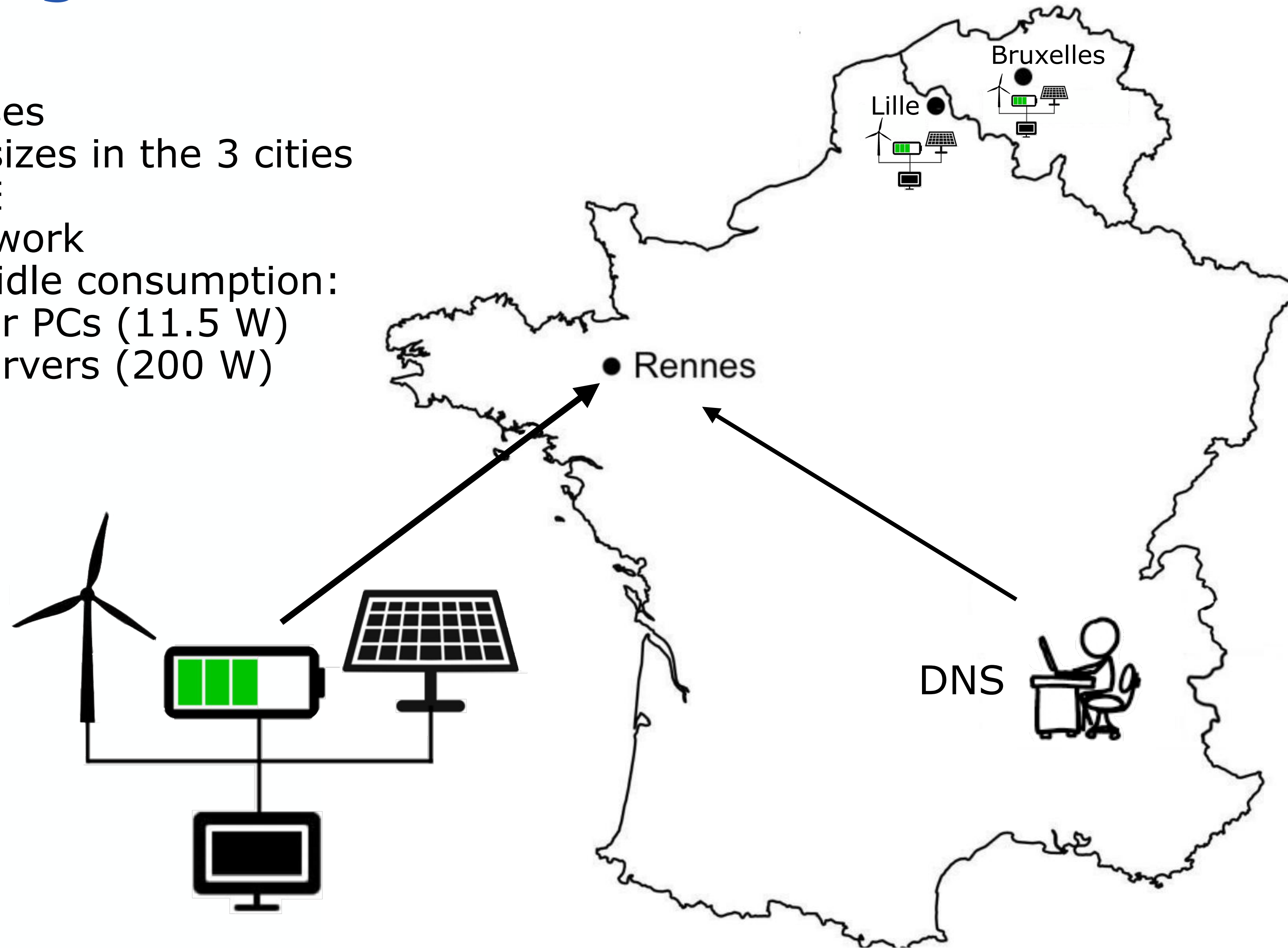
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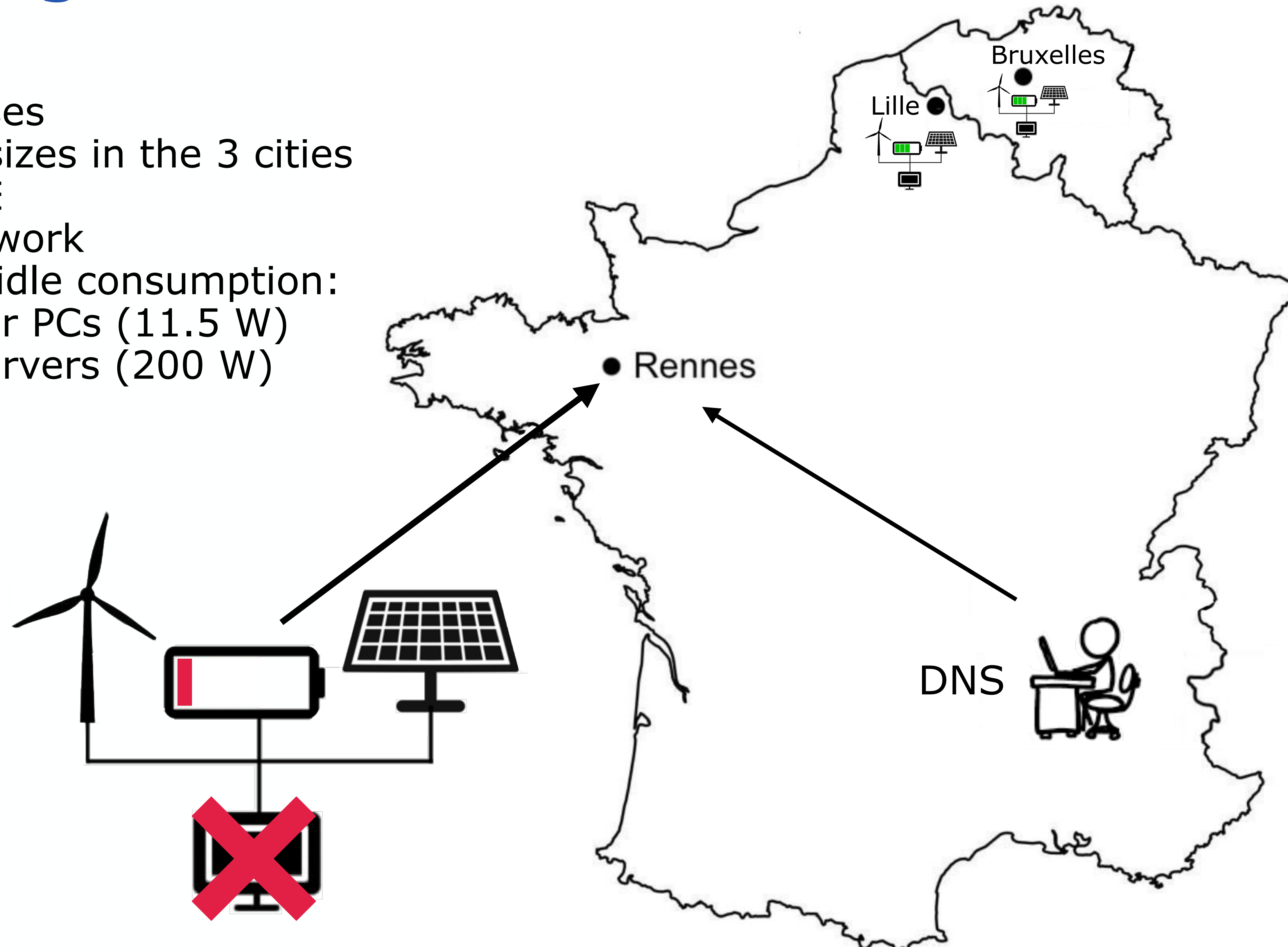
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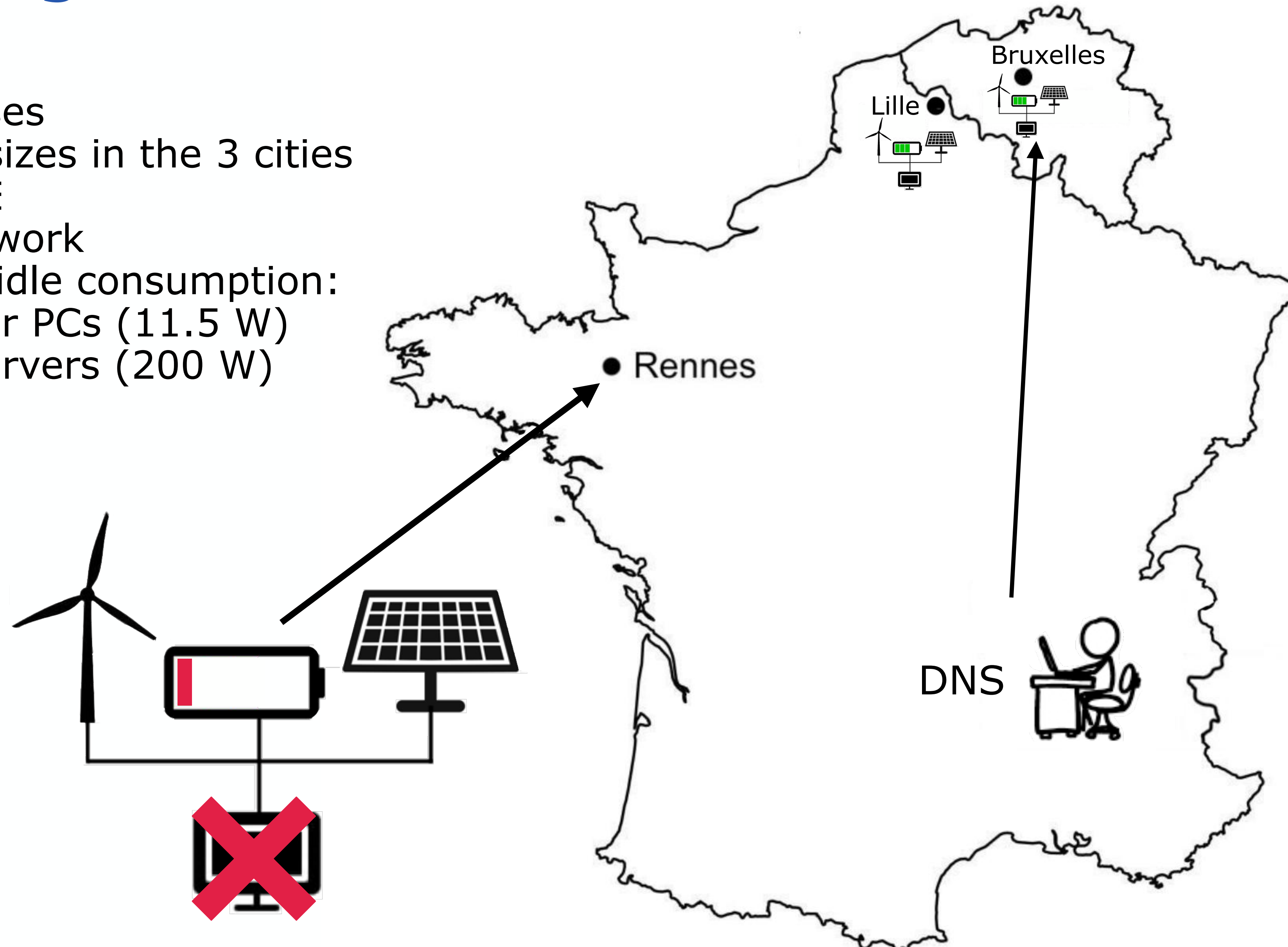
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# Our goal

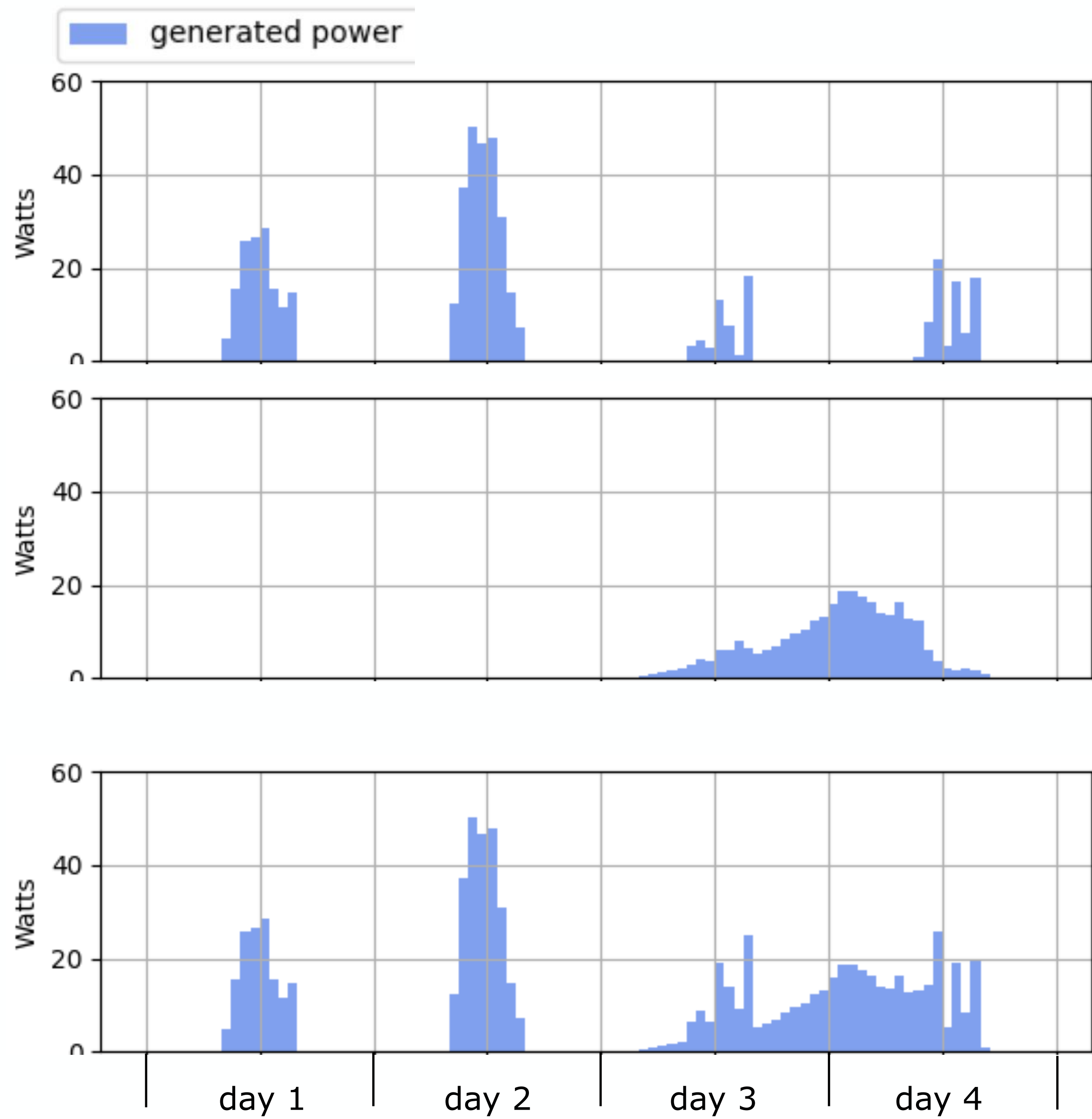
Two performance metrics

- 1) The **uptime** of the service during work-hours
- 2) The carbon **footprint** of the powering infrastructure (mainly during manufacture)

The goal is to **maximize** the uptime,

while **minimizing** the carbon footprint.

# How we compute the uptime



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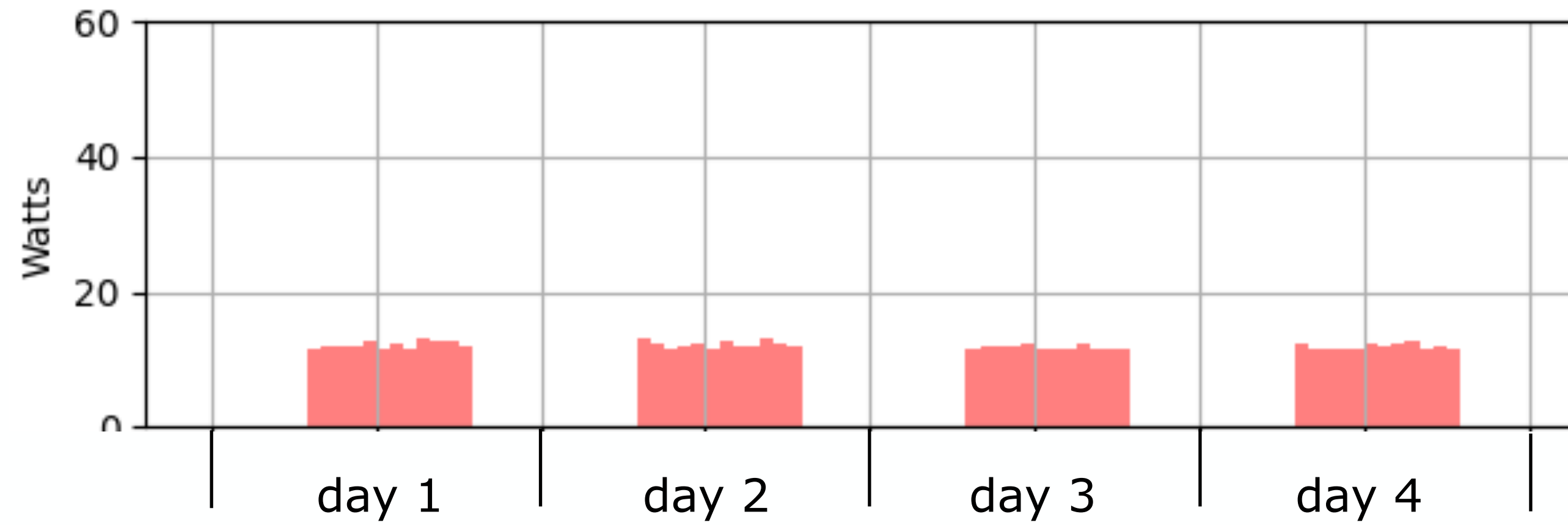
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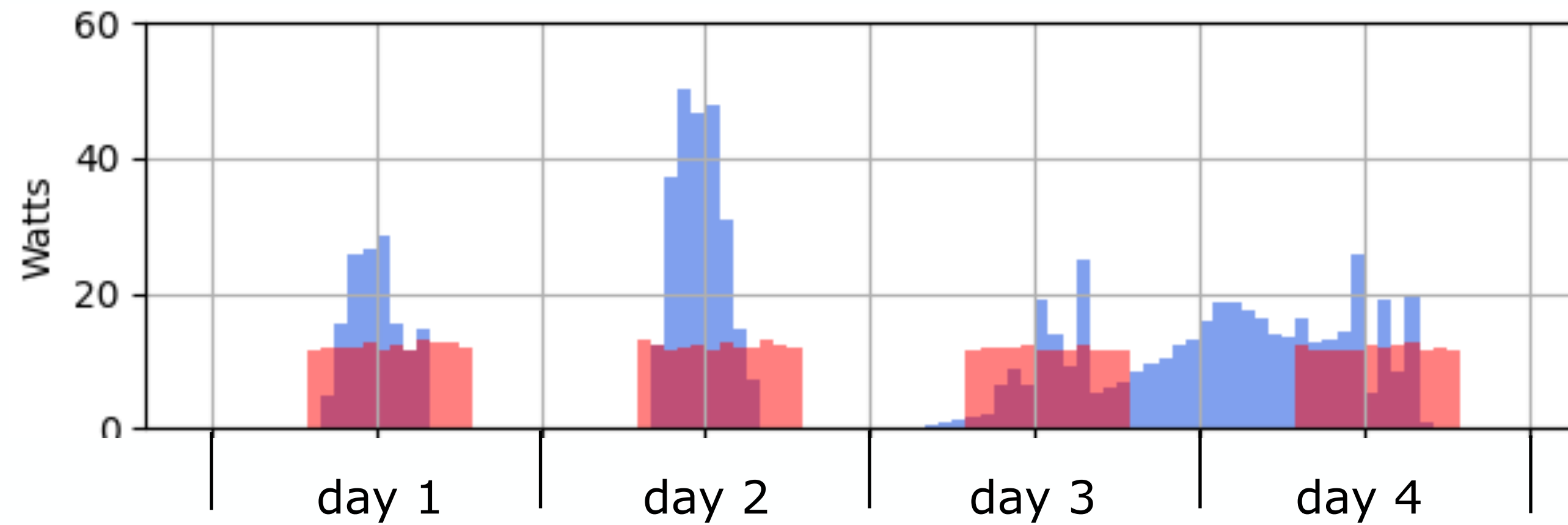
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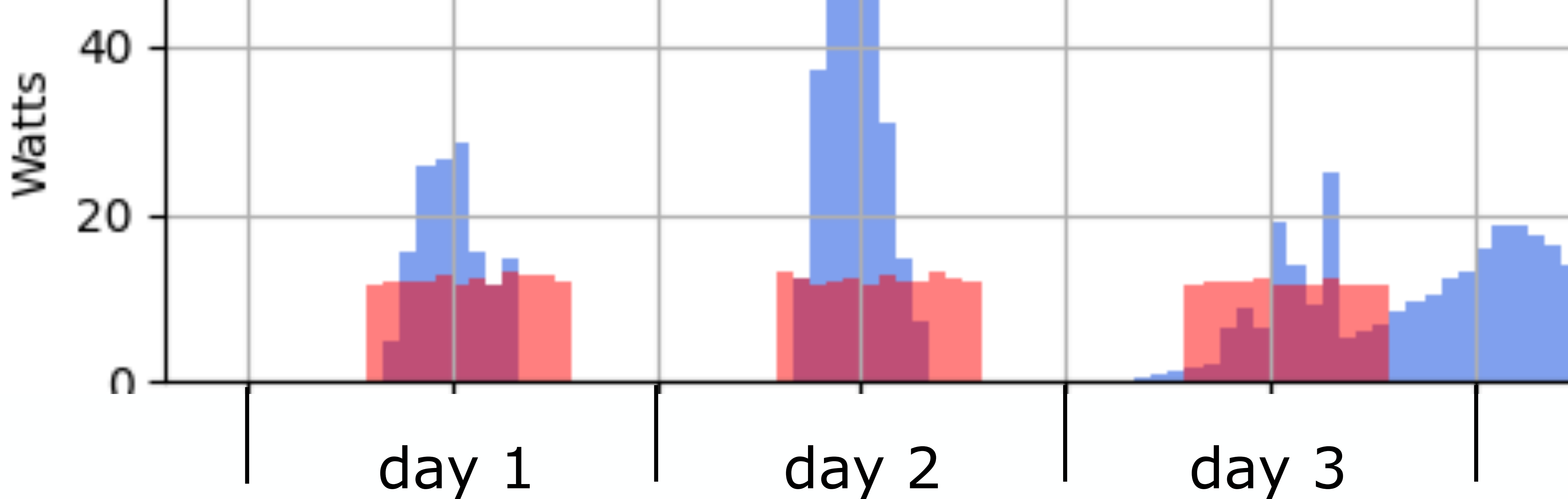
wind

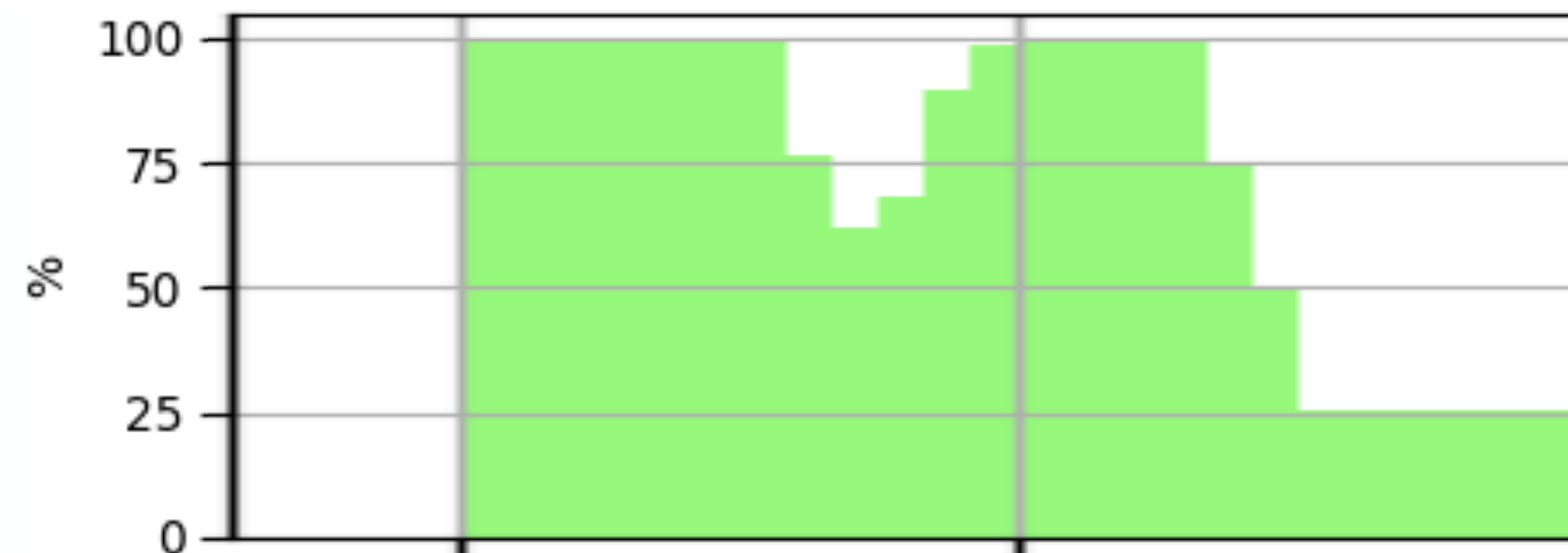
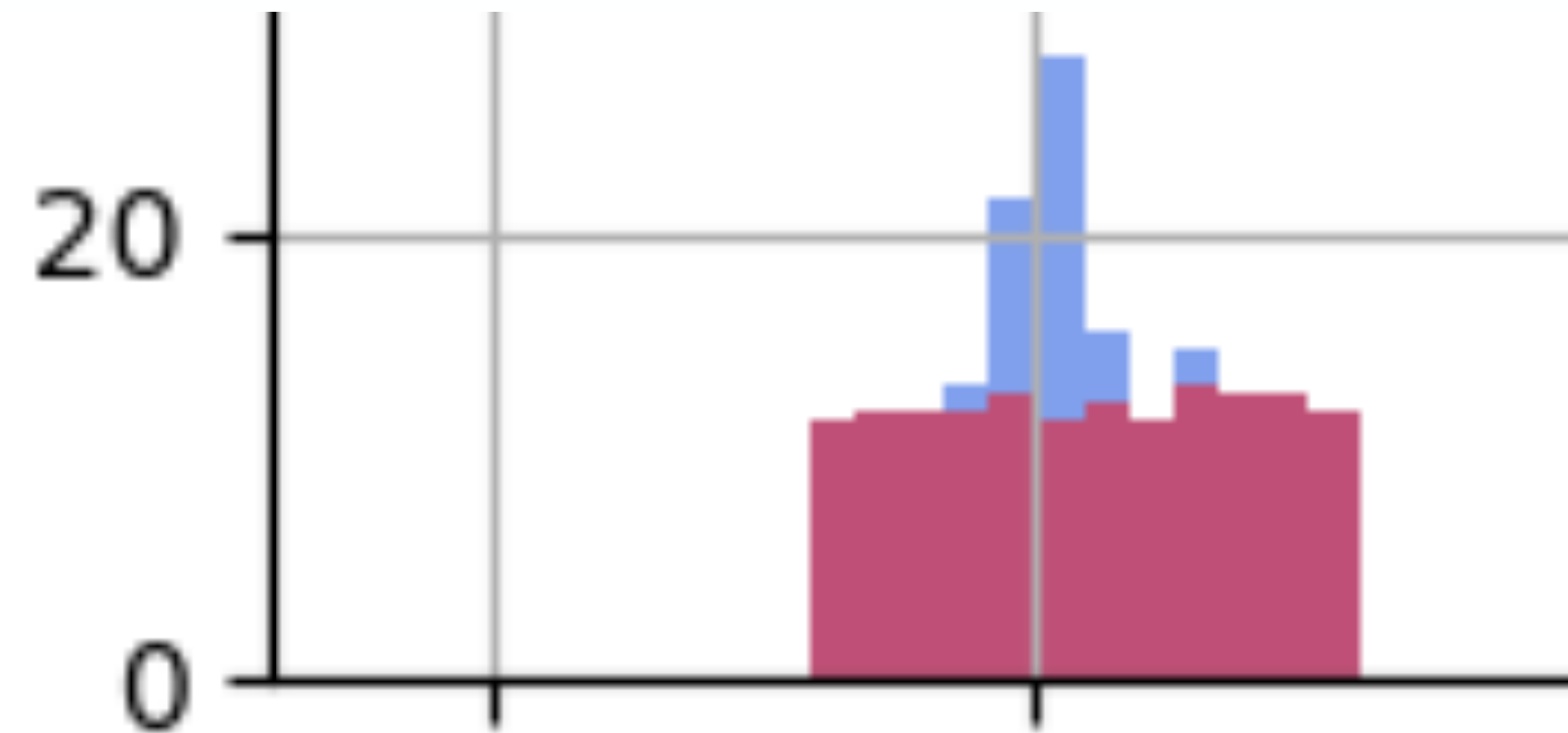
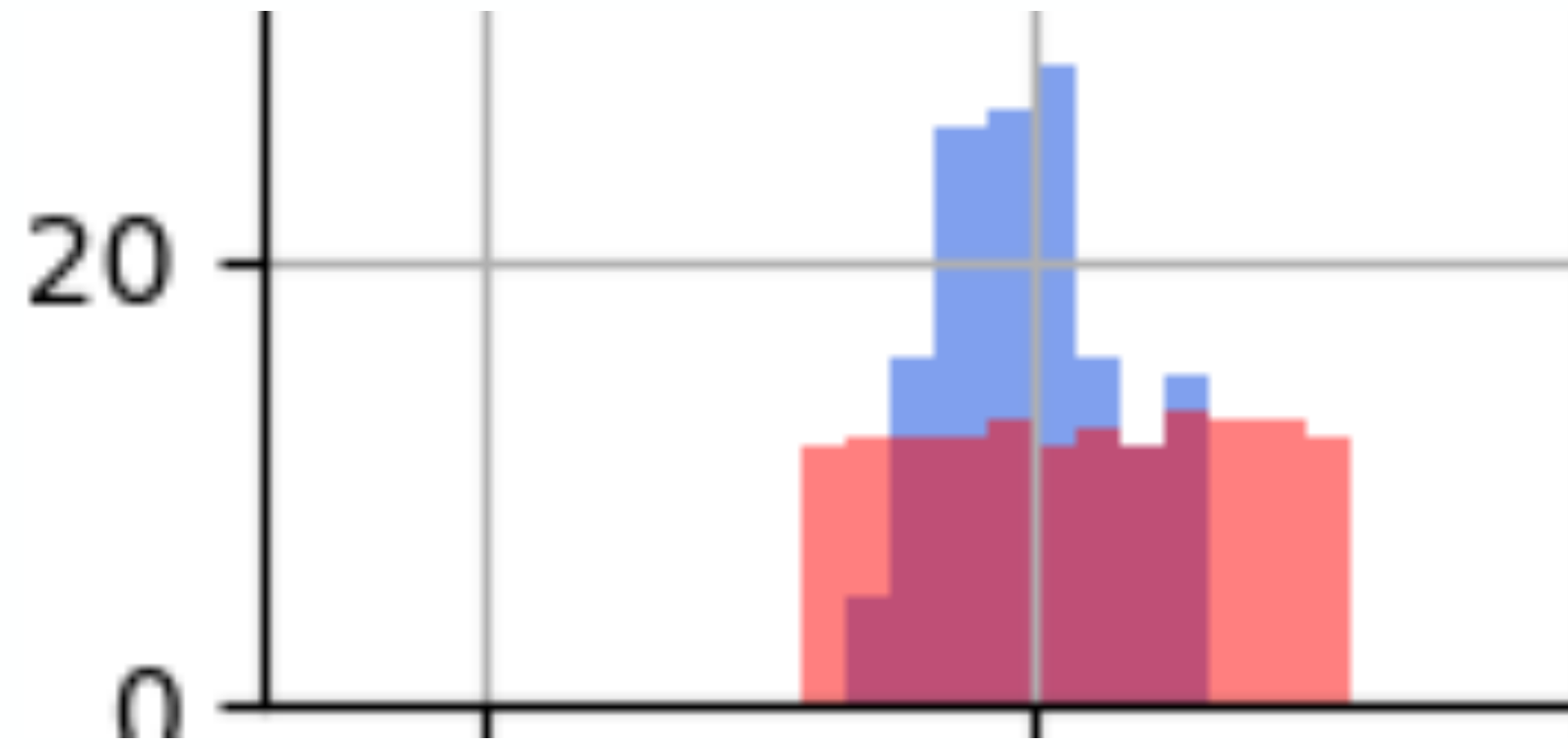
both

workload (from 7am to 7pm)



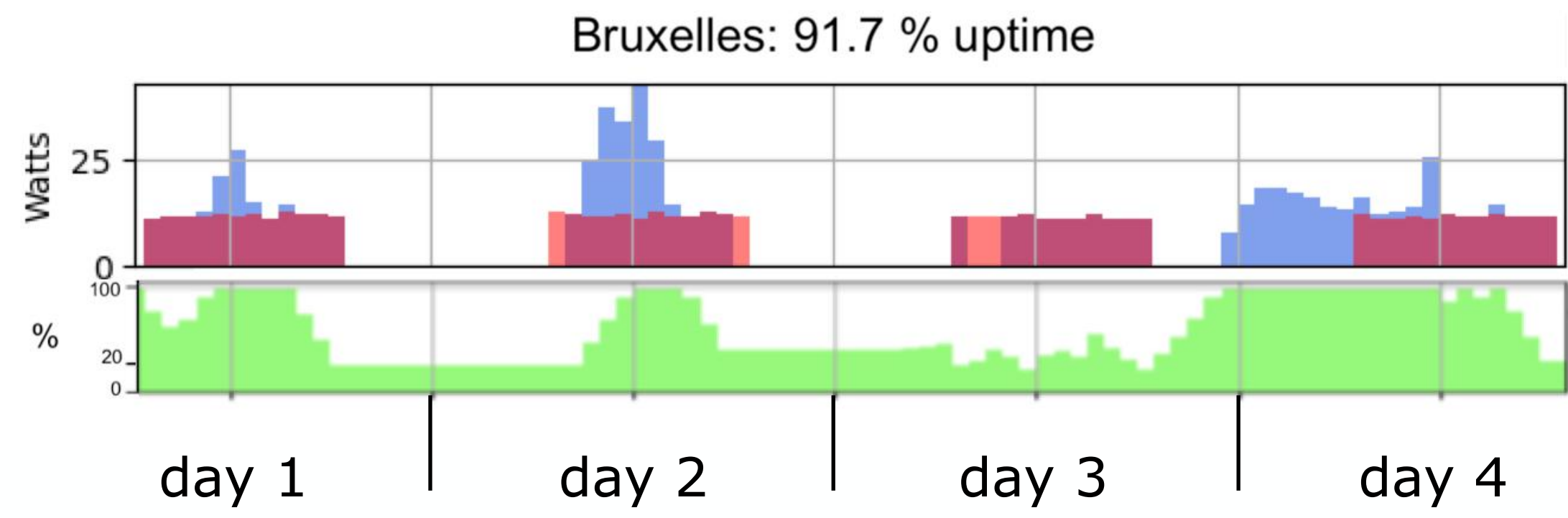


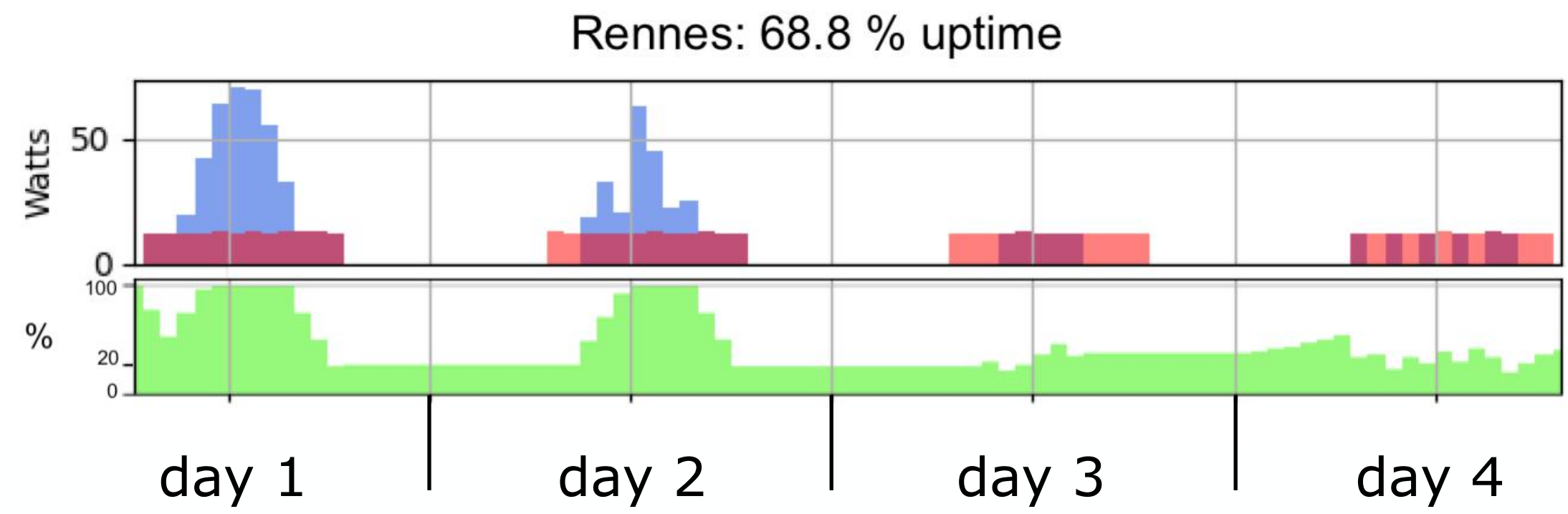


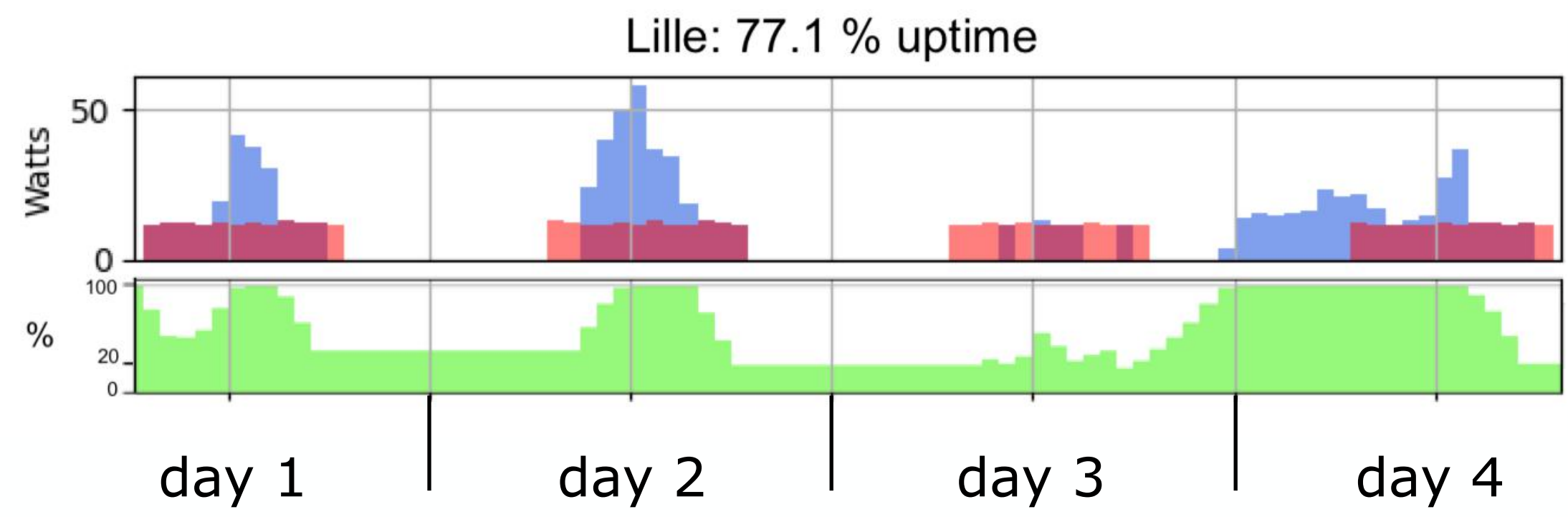


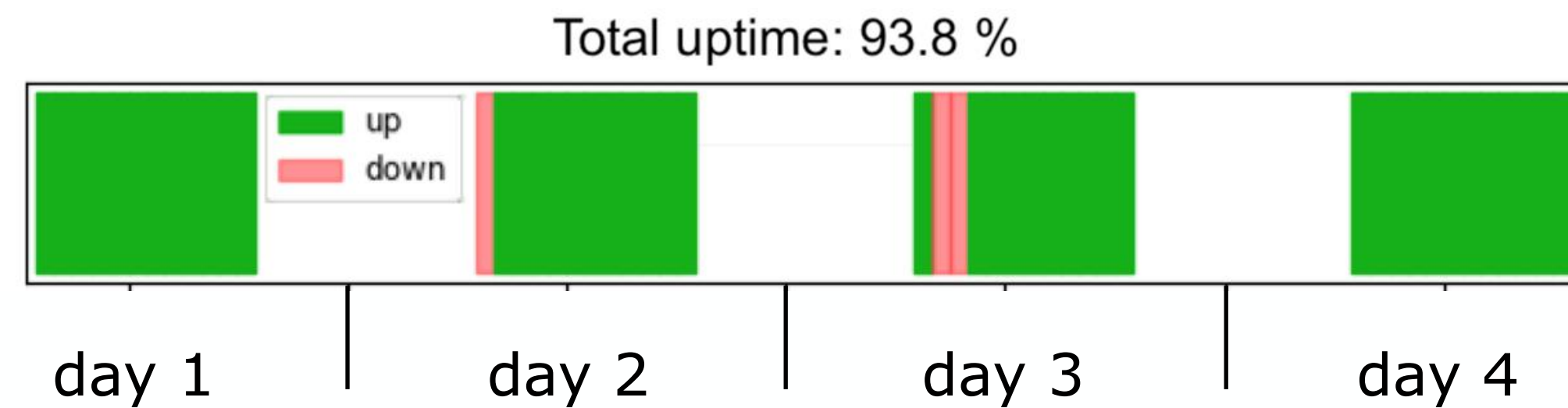
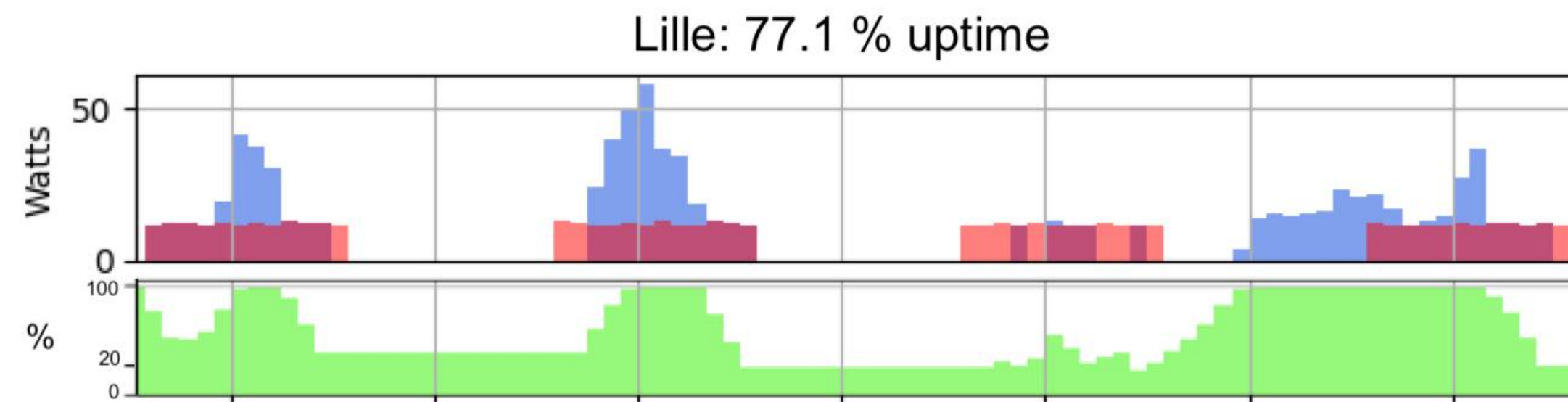
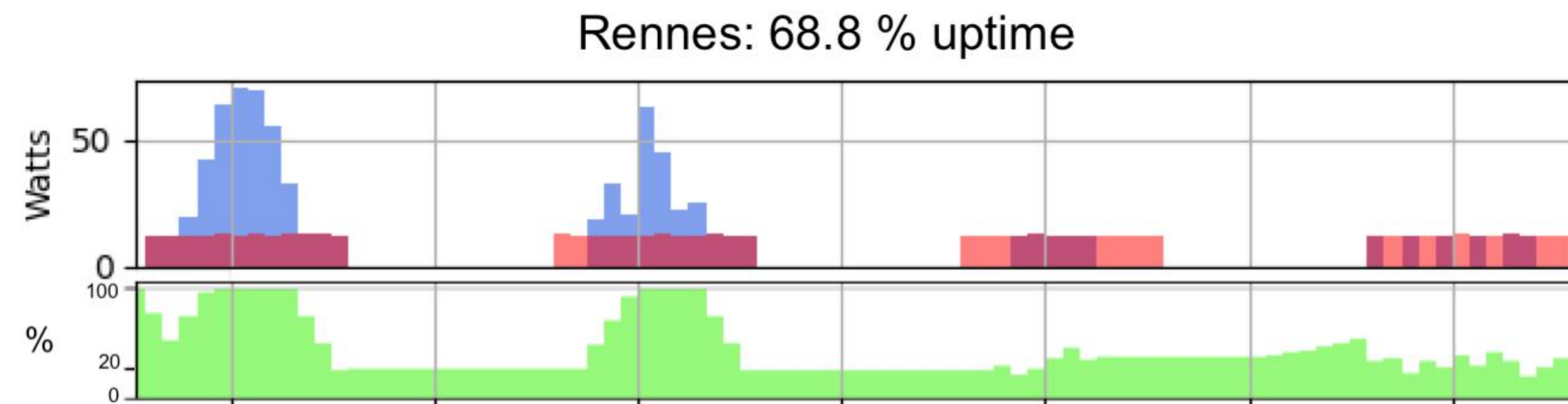
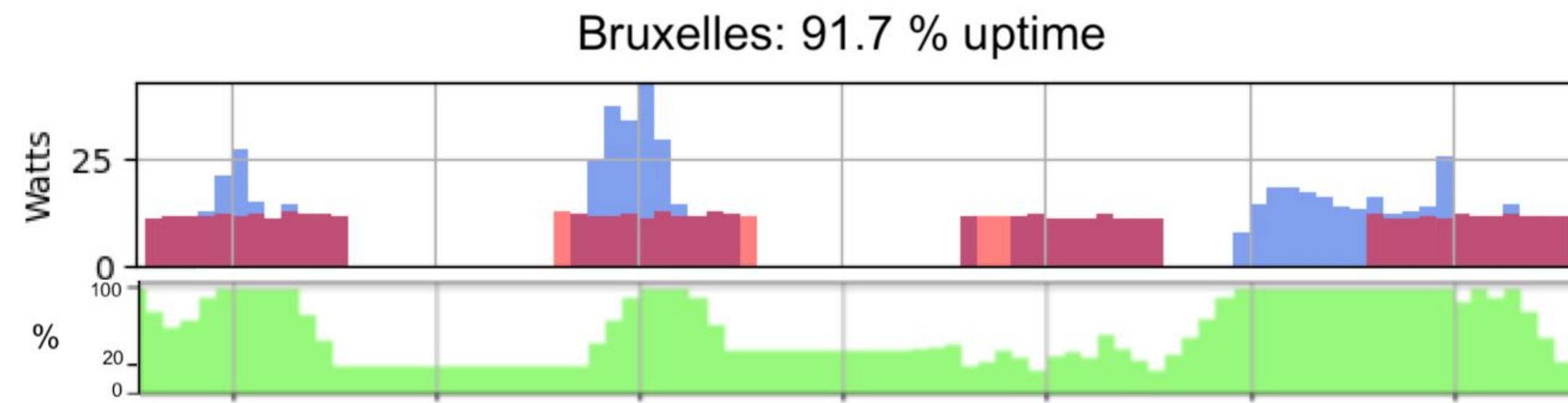
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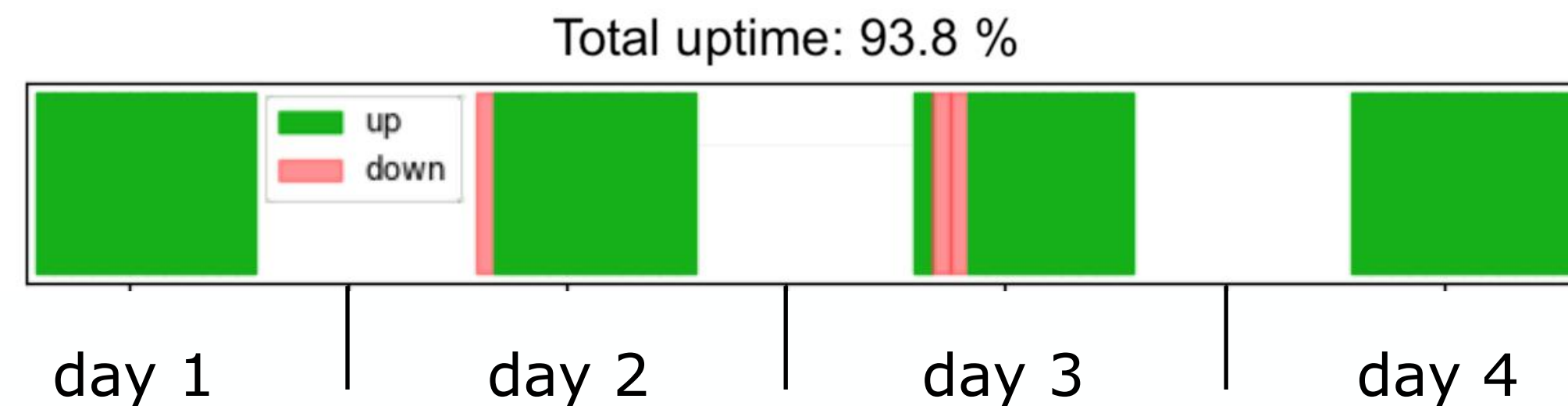
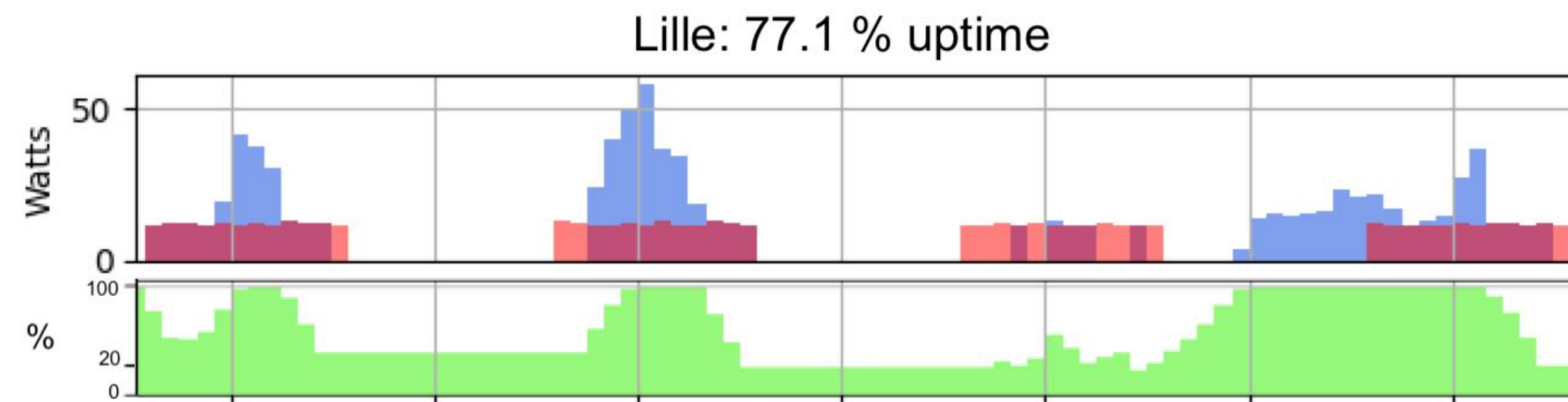
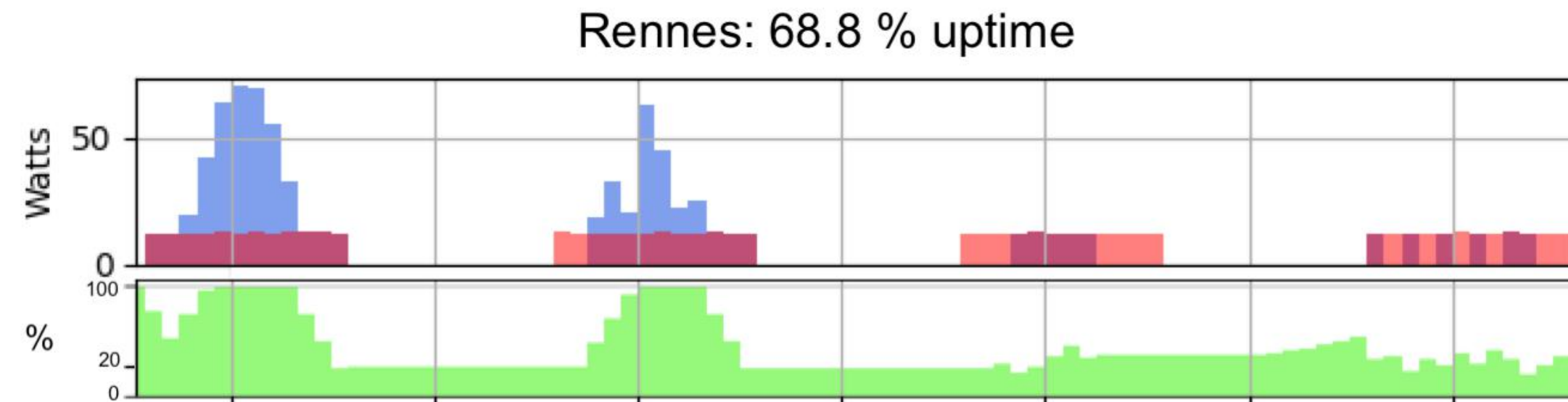
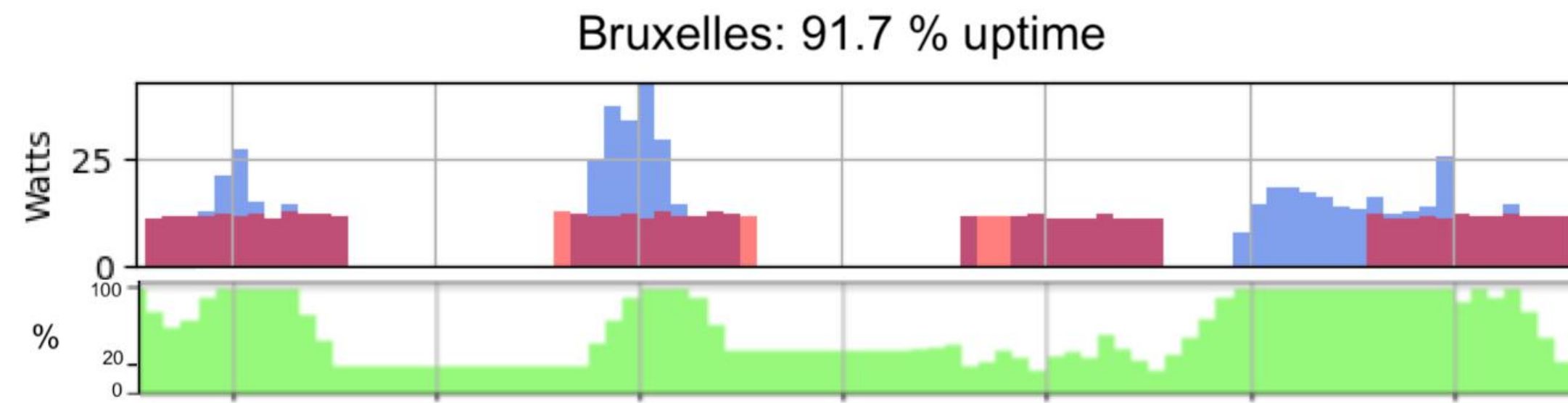
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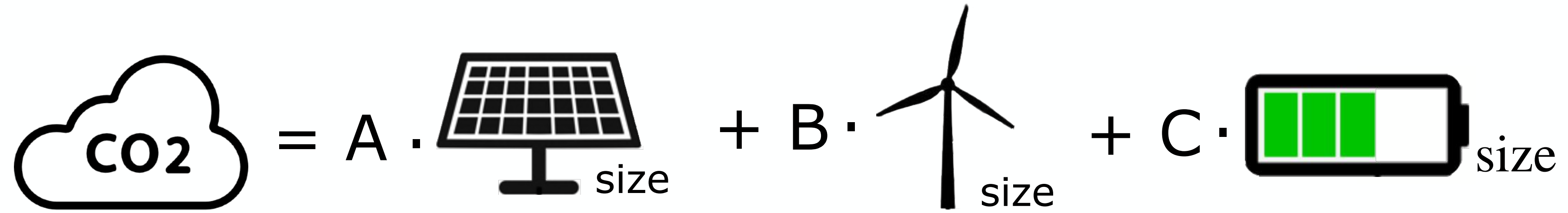




In the following experiment, we will compute the uptime on 365 days (the year 2021)

# How we compute the carbon footprint

# The carbon footprint of the infrastructure

$$\text{CO}_2 = A \cdot \text{size}_{\text{panel}} + B \cdot \text{size}_{\text{wind}} + C \cdot \text{size}_{\text{battery}}$$


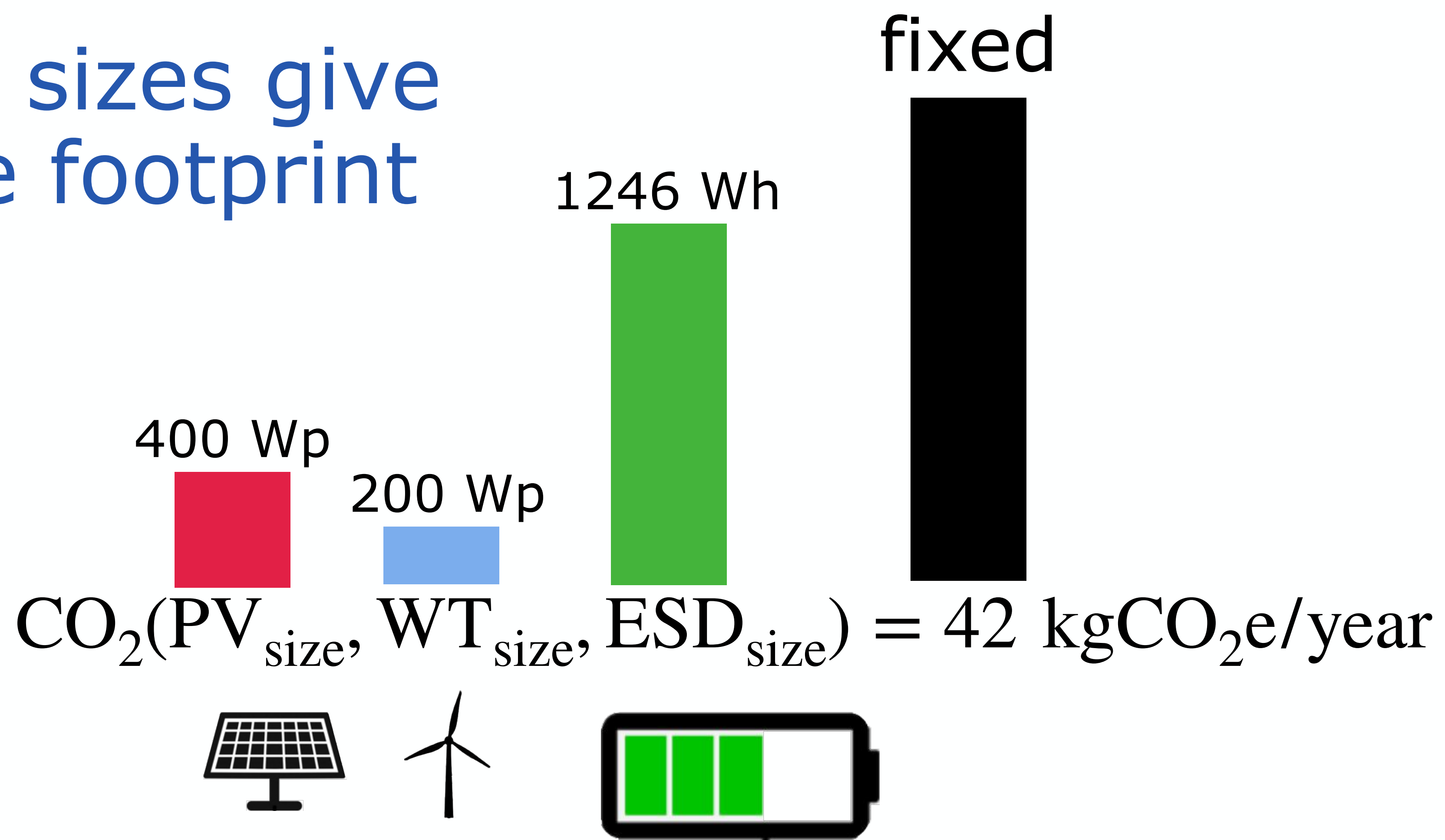
(unit: kgCO<sub>2</sub>e/year)

# Key idea

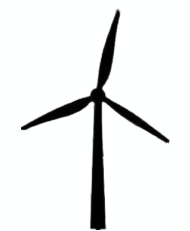
Remember: our goal is to **maximize** the uptime,  
while **minimizing** the carbon footprint.

To do that, we can compare infrastructures with **the same footprint**,  
and choose the one with the best uptime !

# Different sizes give the same footprint



PV = PhotoVoltaic (solar panel)

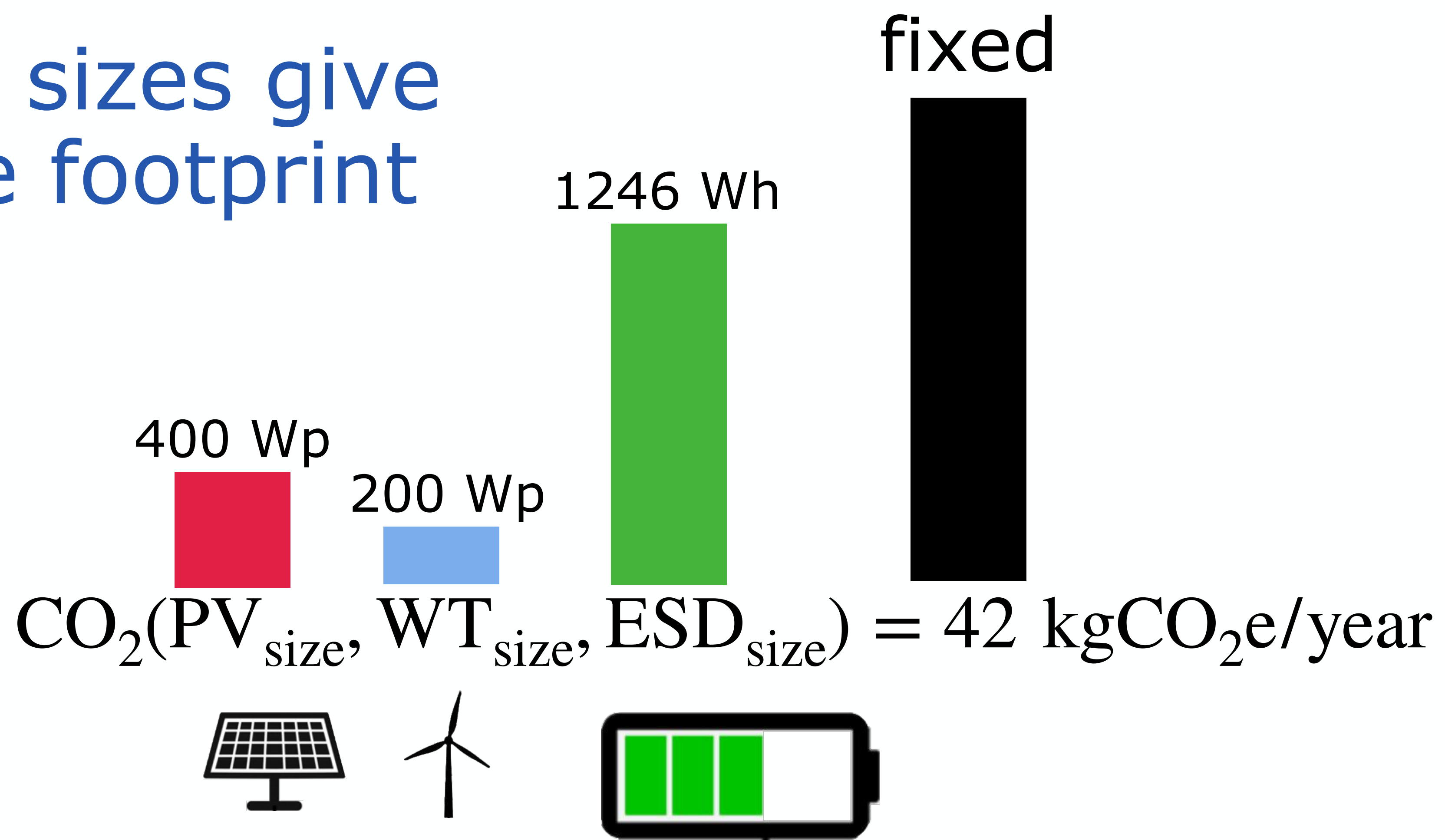


WT = Wind Turbine

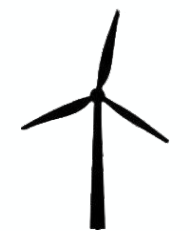


ESD = Energy Storage Device (battery)

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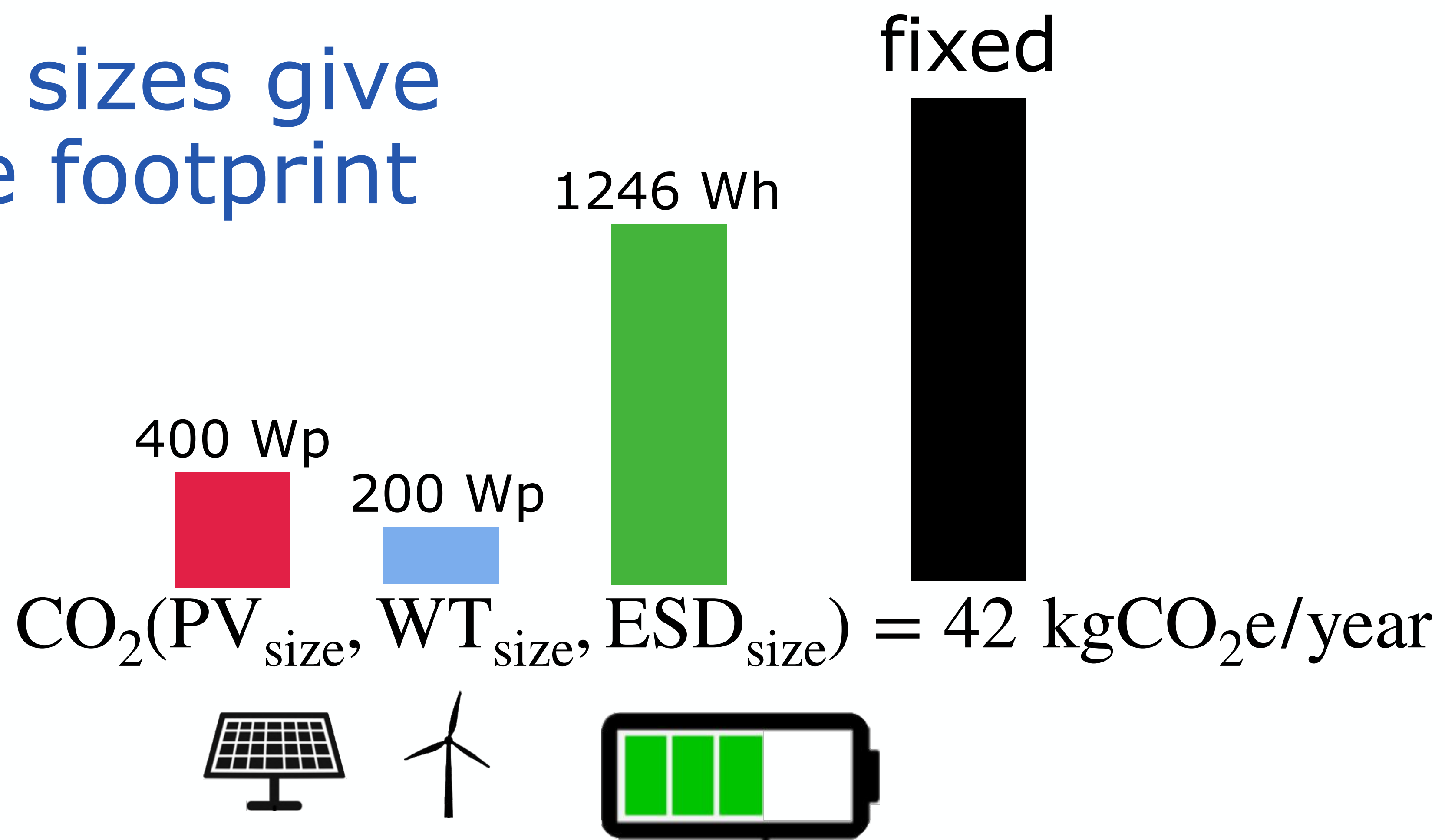


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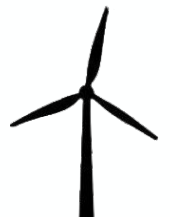


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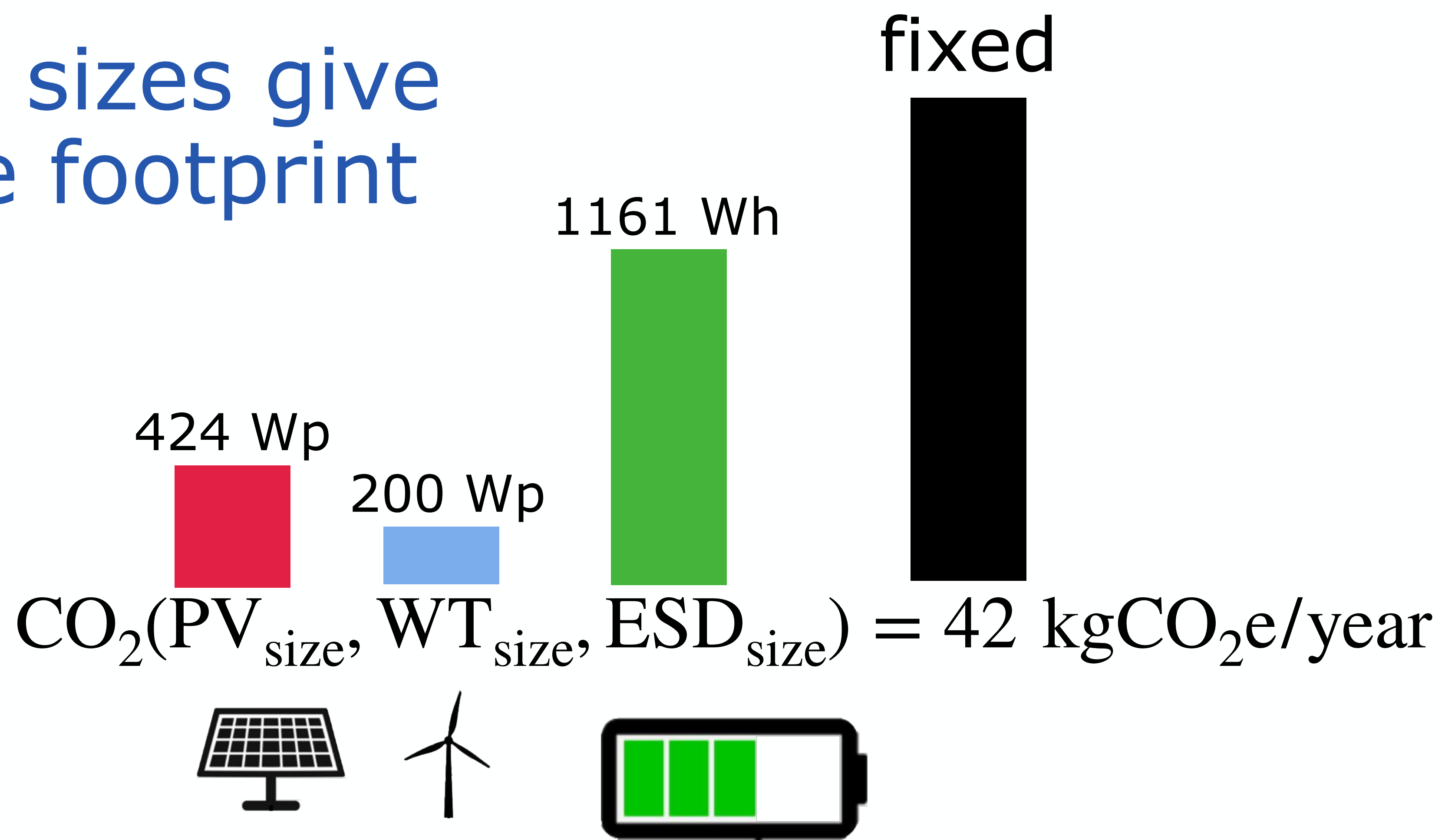


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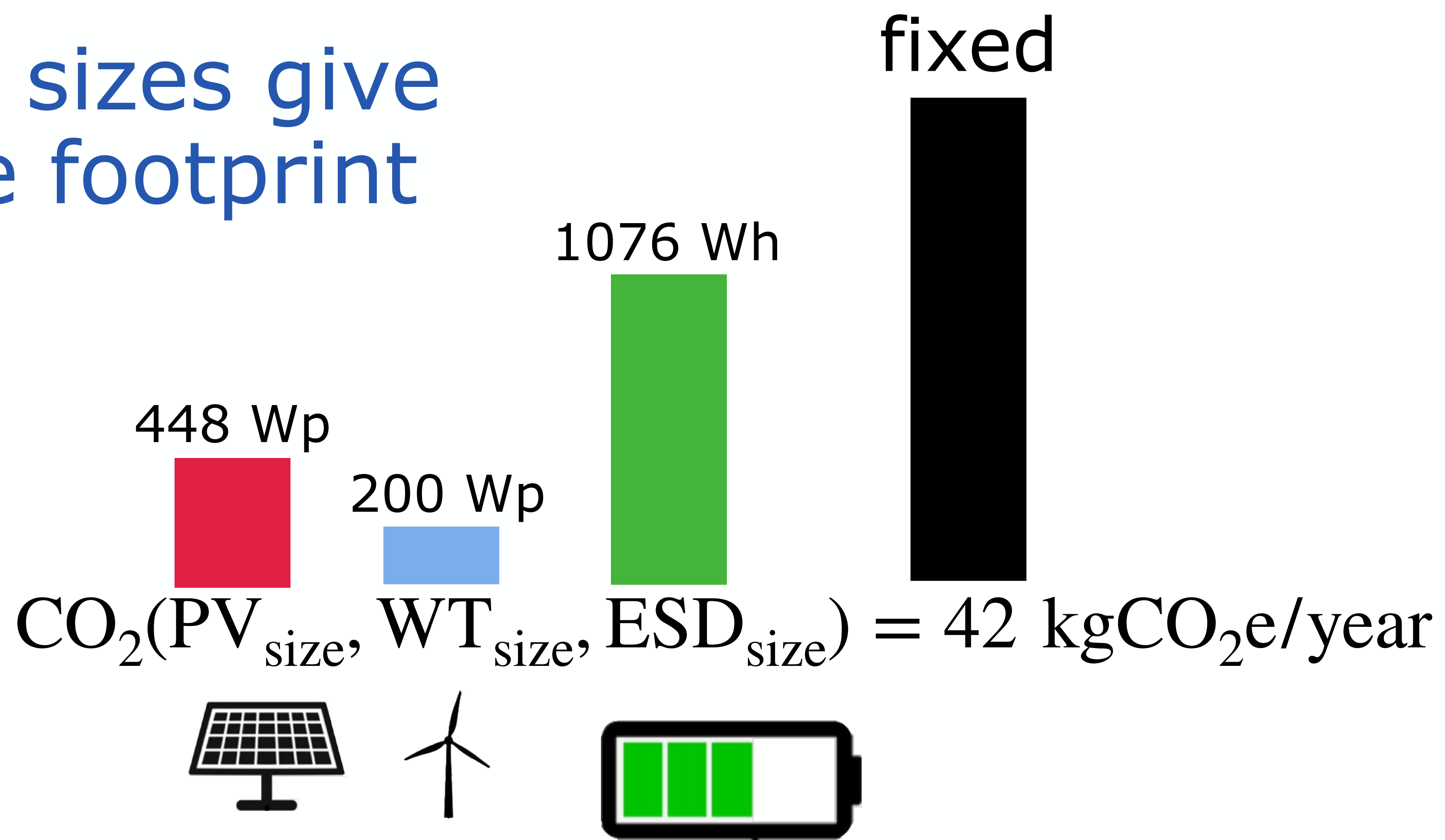
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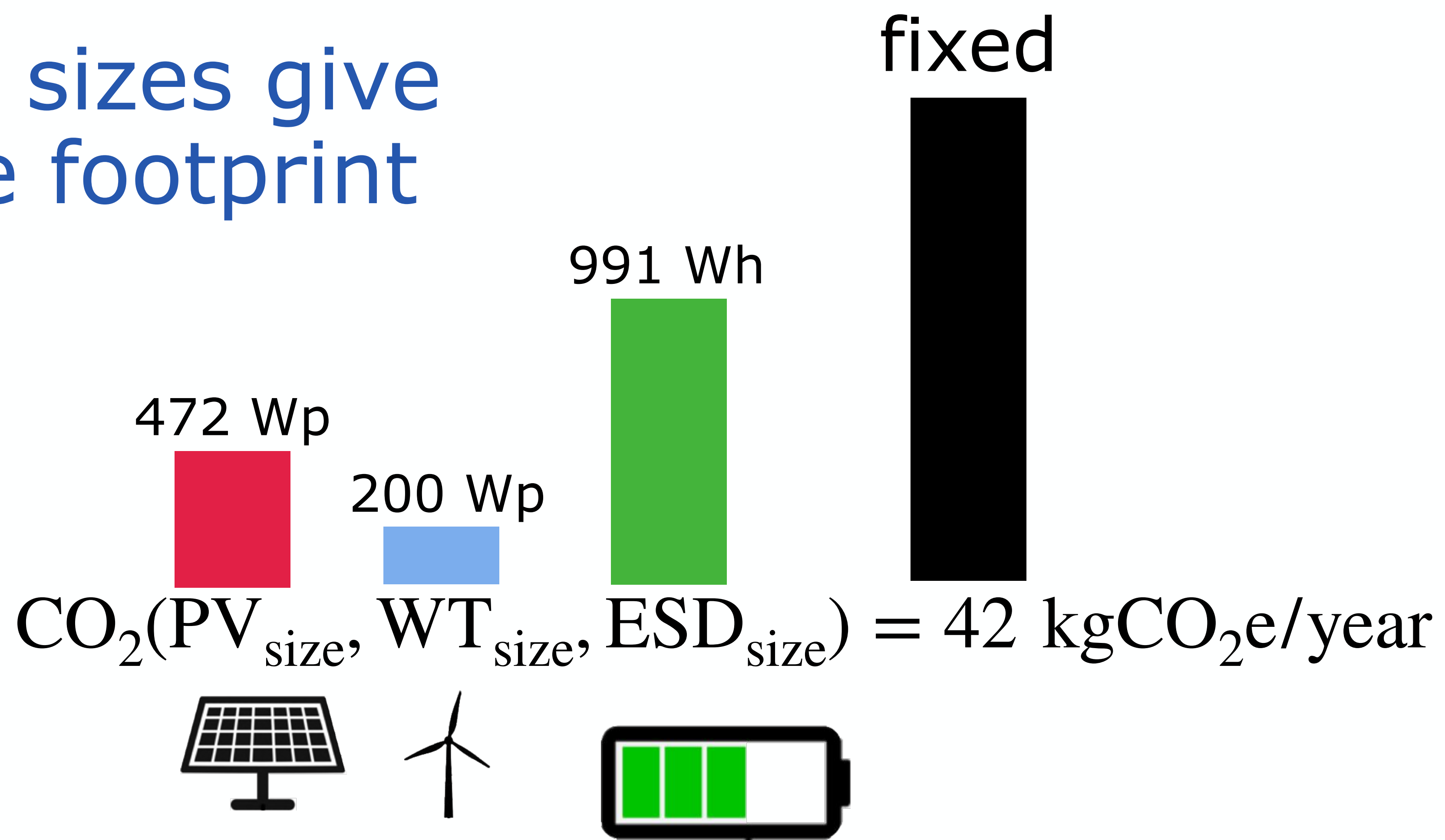
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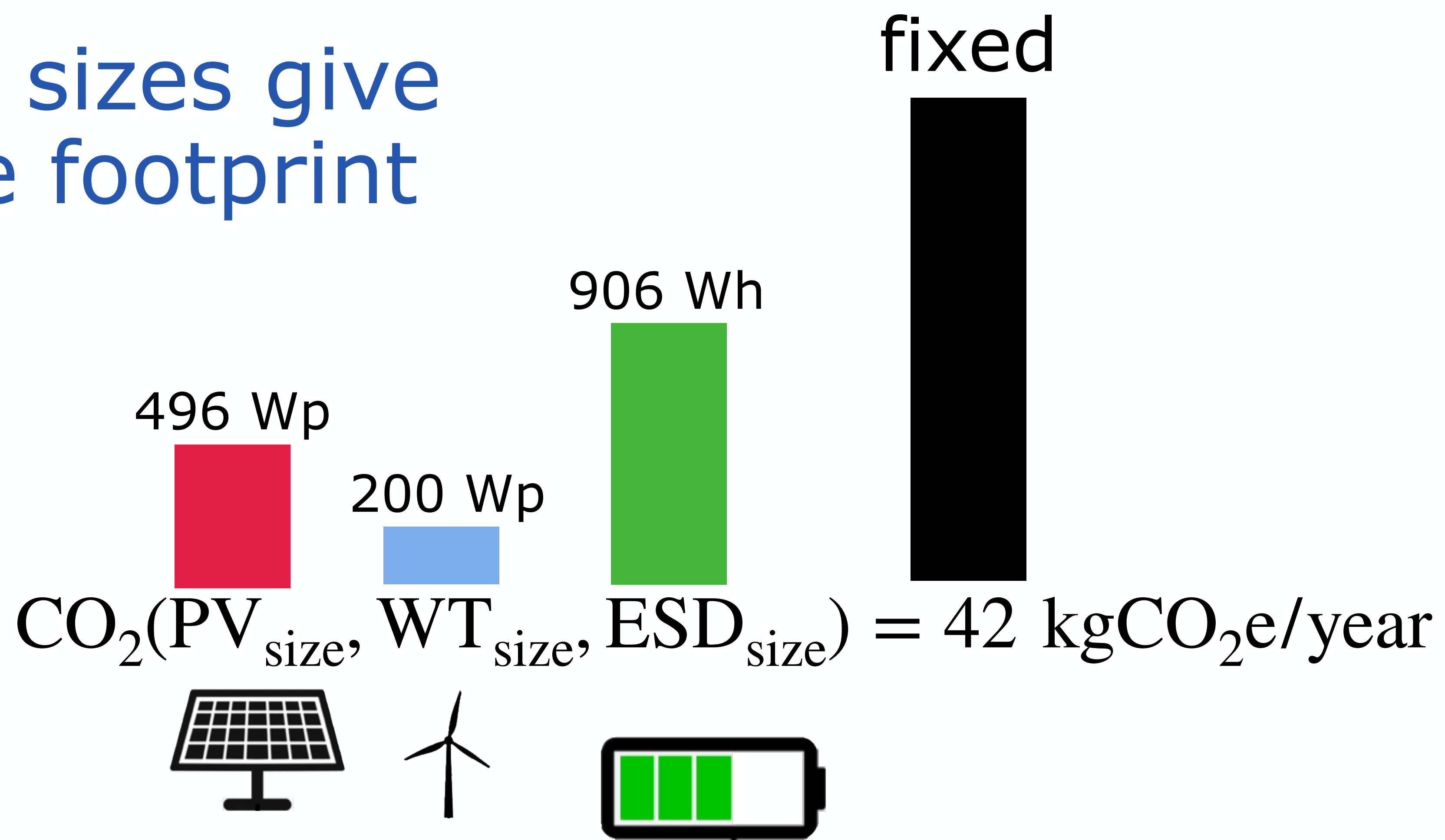
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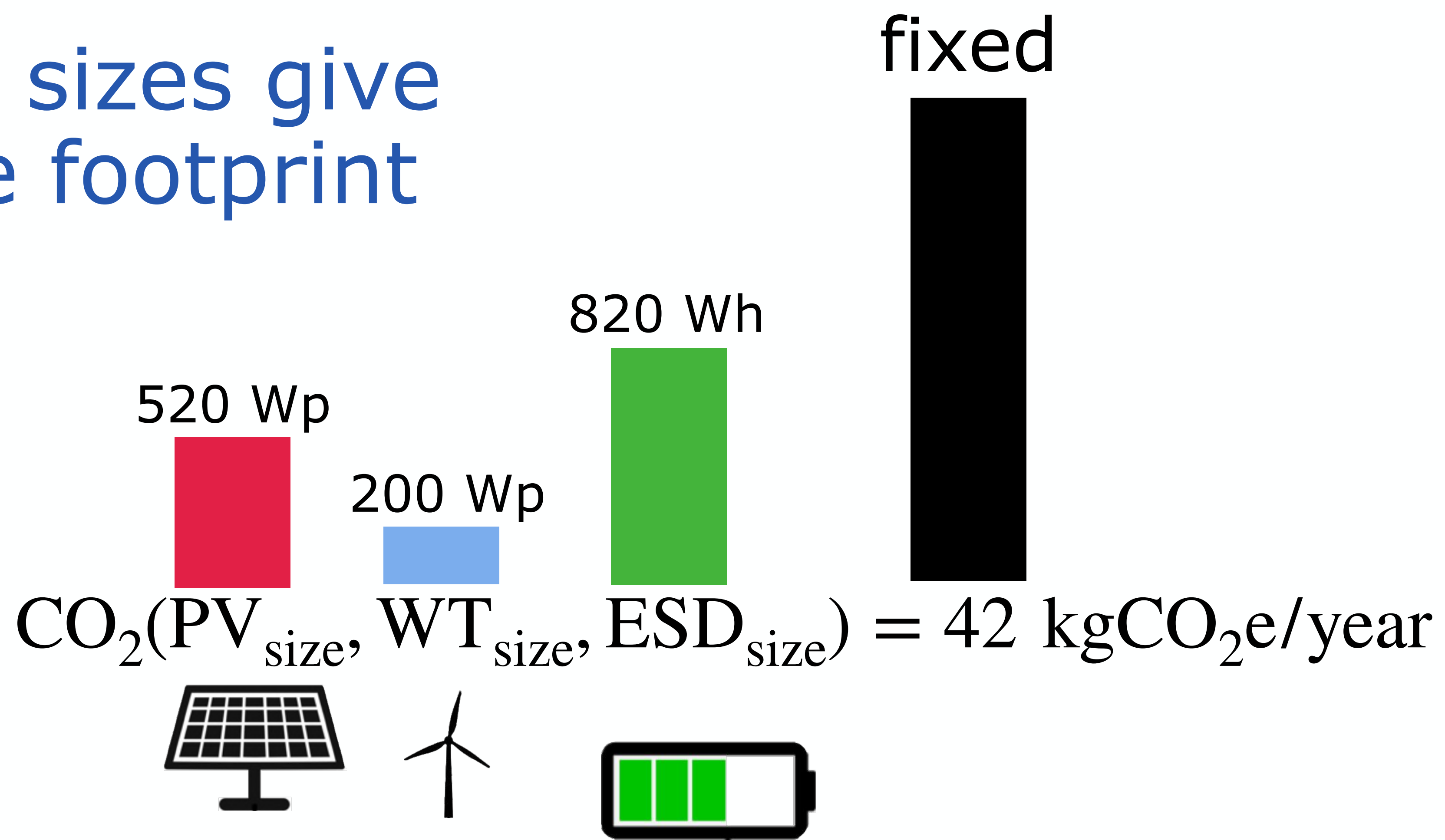
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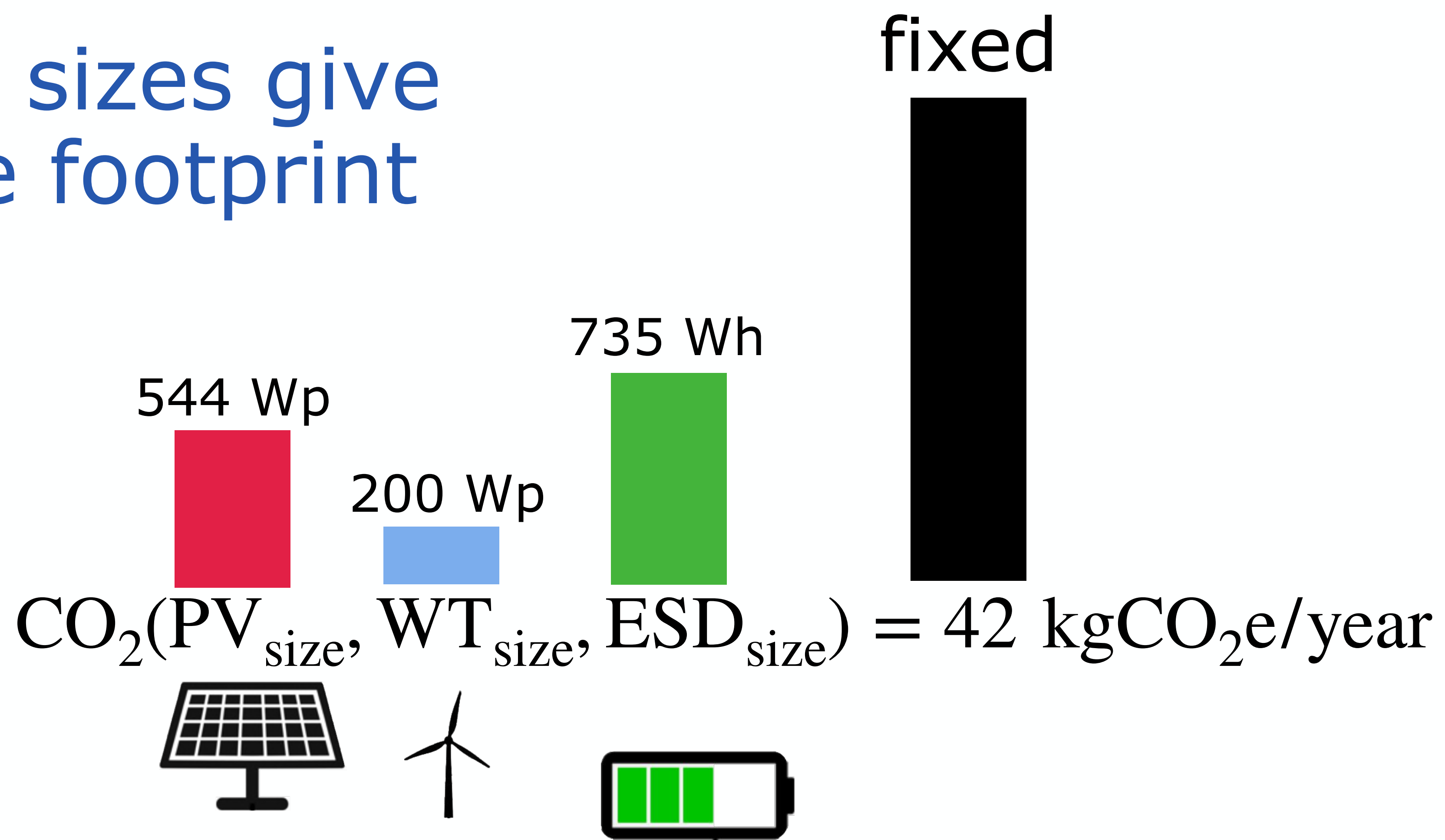
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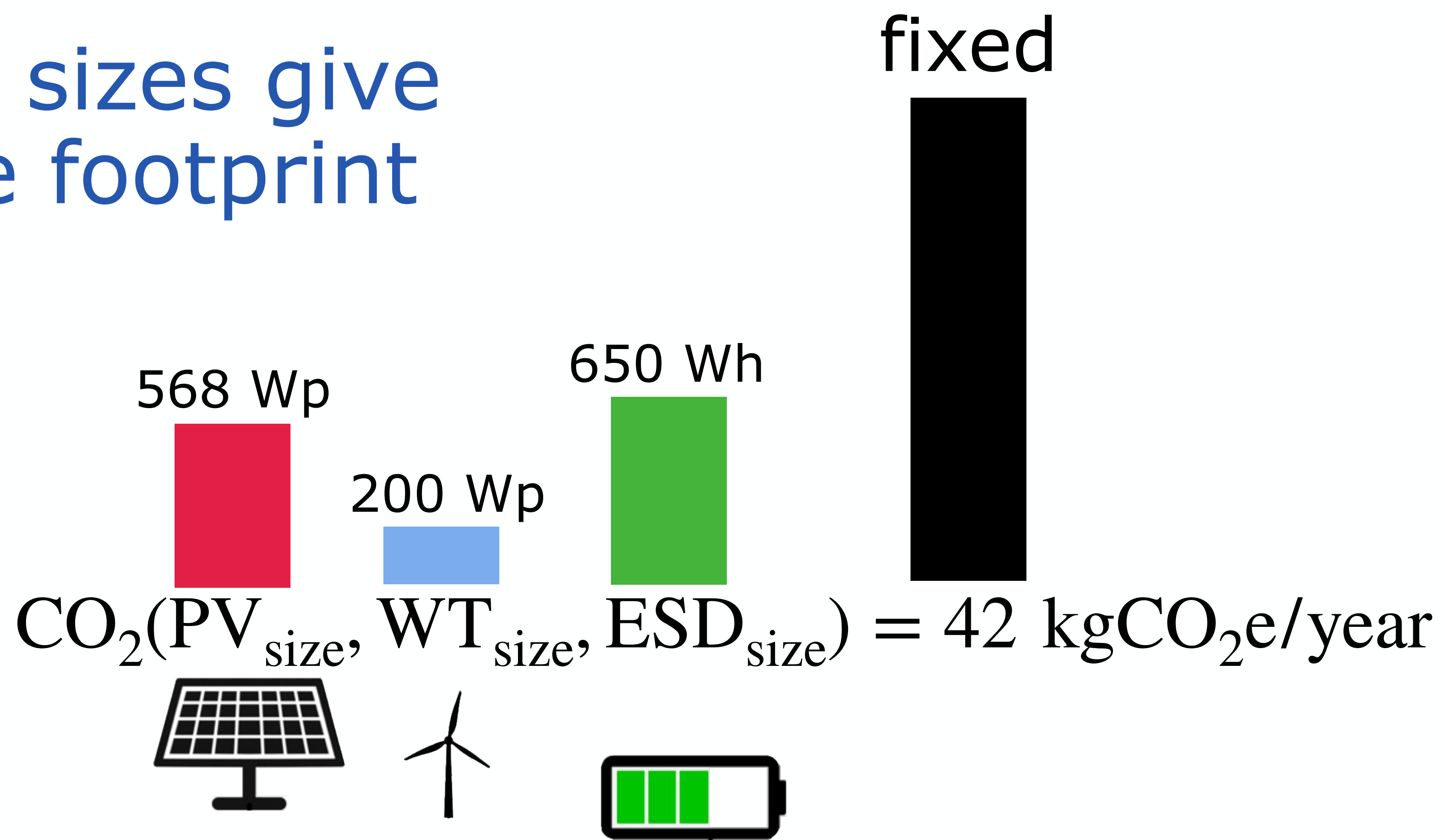
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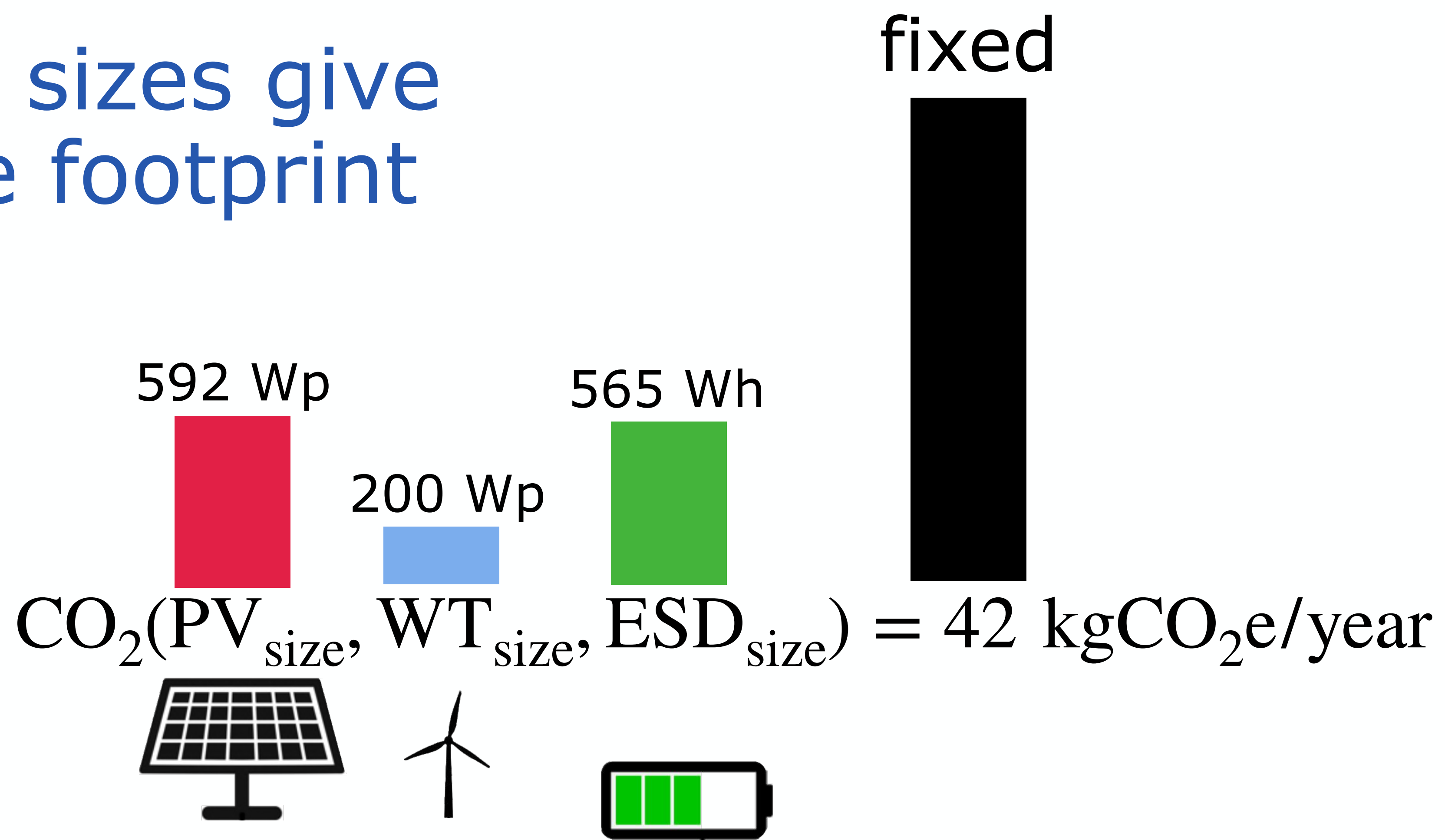
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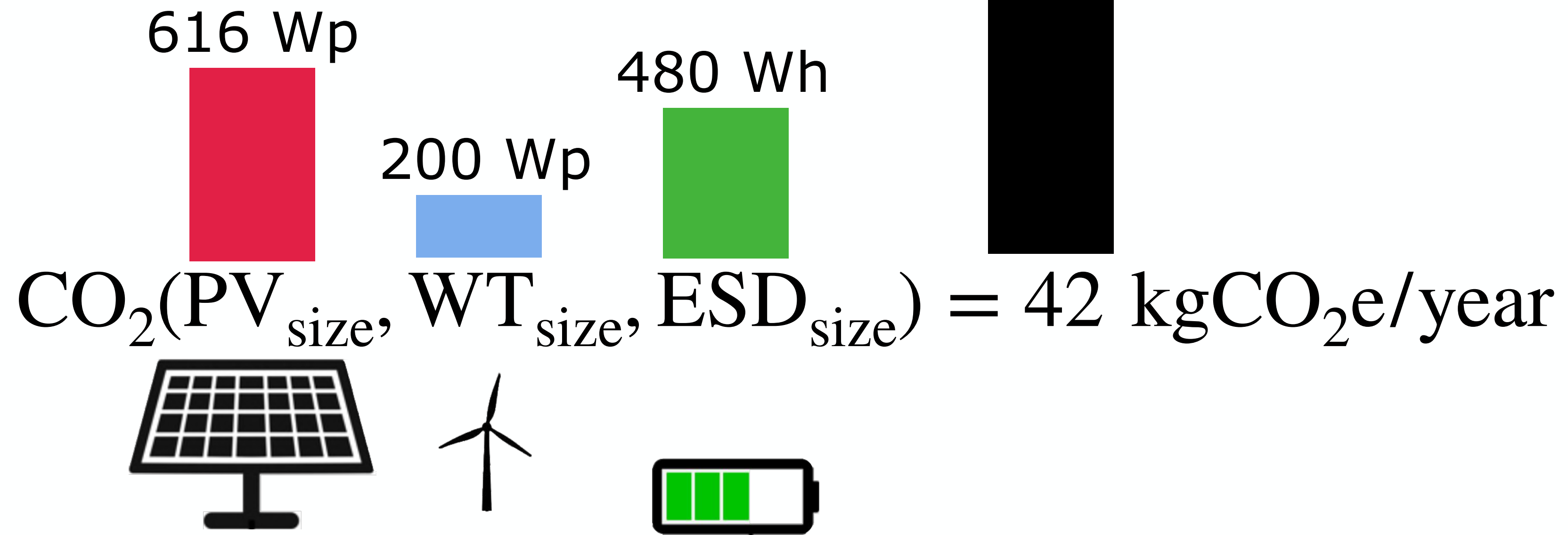
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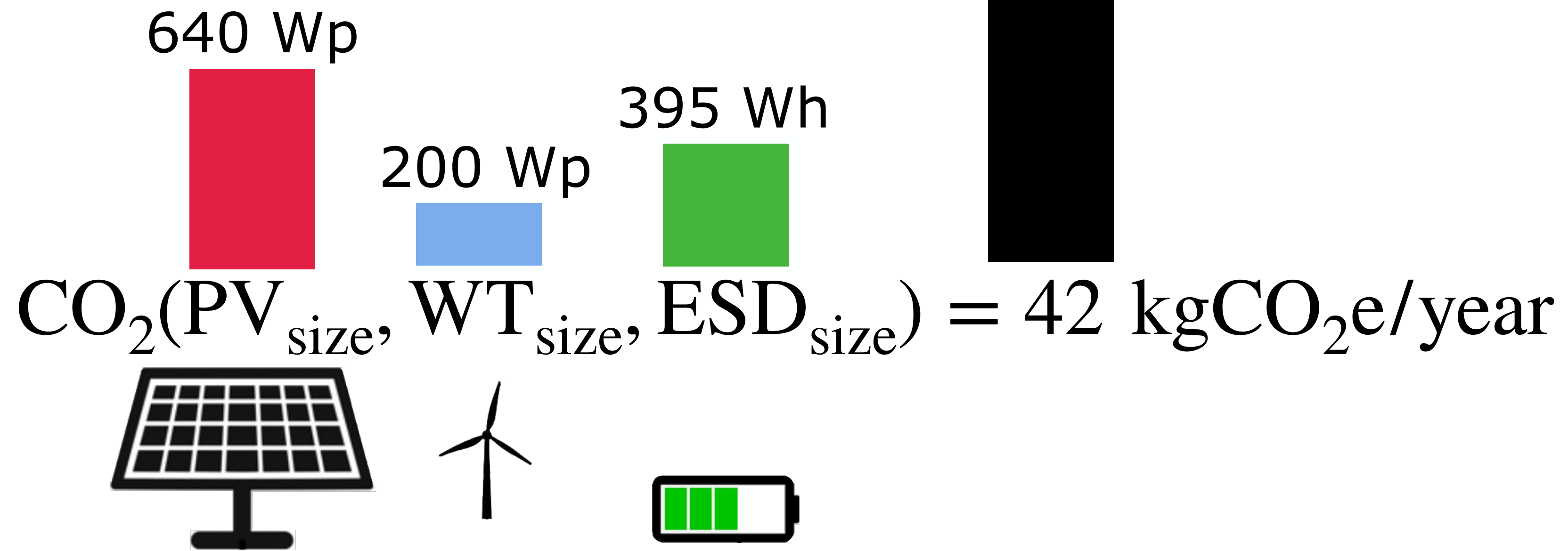
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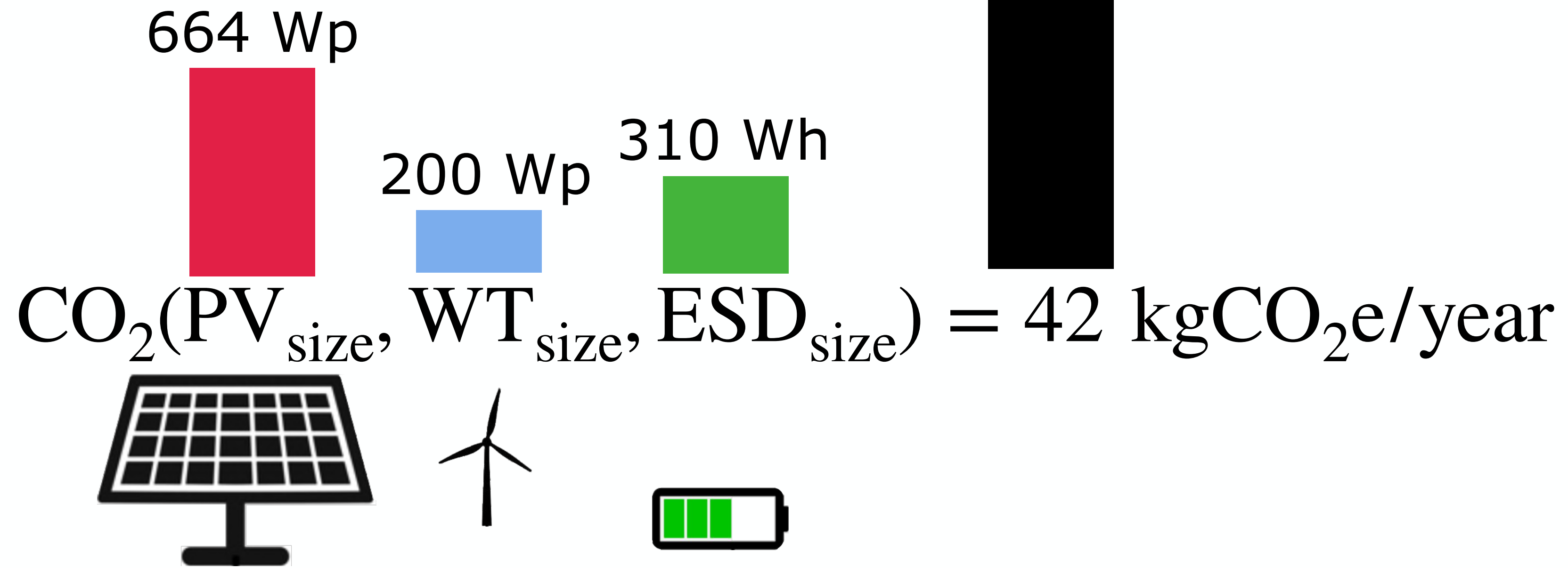
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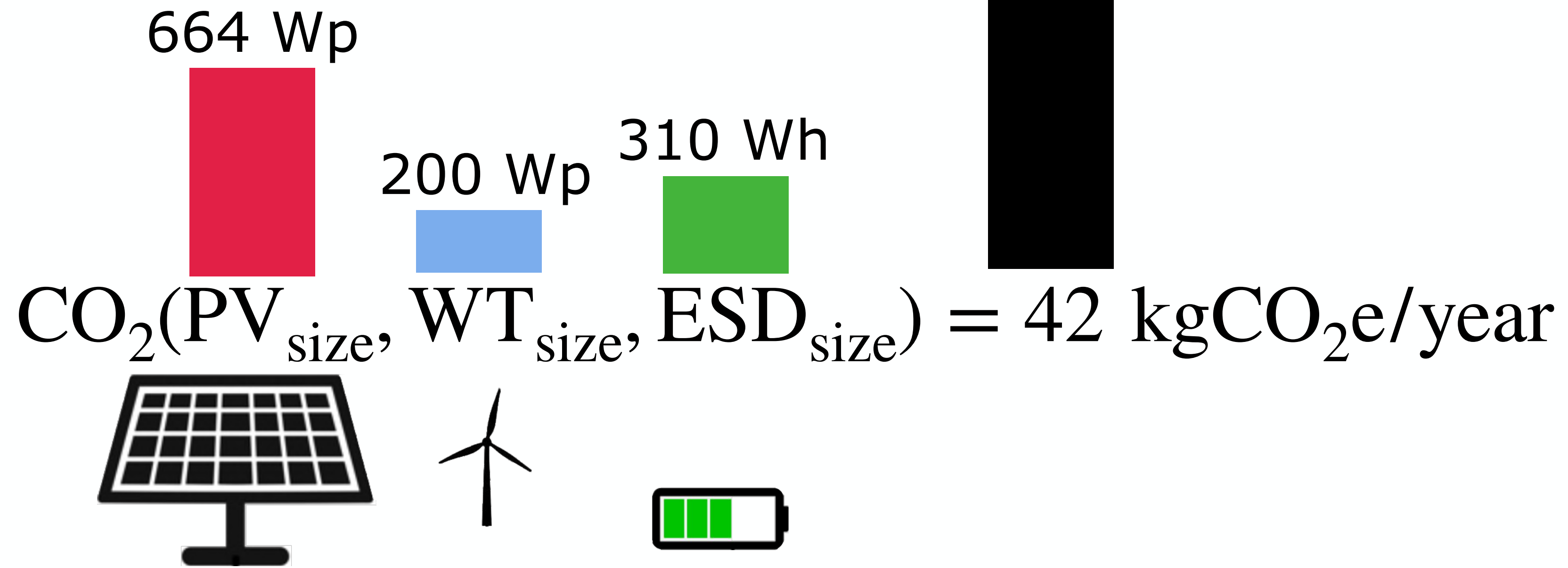
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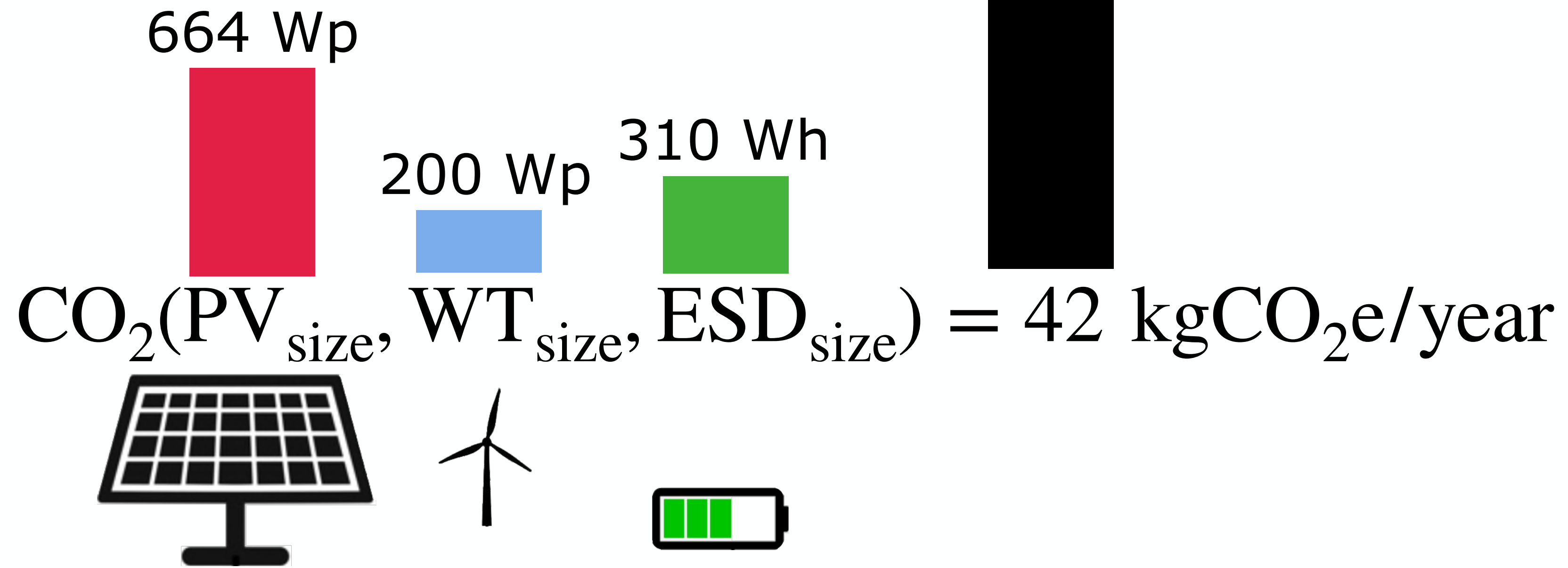
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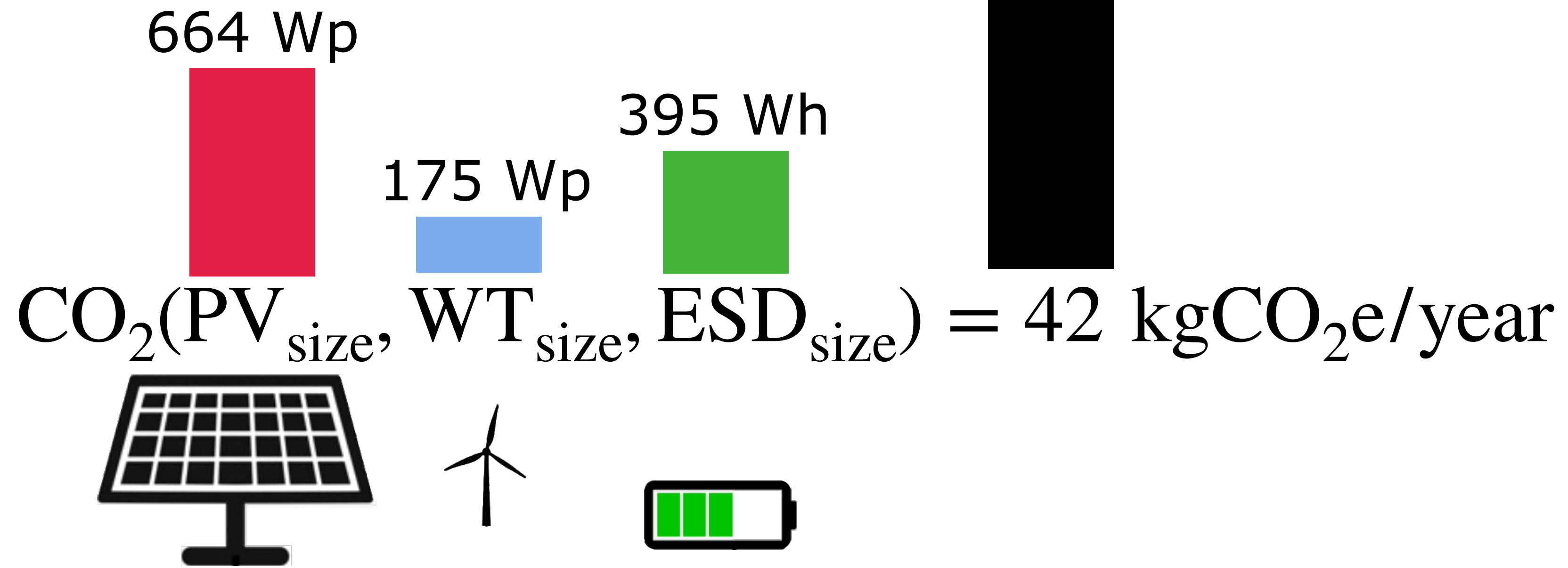
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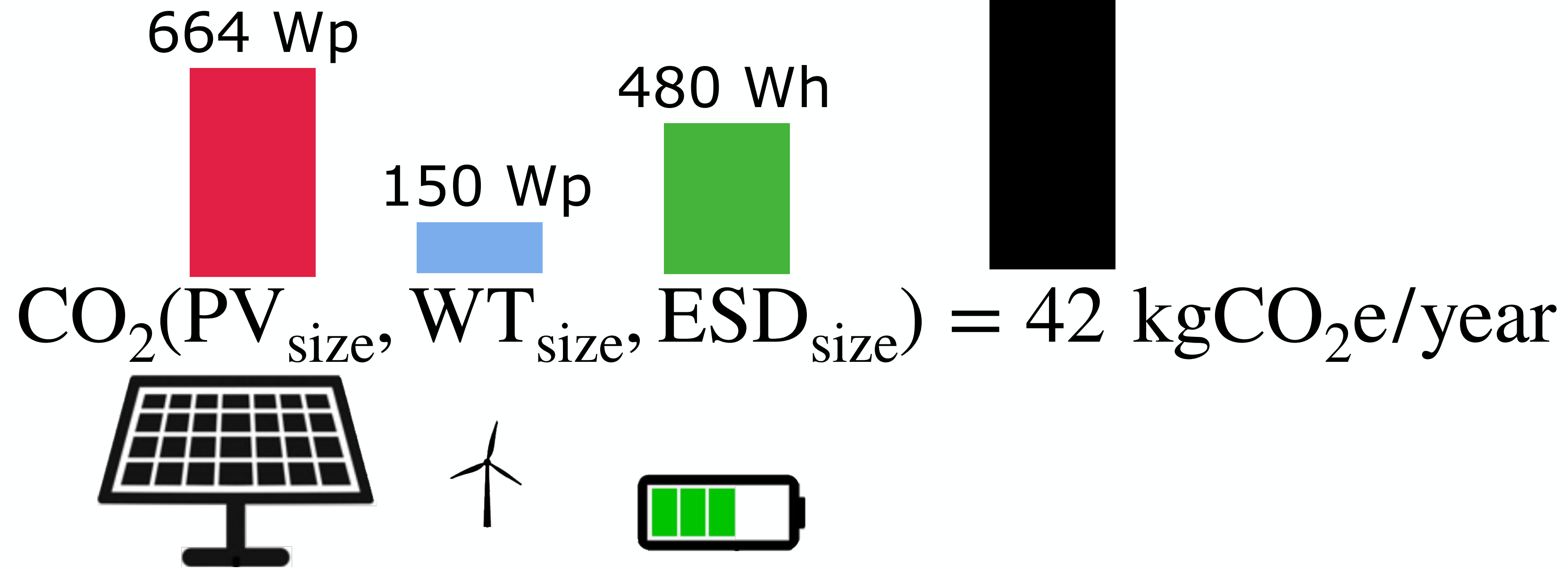
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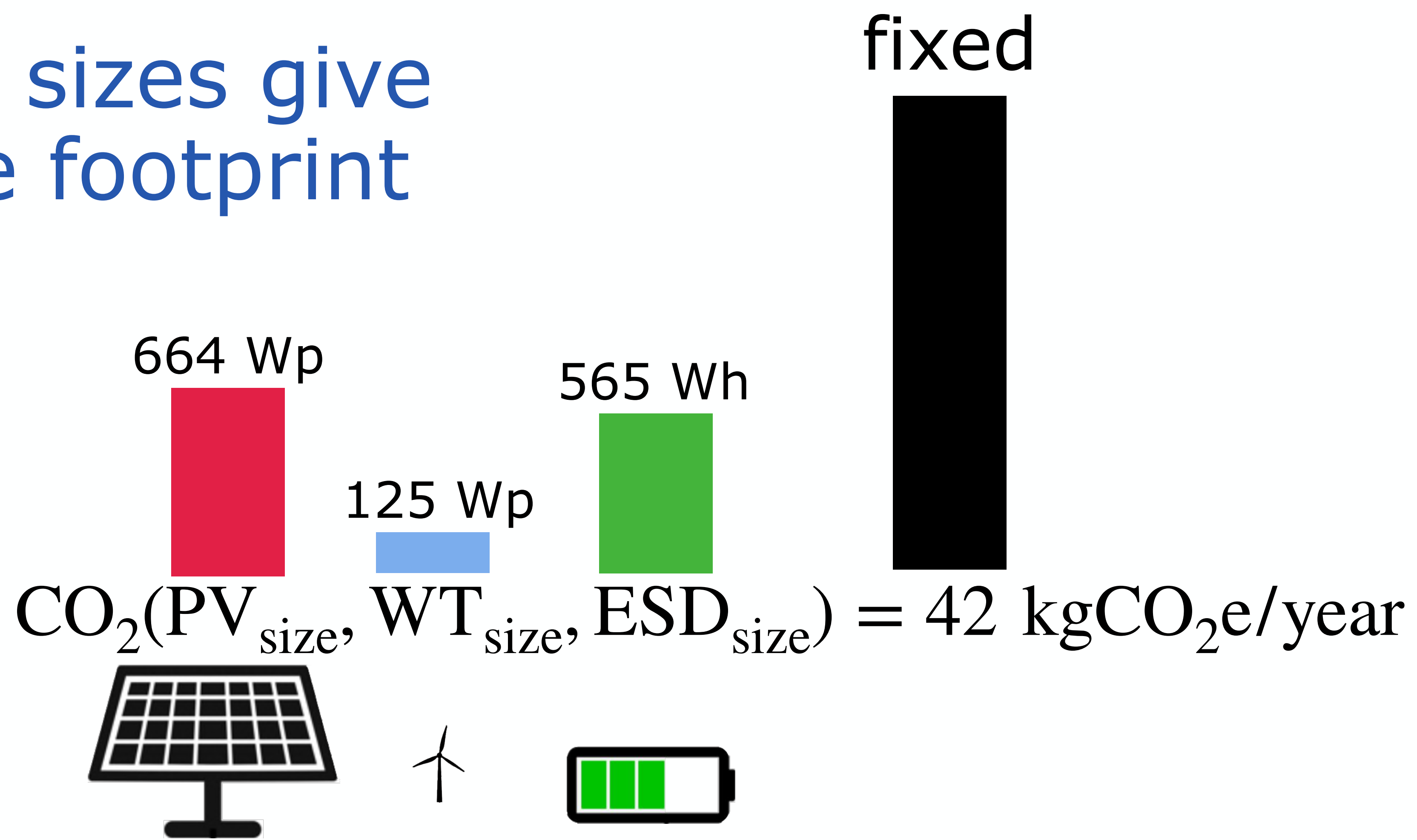
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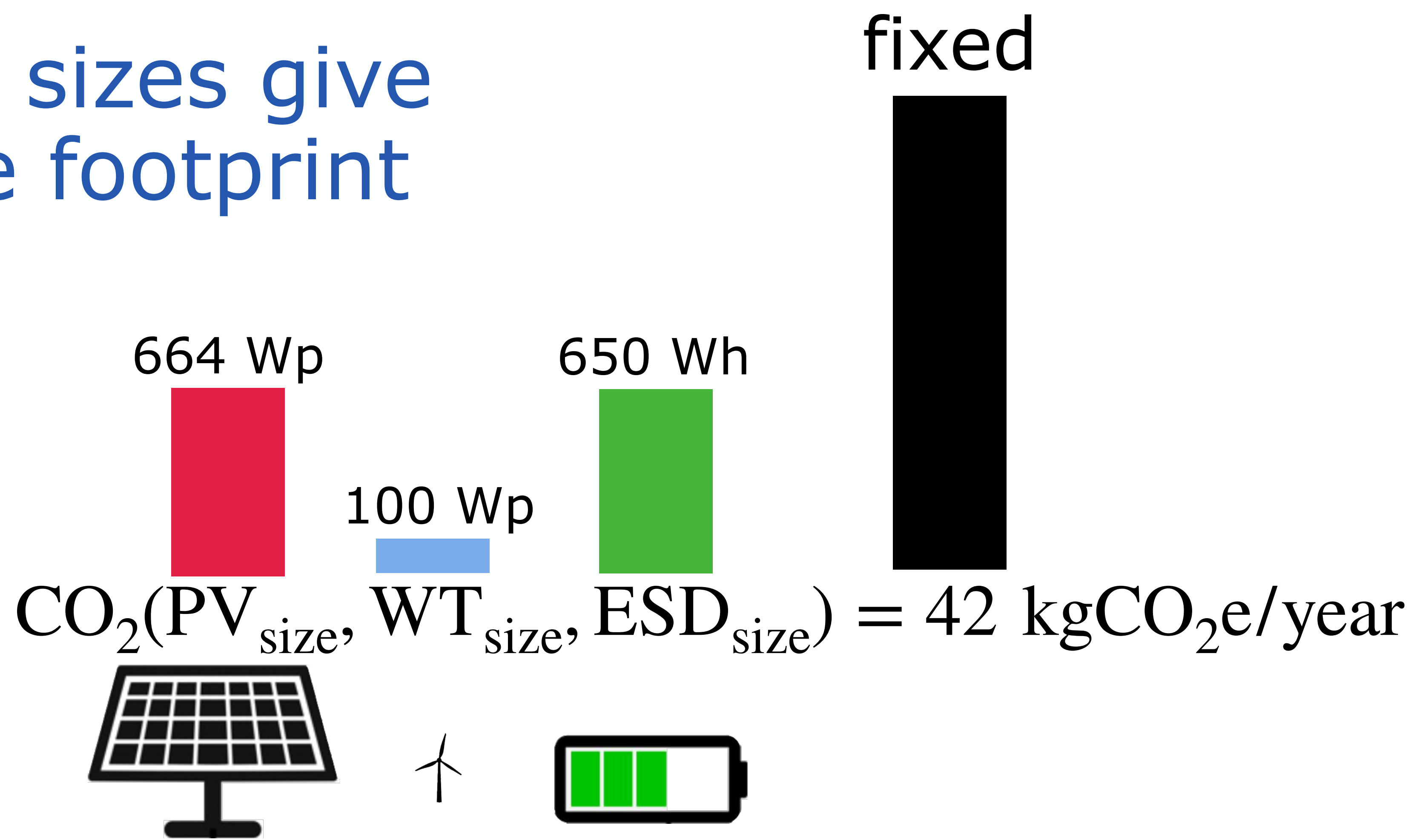
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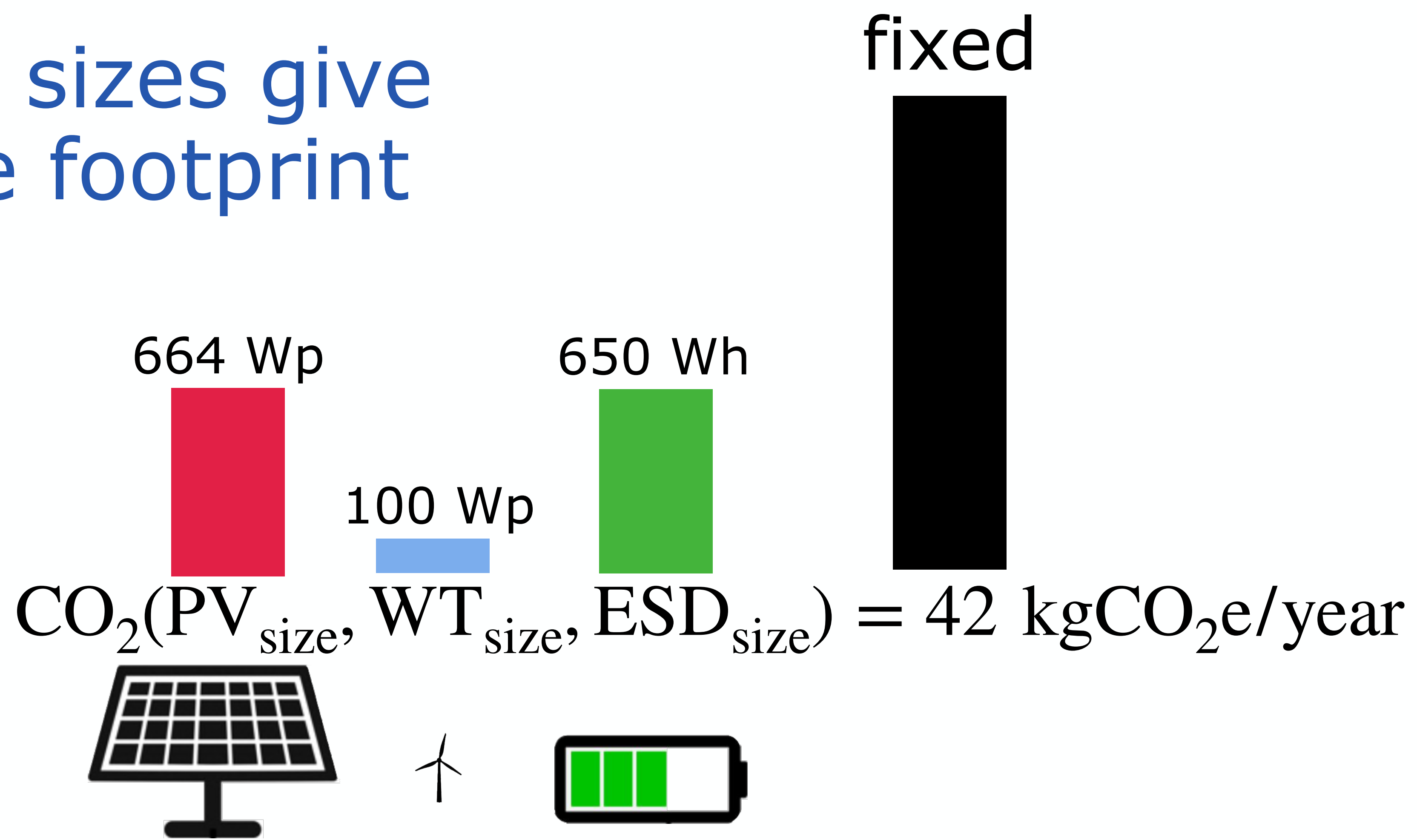
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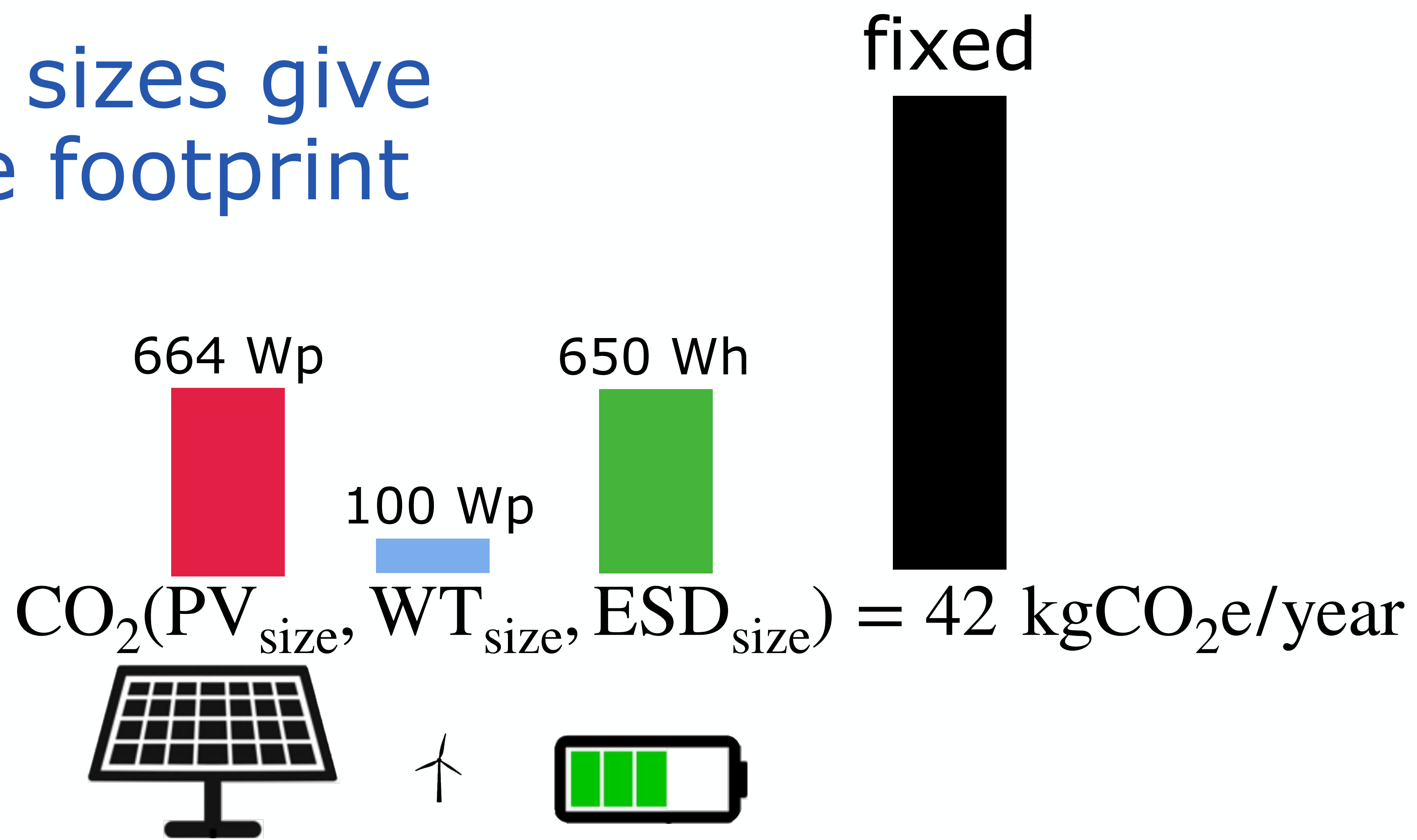
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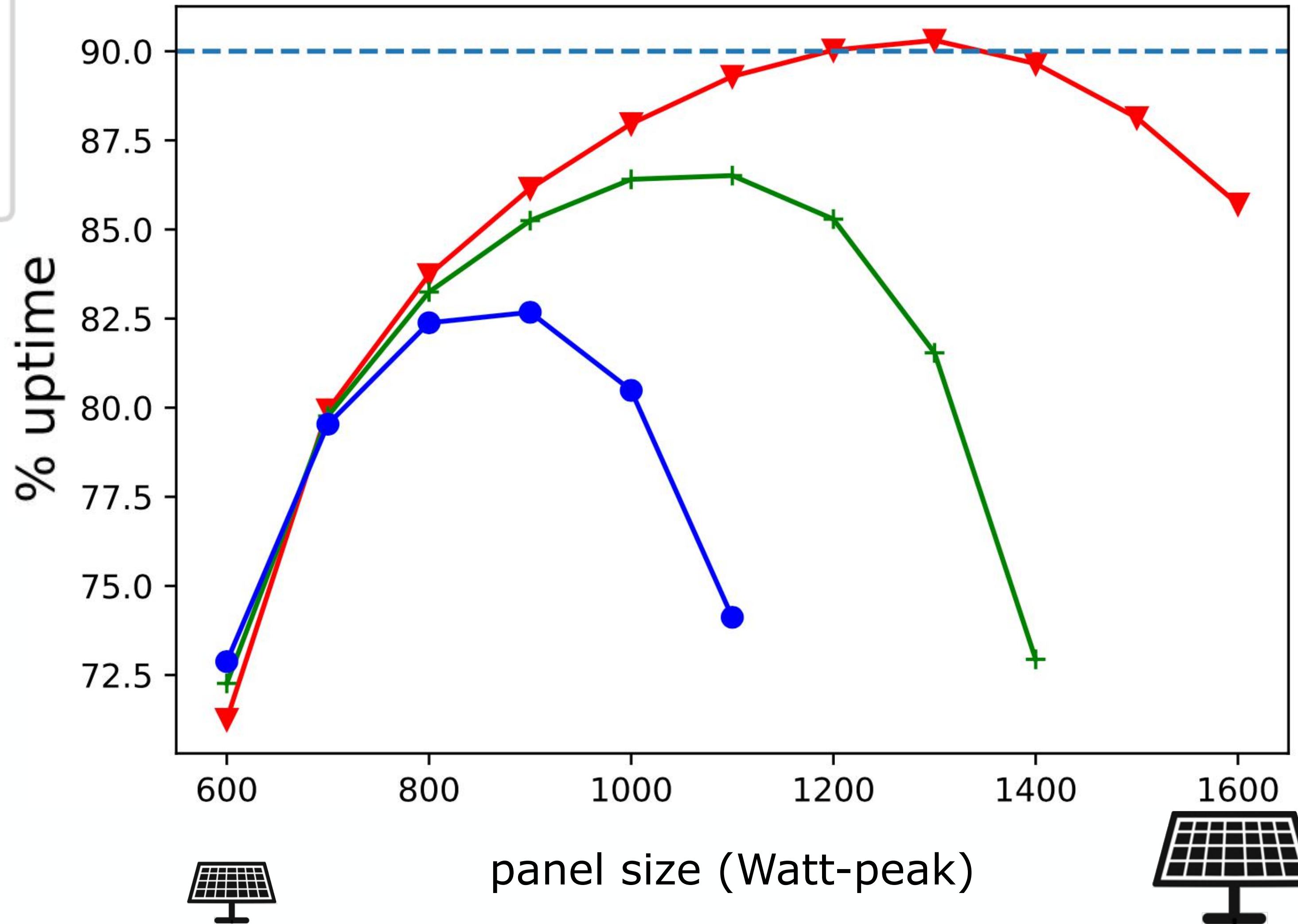


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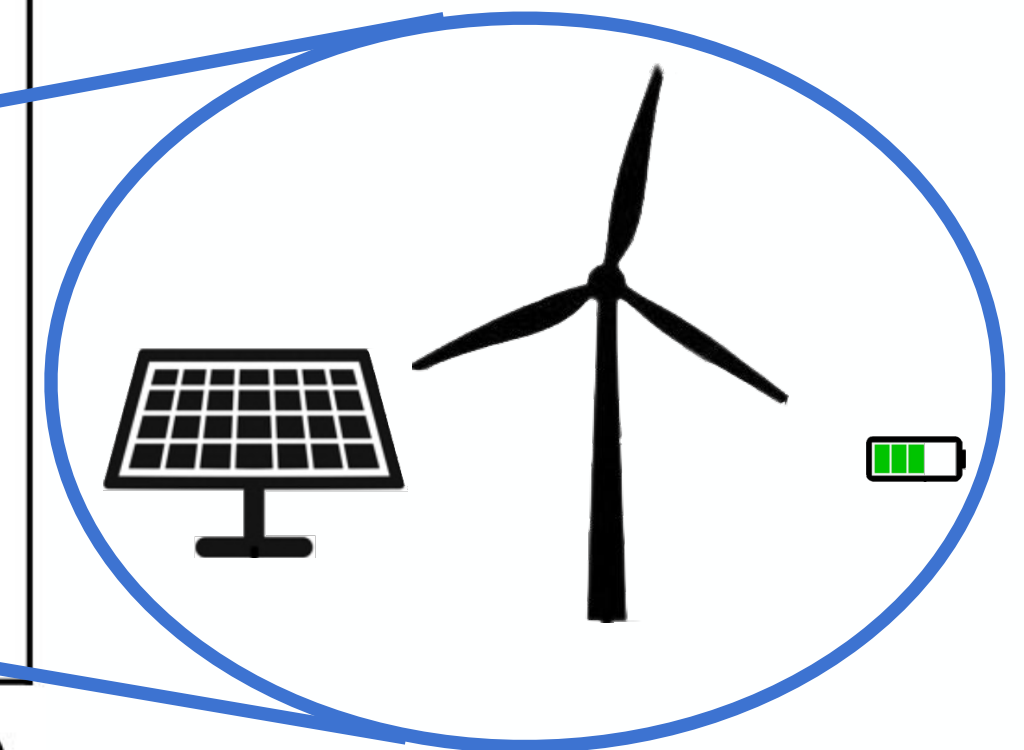
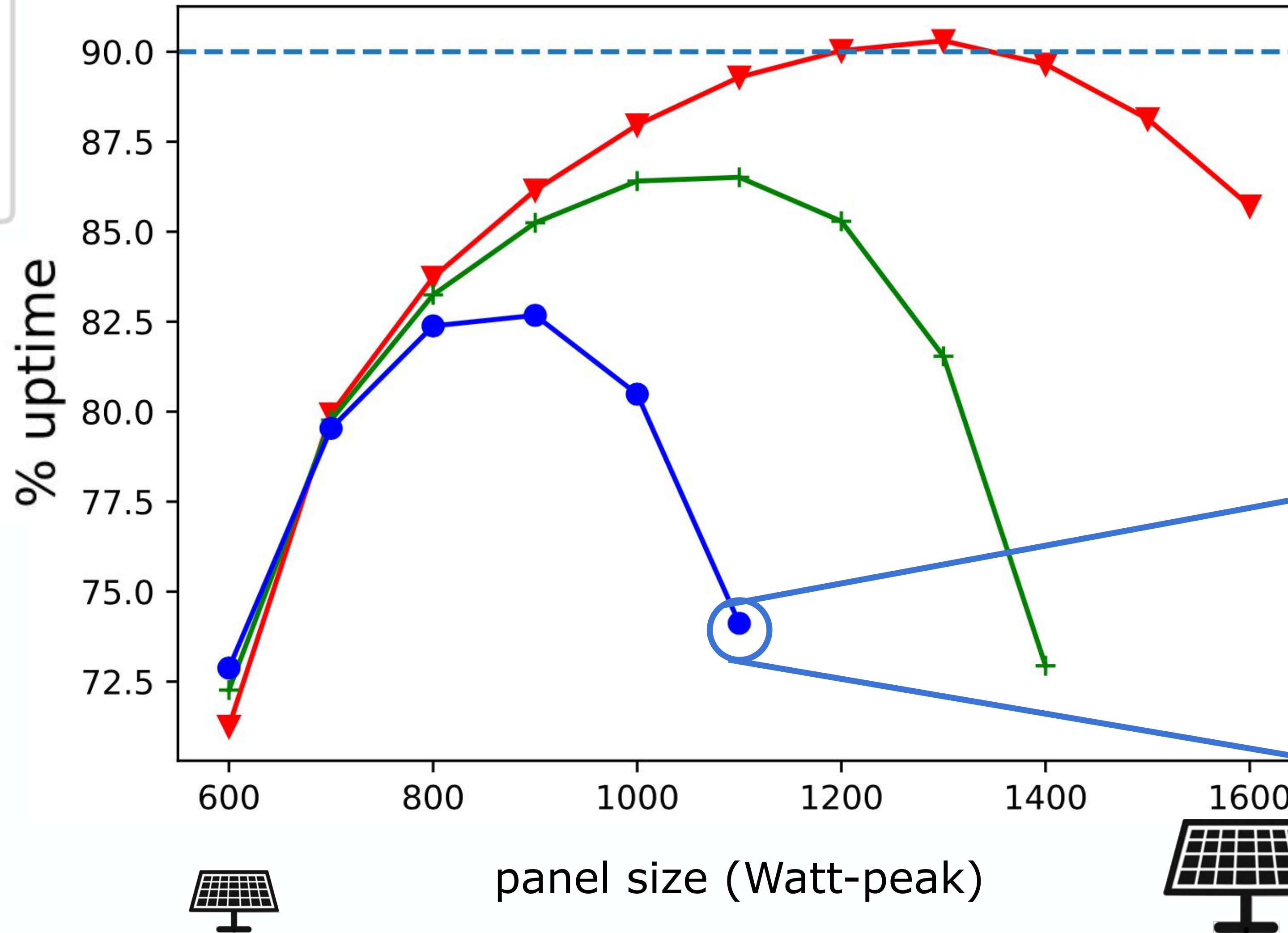
# Results

365 days (year 2021)  
servers (200 W when idle)  
68 kgCO<sub>2</sub>e/year



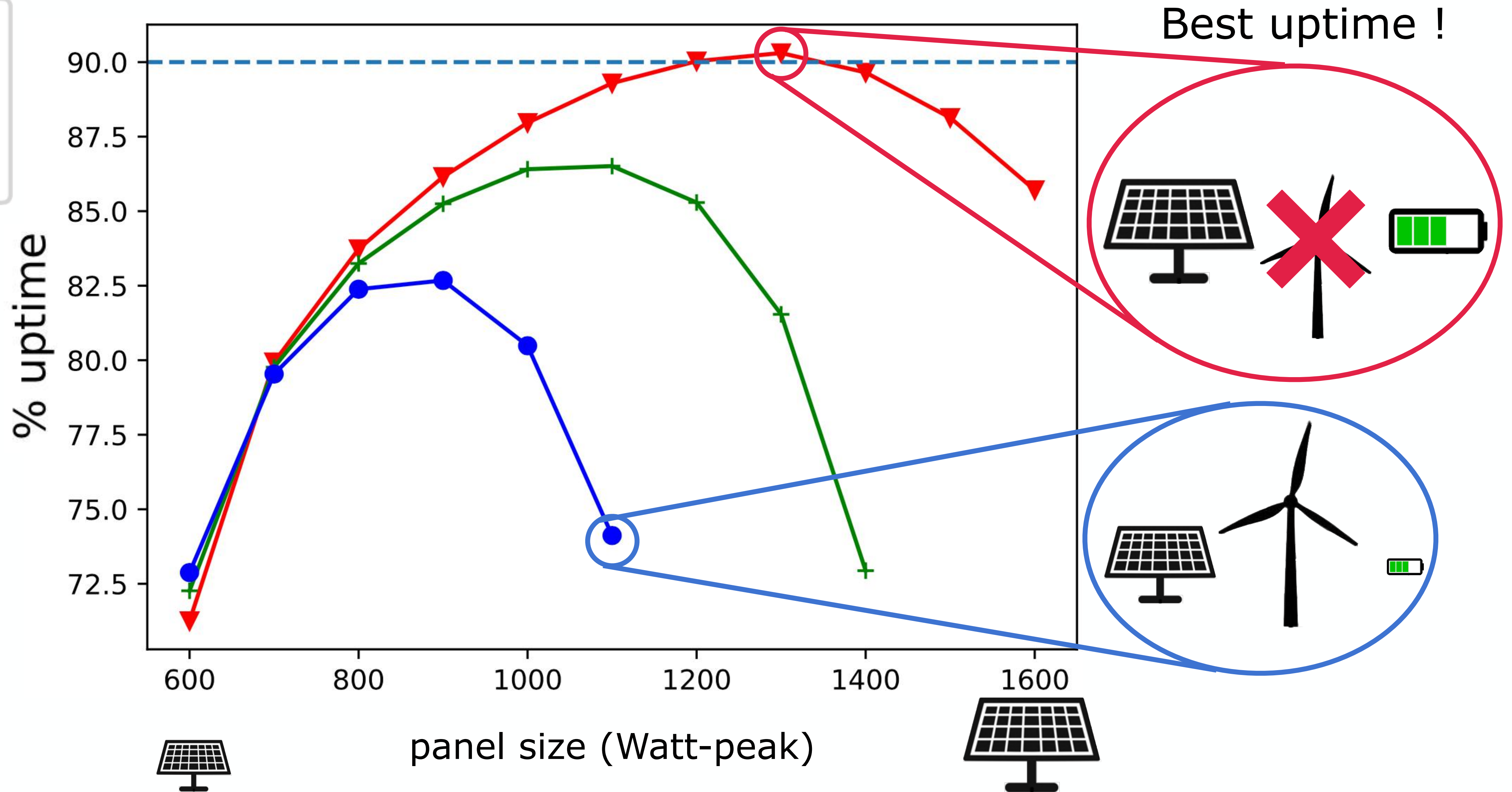
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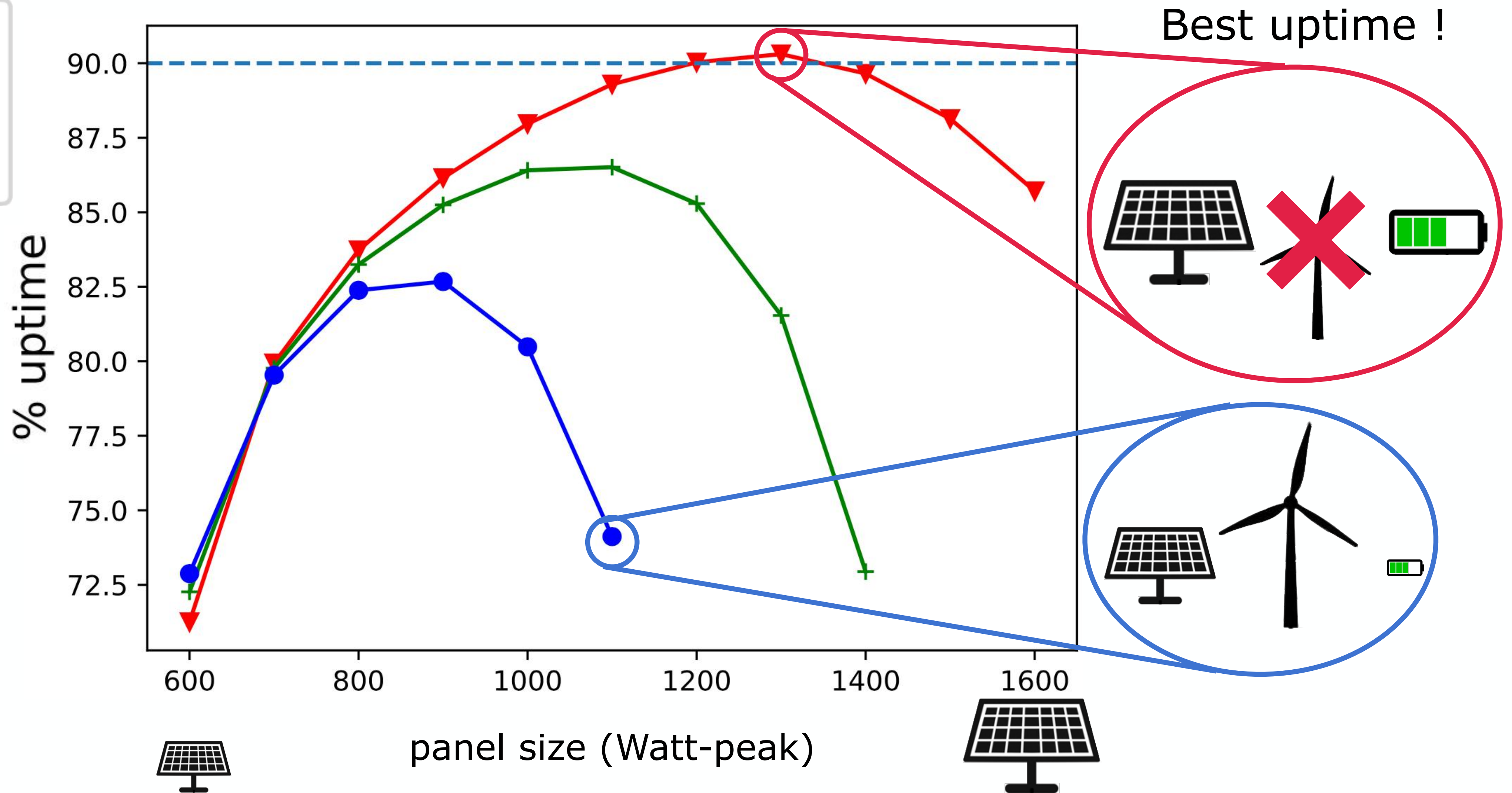
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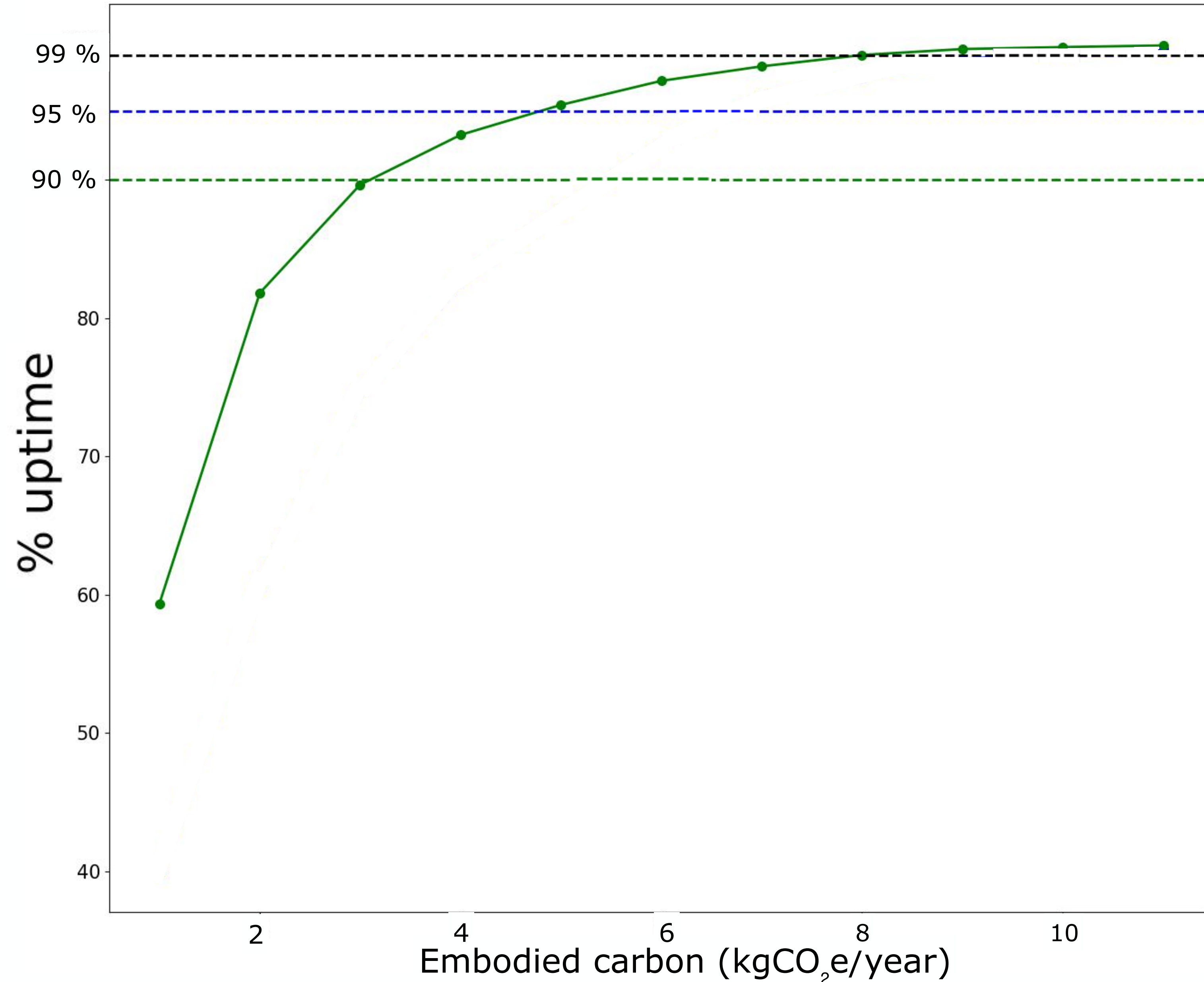


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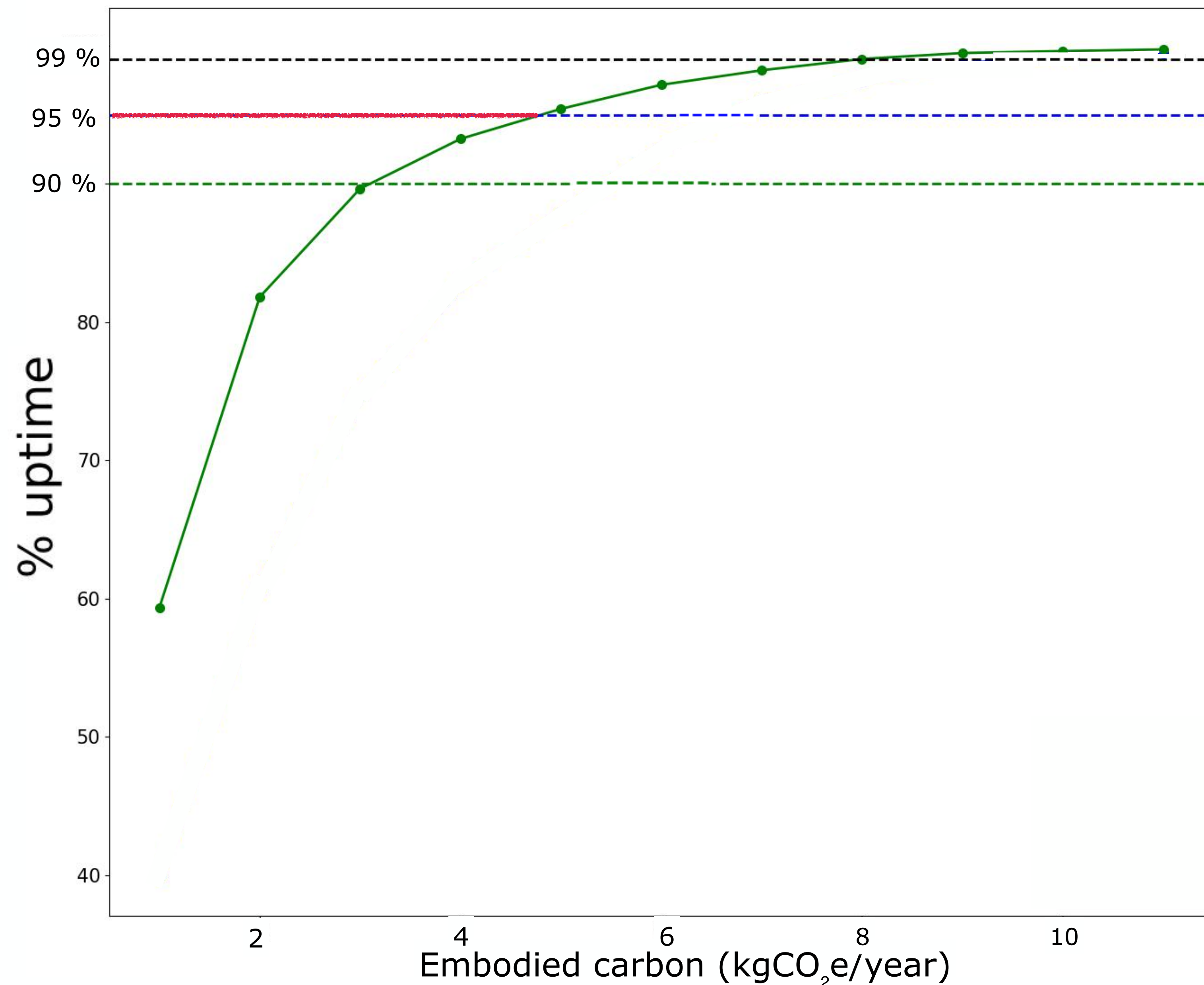


# Maximal uptime for a given carbon footprint



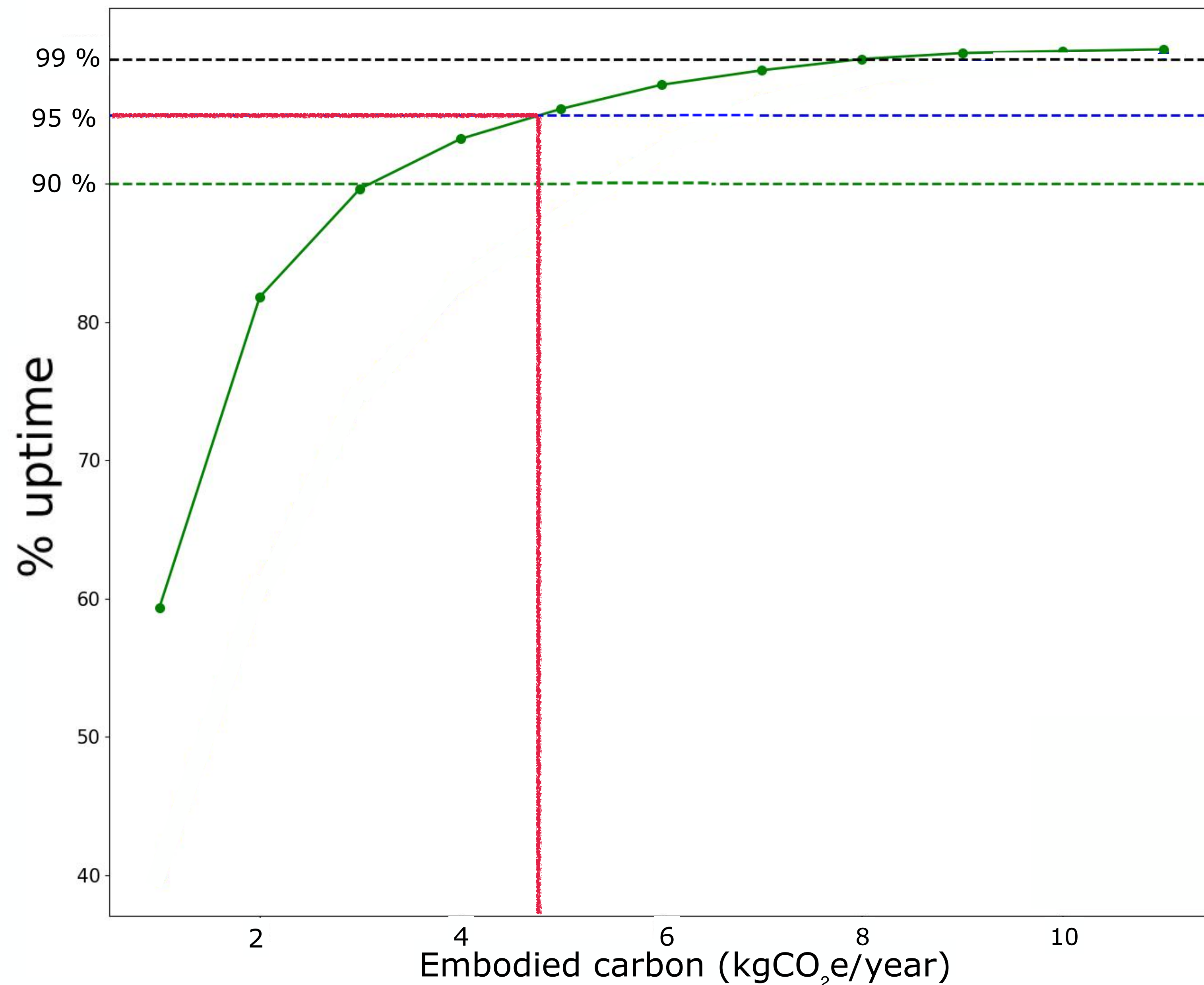
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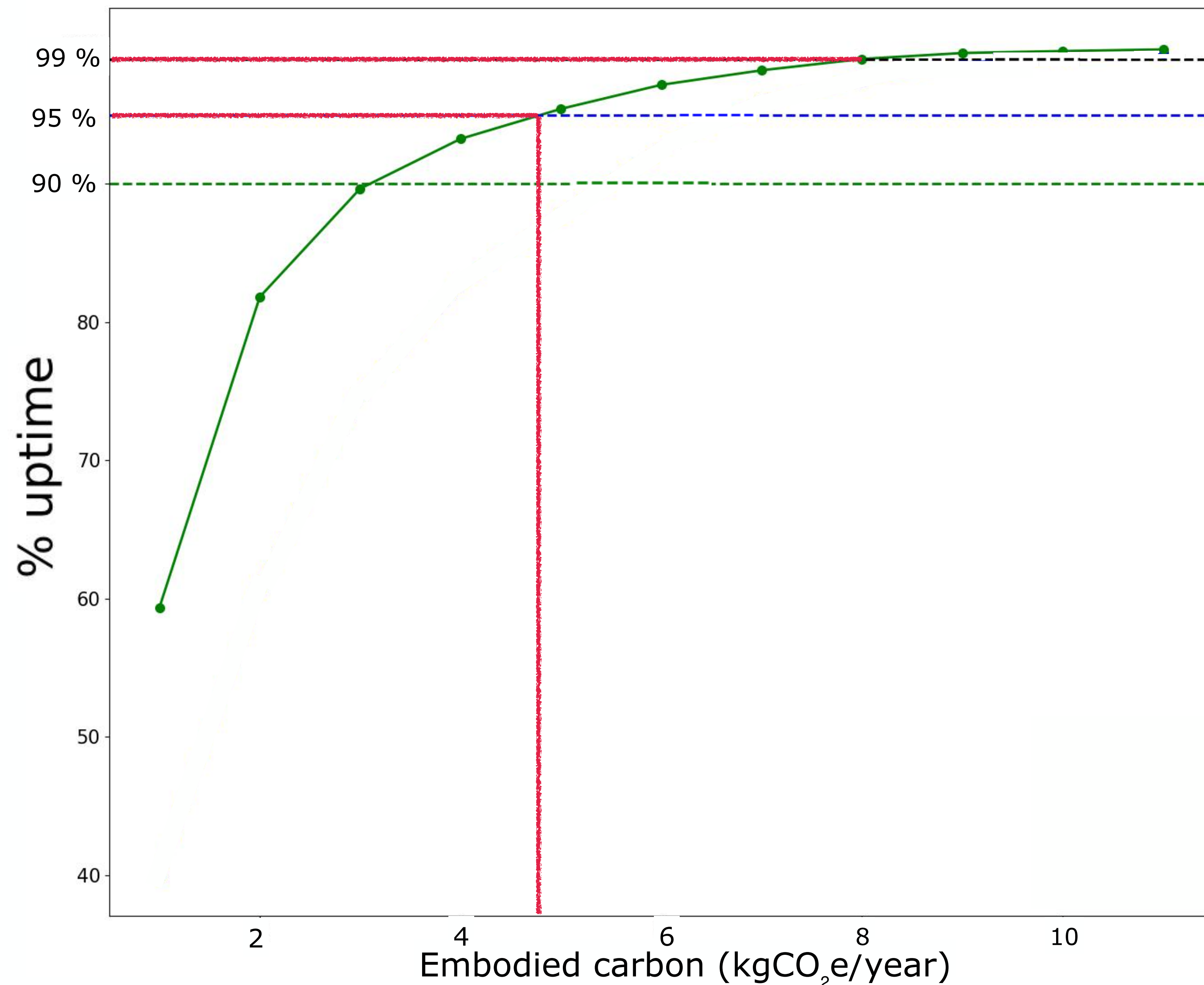
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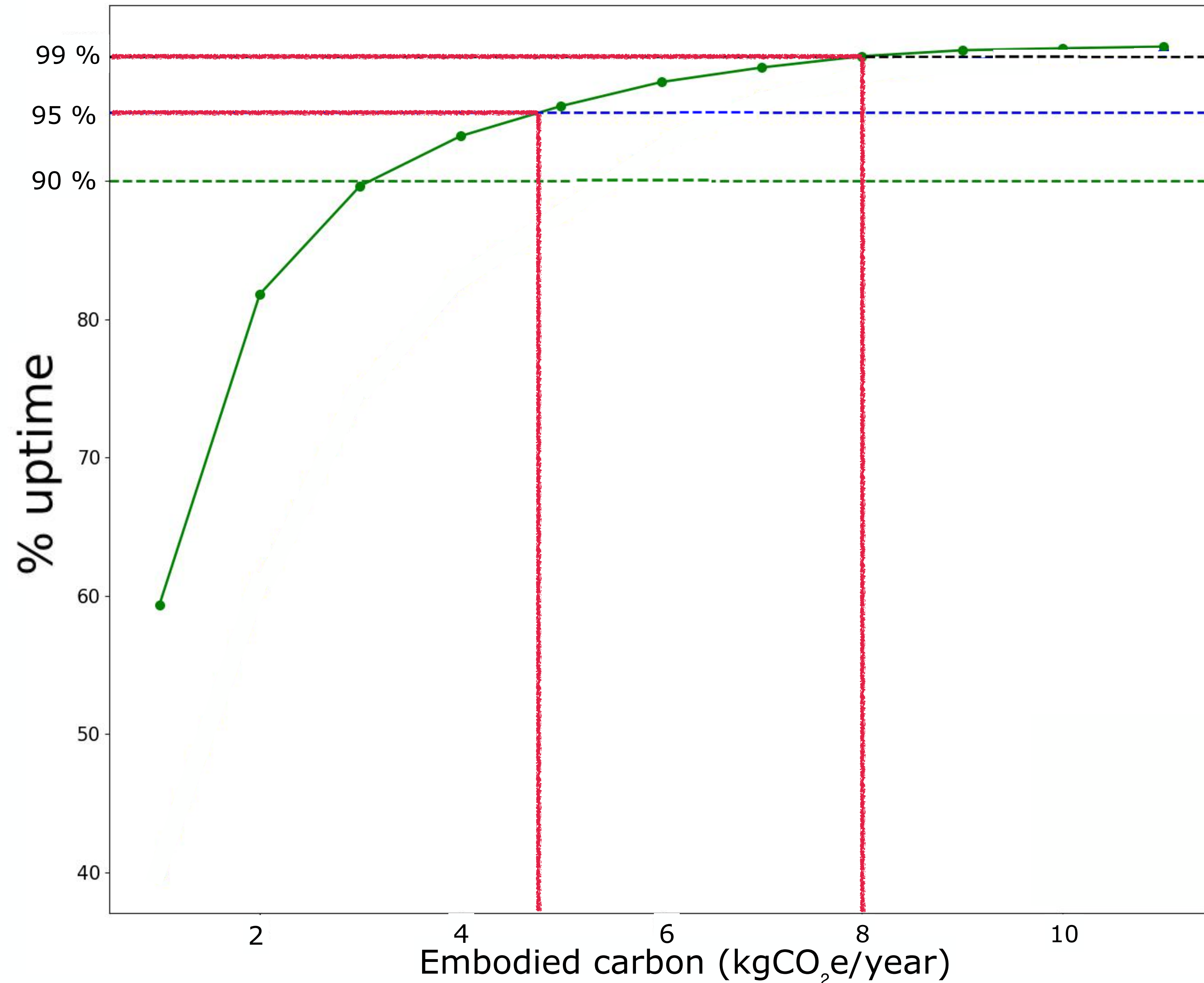
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# Maximal uptime for a given carbon footprint



PCs (11.5 W when idle)

# Maximal uptime for a given carbon footprint



PCs (11.5 W when idle)

# Conclusion

Distributed Fog, only powered by renewable energy.

Servers OFF during non-working hours (social & ecology)

By targeting 95% instead of 99% uptime,  
we nearly divide by 2 the carbon footprint.

In the paper: whole year VS winter period,

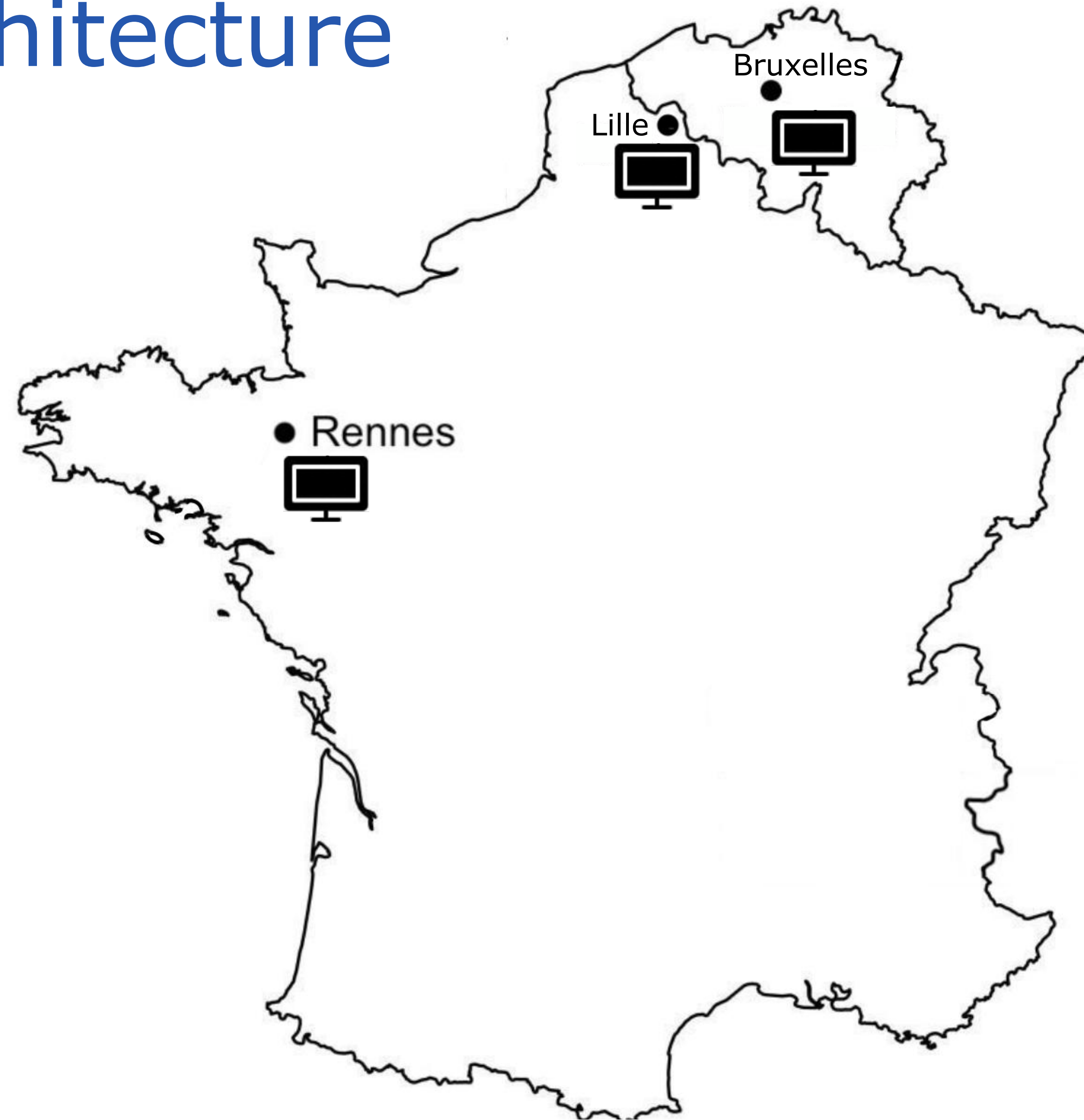
Cumulative Distribution Function

**Future work** : Other criteria for the LCA (water, ADP ...)

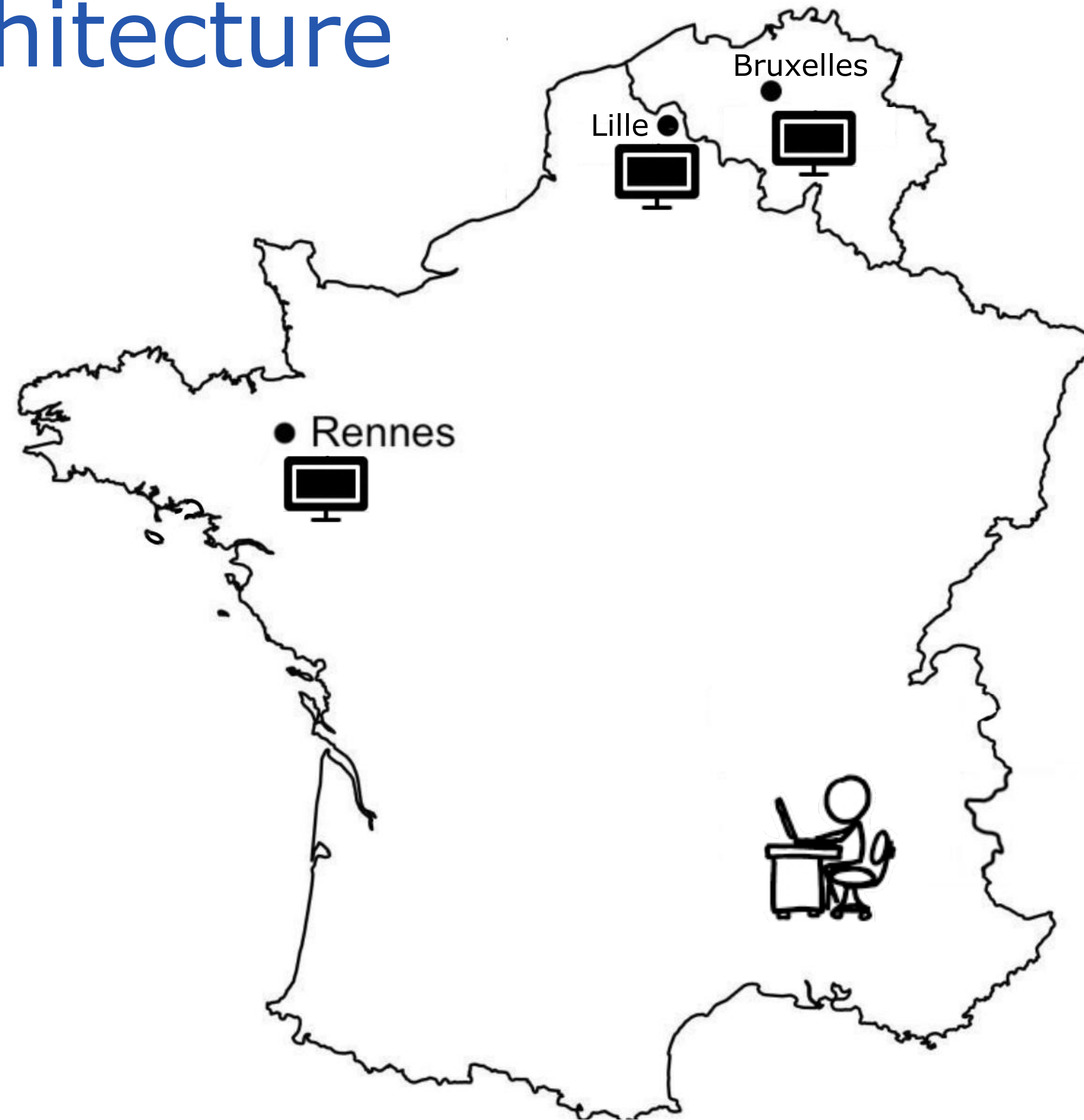
Thank you for your attention :)  
Questions ?

# Backup slides

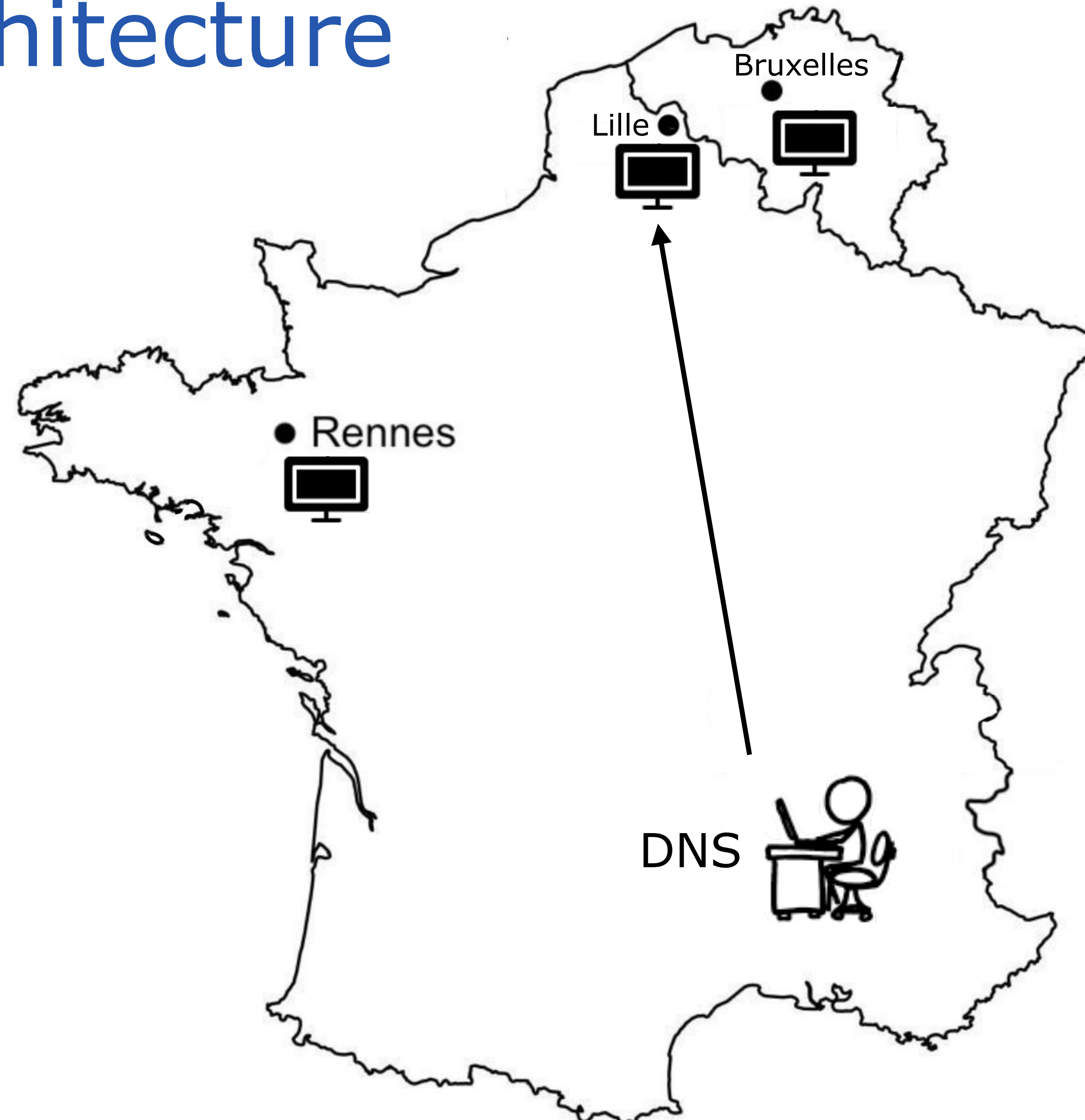
# Deuxfleurs architecture



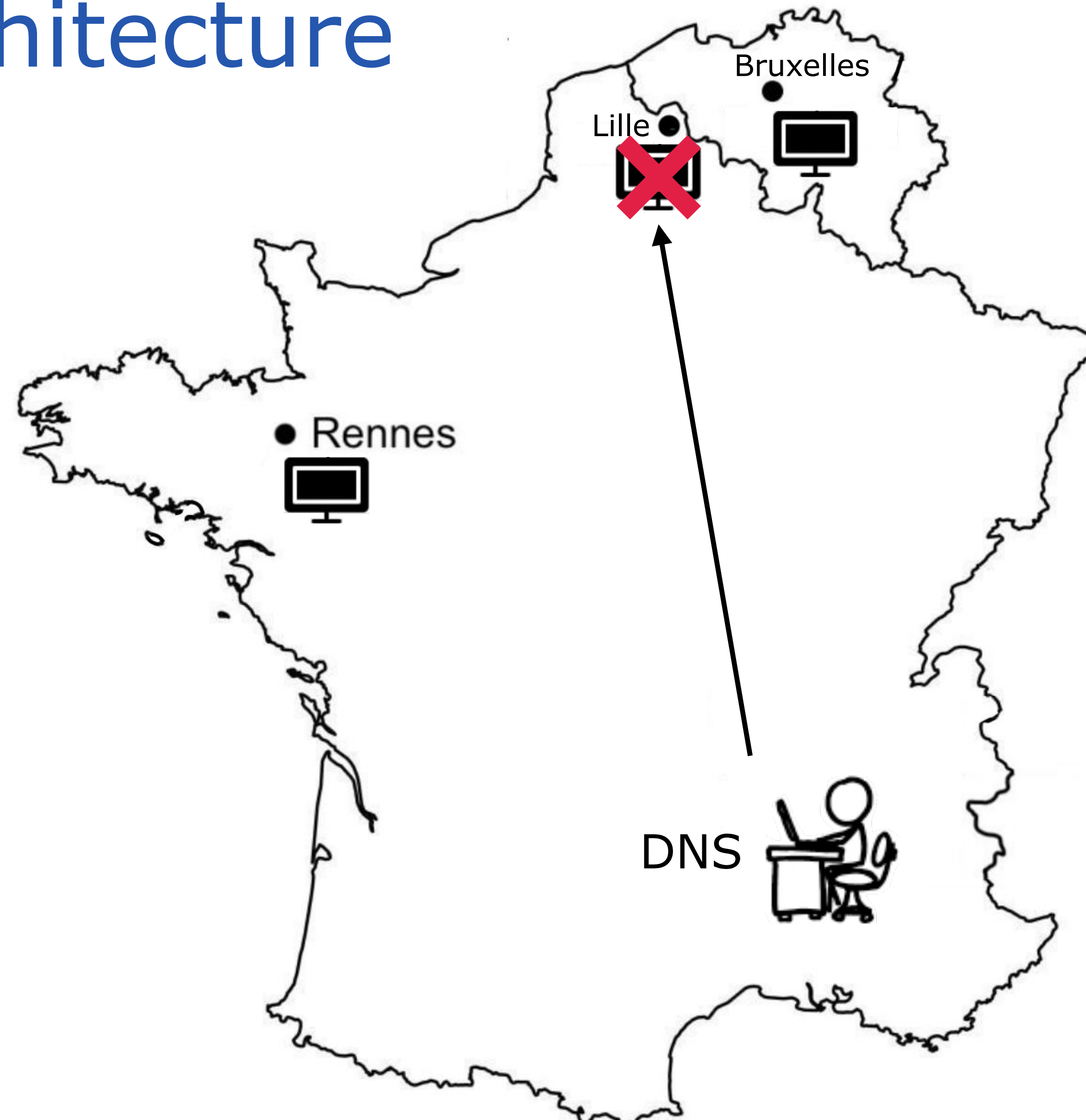
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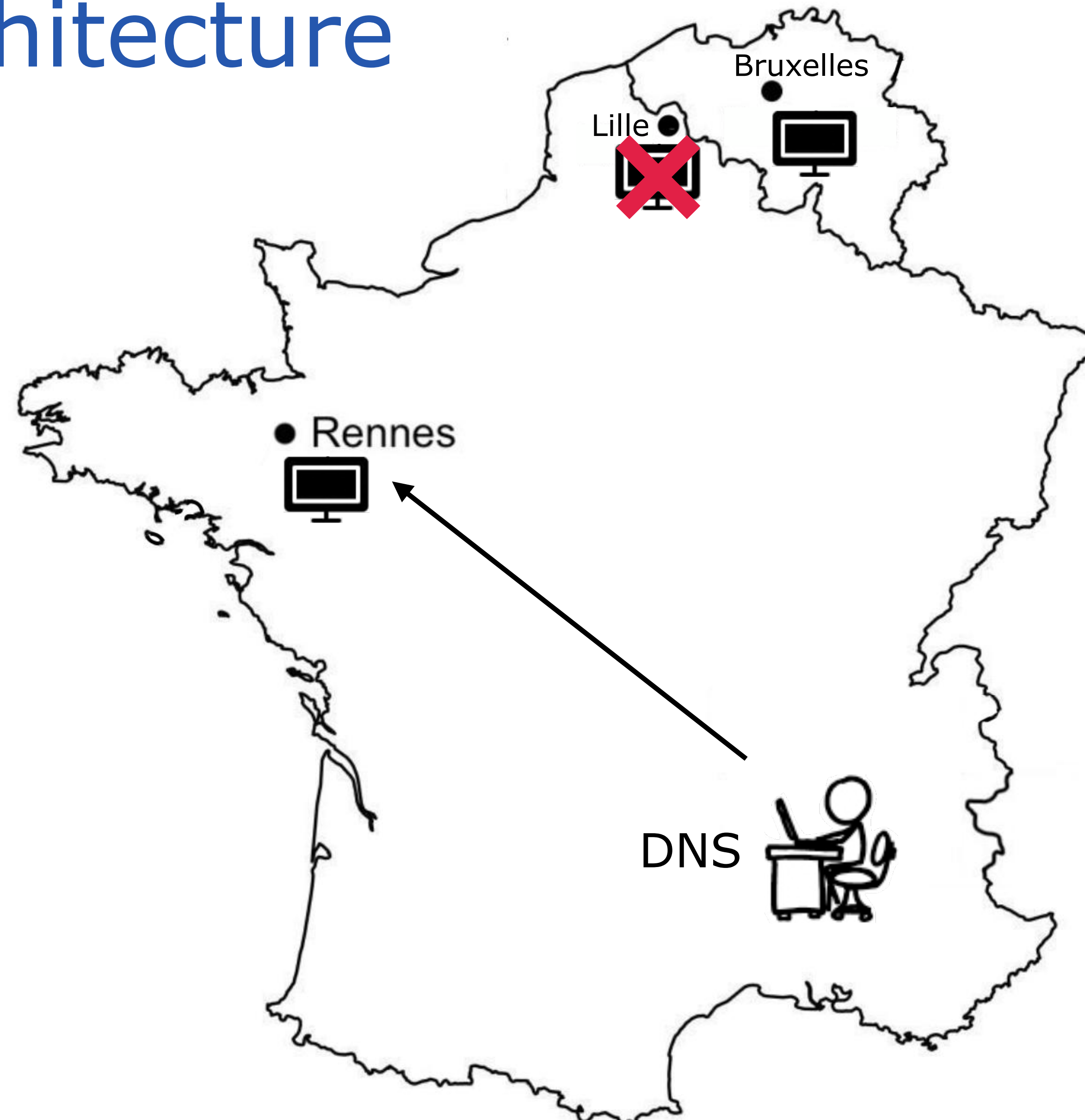
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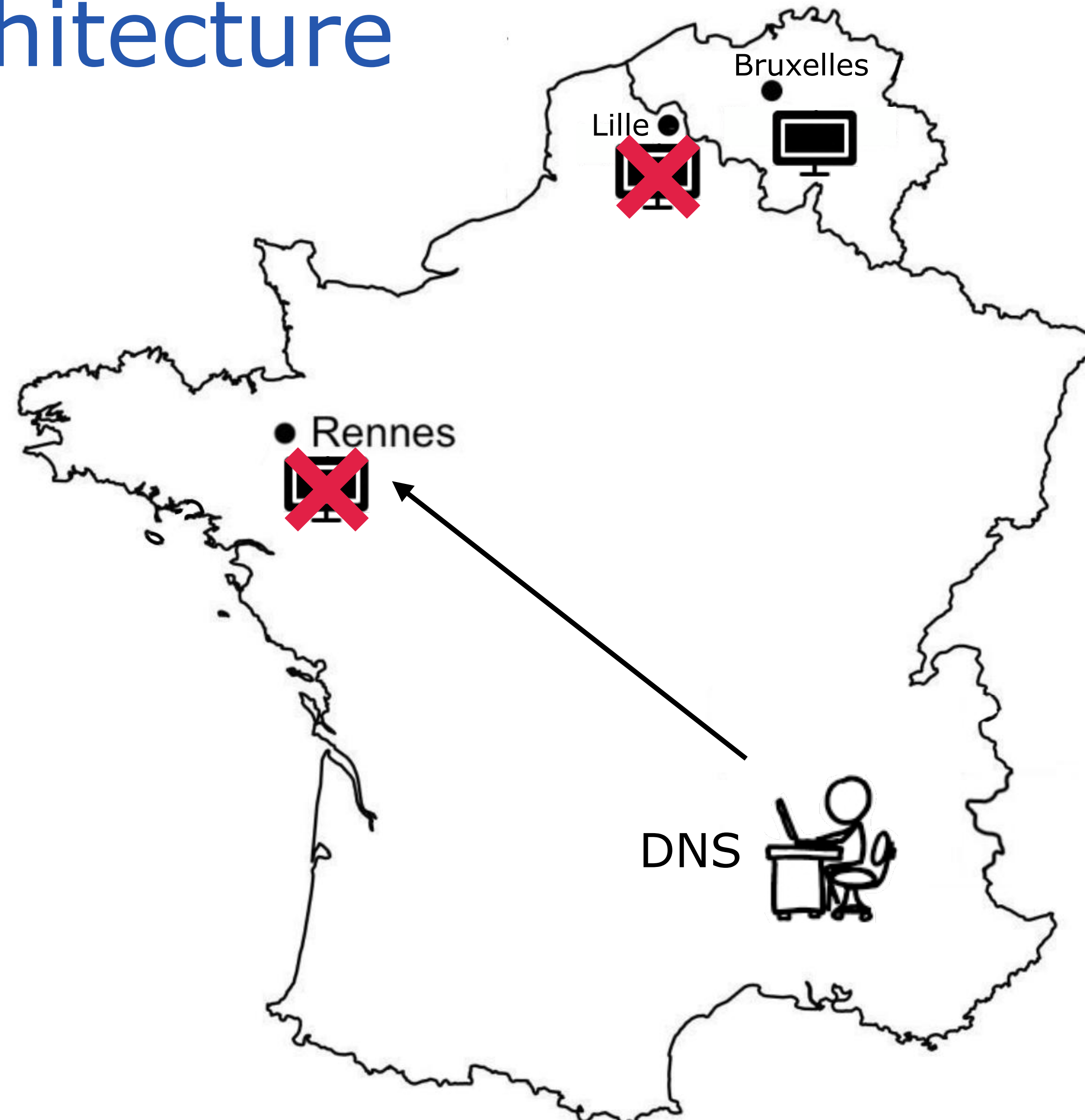
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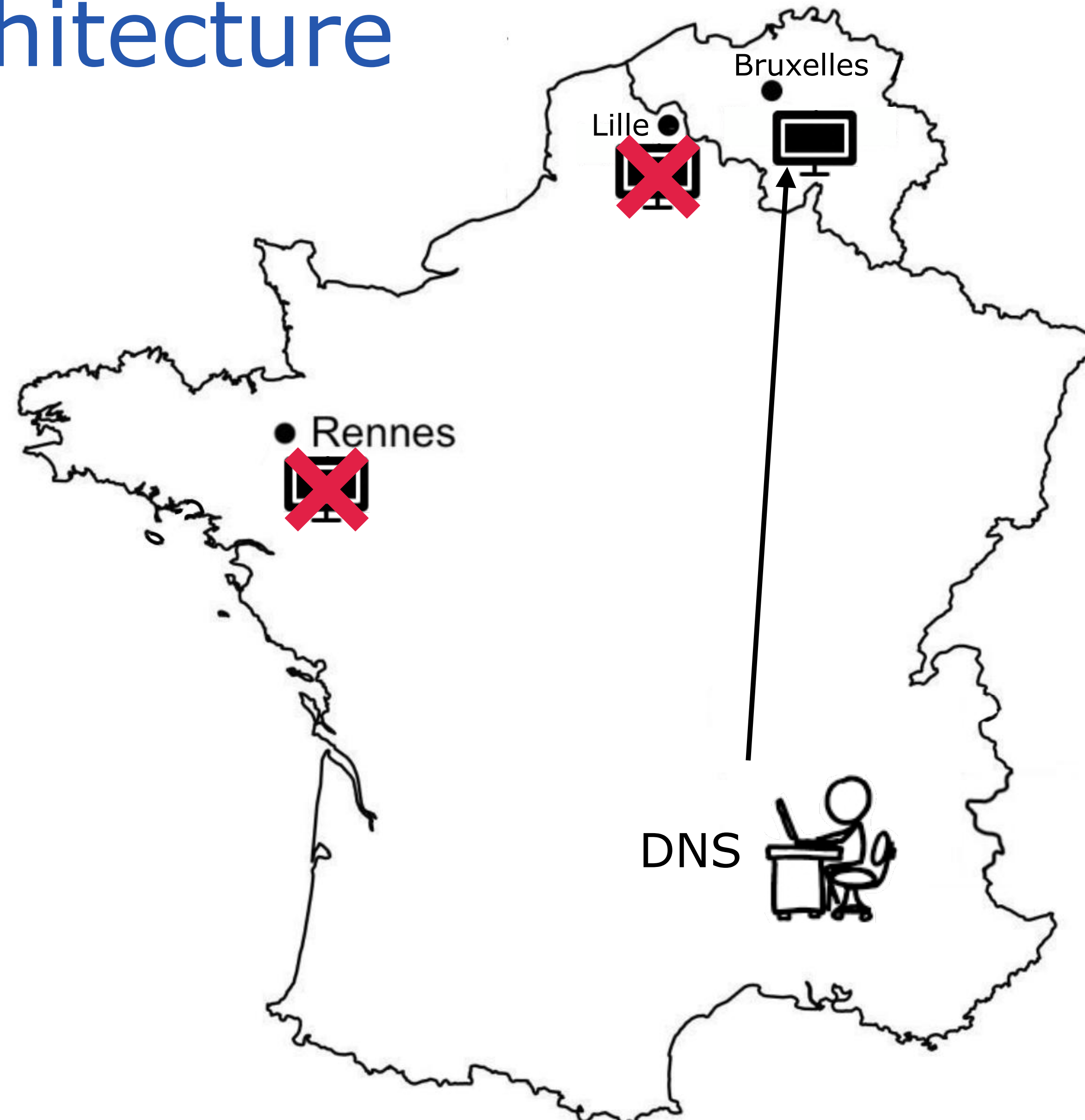
# Deuxfleurs architecture



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# Deuxfleurs architecture



## LOW←TECH MAGAZINE

This is a solar-powered website, which means it sometimes goes offline ✨

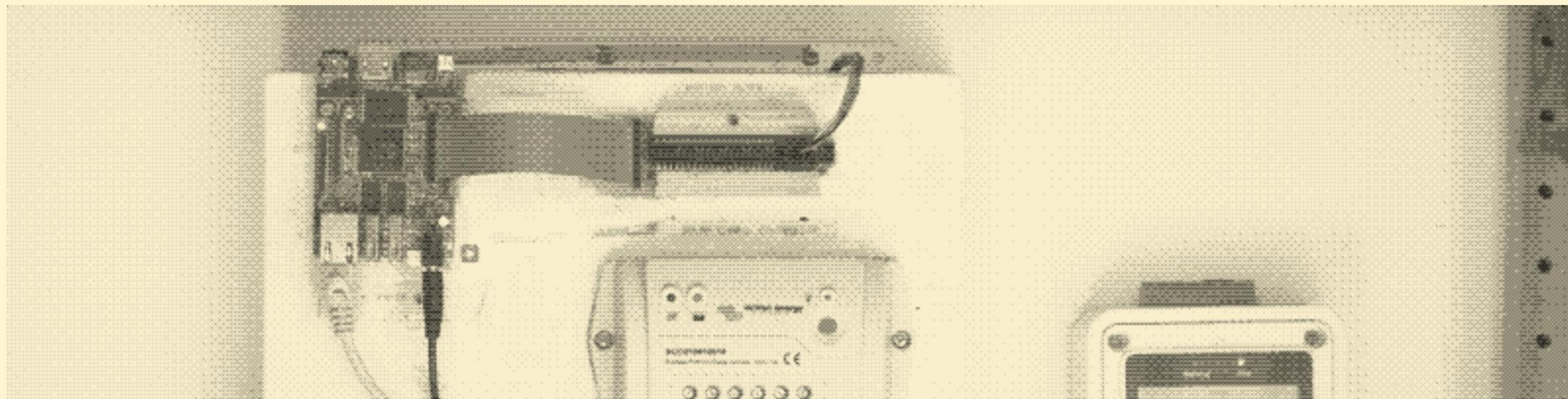
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### About the Solar Powered Website

📄 66%

This website is solar-powered and self-hosted. It has been designed to radically reduce the energy use associated with accessing our content.

Translations [fr](#) [de](#) [nl](#) [es](#) [it](#) [pt](#)

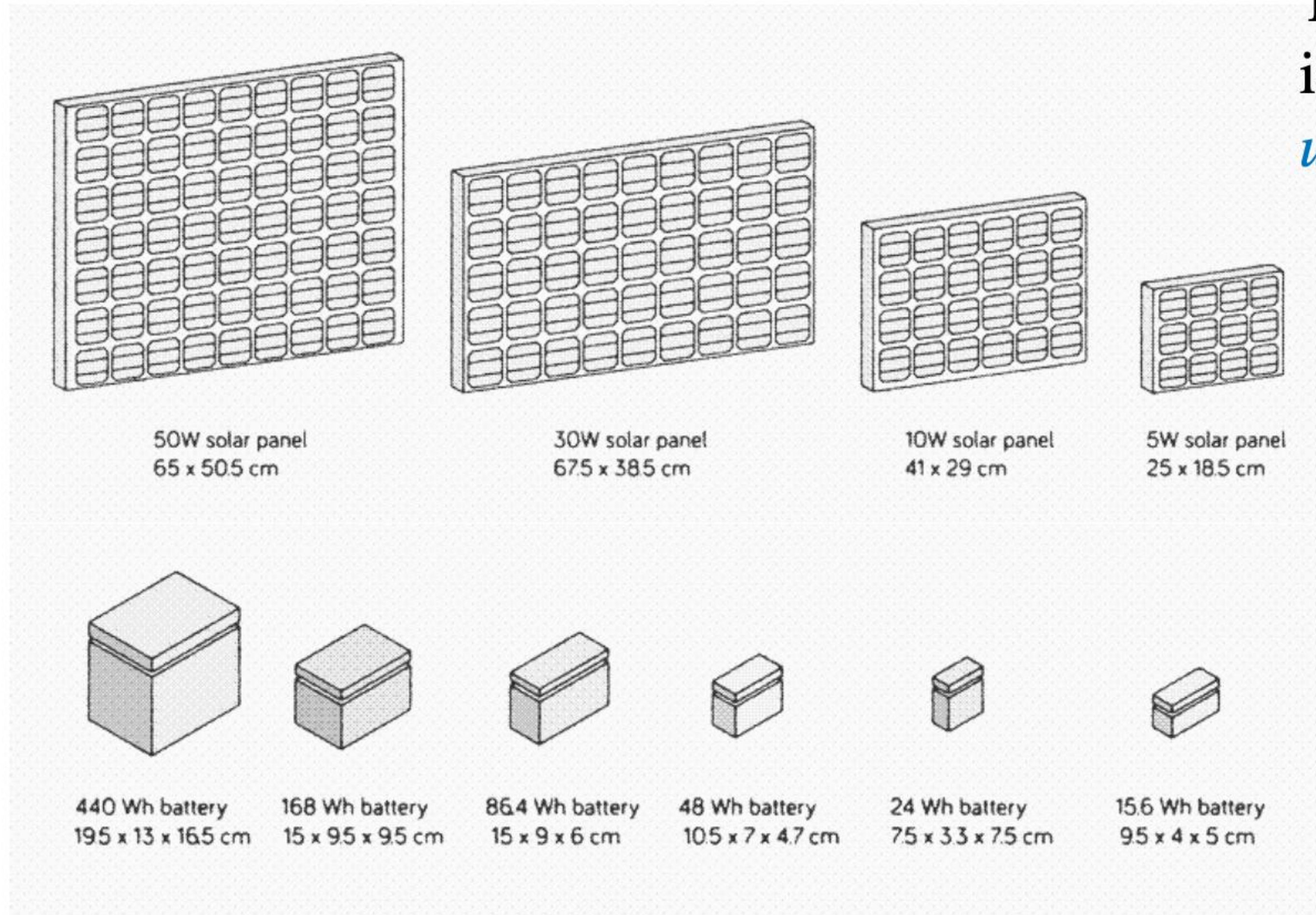


755.33KB

↑

# How sustainable is a solar-powered website ?

The sizing of battery and solar panel is a compromise between *uptime* and *sustainability*.



Life expectancy : 25 years

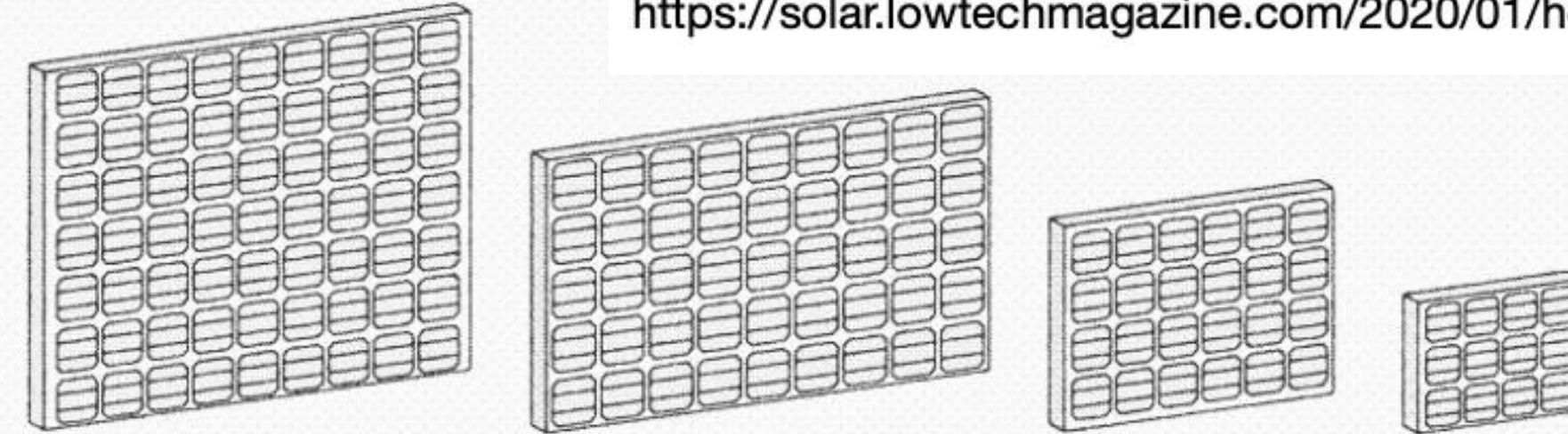
Life expectancy : 5 years

<https://solar.lowtechmagazine.com/2020/01/how-sustainable-is-a-solar-powered-website/>

## Embodied energy in carbon emissions (kg / year) for different solar setups

- Includes embodied energy of the server and charge controller
- n/a = solar panel cannot charge the battery completely, no matter the season.

<https://solar.lowtechmagazine.com/2020/01/how-sustainable-is-a-solar-powered-website/>



	<b>50 W</b>	<b>30 W</b>	<b>10 W</b>	<b>5 W</b>
	<b>440 Wh</b>	15.14 kg	13.11 kg	n/a
	<b>168 Wh</b>	10.47 kg	8.44 kg	6.40 kg
	<b>86.4 Wh</b>	8.76 kg	6.71 kg	4.69 kg
	<b>48 Wh</b>	8.41 kg	6.38 kg	4.34 kg
	<b>24 Wh</b>	7.89 kg	5.94 kg	3.90 kg
	<b>15.6 Wh</b>	7.85 kg	5.83 kg	3.79 kg

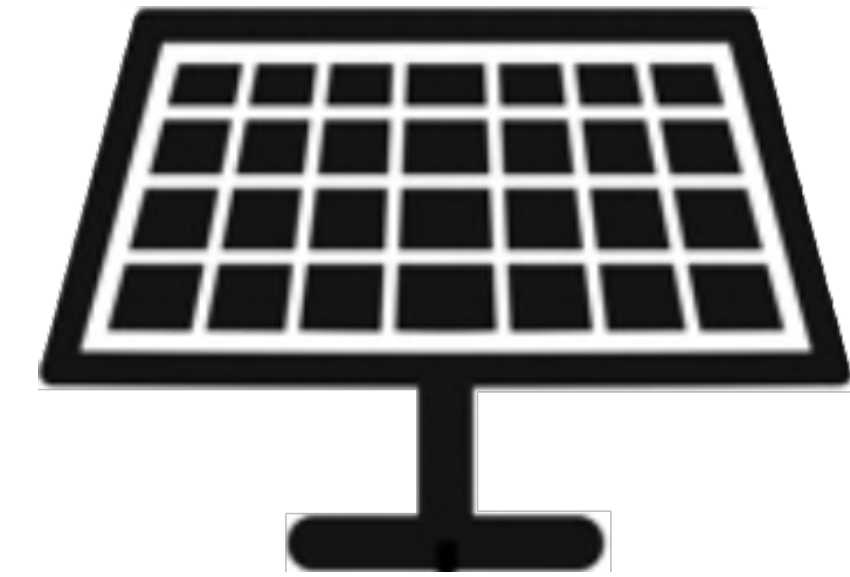
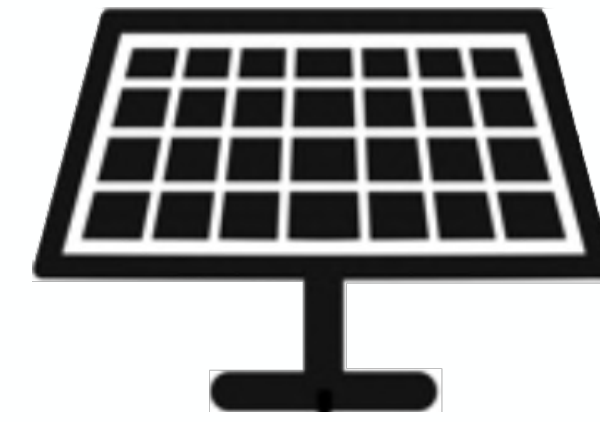
# Data come from PVGIS: [re.jrc.ec.europa.eu/](https://re.jrc.ec.europa.eu/)

The screenshot displays the PVGIS (Photovoltaic Geographical Information System) web interface. At the top, there is a navigation bar with the European Commission logo and the text "PHOTOVOLTAIC GEOGRAPHICAL INFORMATION SYSTEM". Below this is a breadcrumb trail: "European Commission > EU Science Hub > PVGIS > Interactive tools". A secondary navigation bar includes links for "Home", "Tools", "Downloads", "Documentation", and "Contact us".

The main interface is divided into several sections:

- Map:** A map of Europe with a location pin placed in France. A scale bar indicates 1000 km.
- Cursor Information:** Shows the selected location coordinates as 48.137, -0.111, an elevation of 108 meters, and the PVGIS version as 5.3.
- Use terrain shadows:** Includes a checked option for "Calculated horizon" and a button to "Switch to version 5.2".
- Export Options:** Buttons for downloading data as "csv" or "json". A message states "Parcourir... Aucun fichier sélectionné."
- HOURLY RADIATION DATA:** A section with a purple header containing various configuration options:
  - Solar radiation database:** Set to "PVGIS-SARAH3".
  - Start year:** 2021, **End year:** 2022.
  - Mounting type:** "Fixed" is selected. Other options include "Vertical axis", "Inclined axis", and "Two axis".
  - Slope [°]:** (0-90), **Azimuth [°]:** (-180-180).
  - Optimization:** "Optimize slope and azimuth" is checked.
  - PV power:** "PV power" is checked. "Radiation components" is unchecked.
  - PV technology:** "Crystalline Silicon (original)".
  - Installed peak PV power [kWp]:** 1.
  - System loss [%]:** 14.
- Navigation:** A vertical sidebar on the left allows switching between "GRID CONNECTED", "TRACKING PV", "OFF-GRID", "MONTHLY DATA", "DAILY DATA", "HOURLY DATA", and "TMY".
- Input Fields:** At the bottom, there are fields for "Address:" (with "Eg. Ispra, Italy" as an example) and "Lat/Lon:" (with "Eg. 45.815" and "Eg. 8.611" as examples), each with a "Go!" button.

# The carbon footprint depends of the size



Size (Watts-peak)

10

100

1000

Carbon emissions  
during manufacturing  
(kg CO<sub>2</sub>e)

11

110

1100

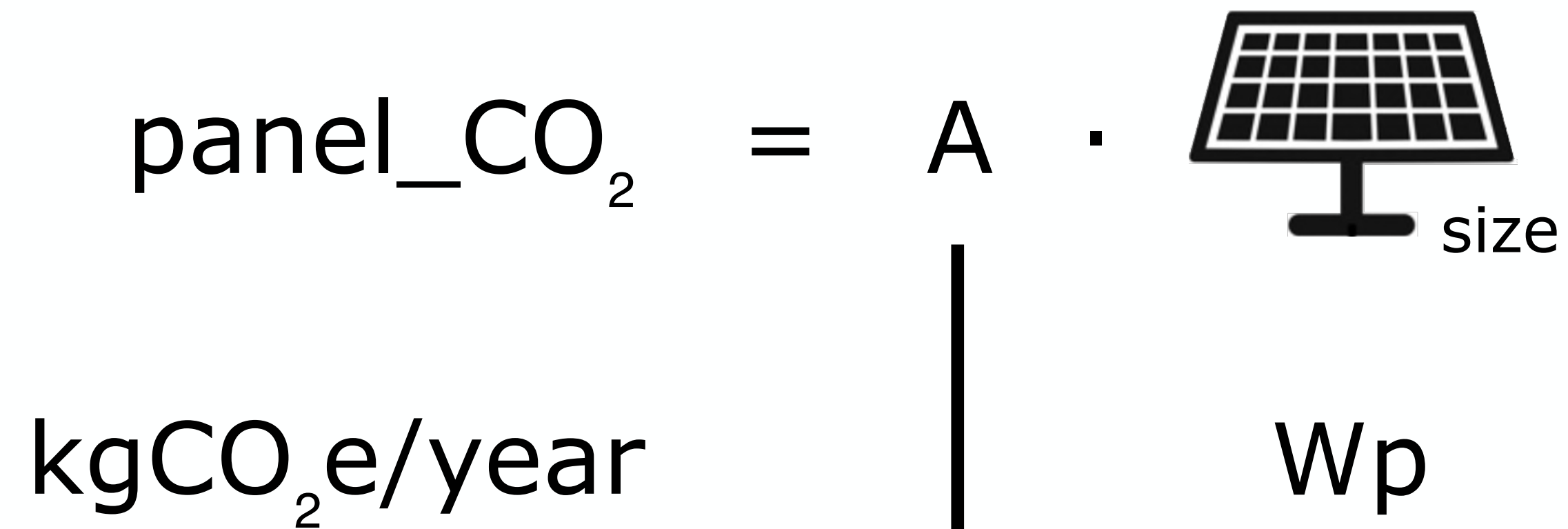
carbon emissions during manufacturing = 1.1 kgCO<sub>2</sub>e/Wp

# The carbon footprint depends of the size

$$\text{panel\_CO}_2 = A \cdot \text{size}$$

kgCO<sub>2</sub>e/year

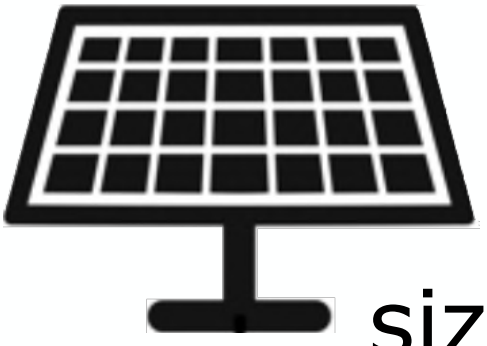
Wp




$$A = \frac{1.1 \text{ kgCO}_2\text{e/Wp}}{30 \text{ years}}$$

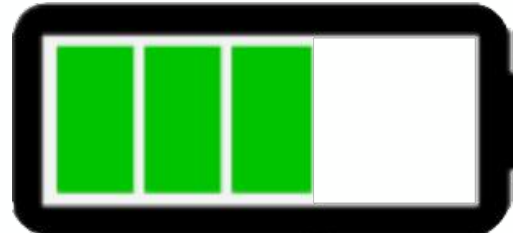
(amortized model)

# The carbon footprint depends of the size

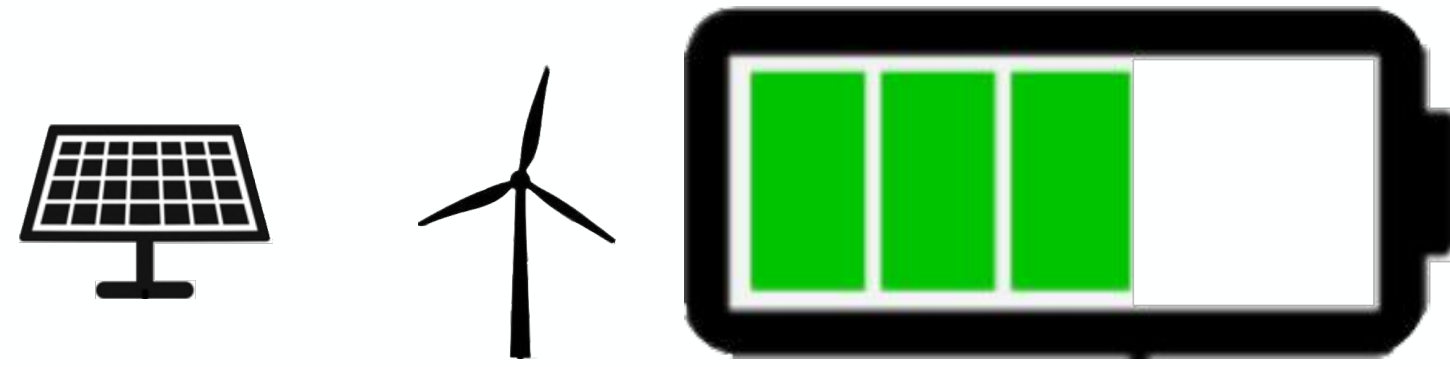
$$\text{panel\_CO}_2 = A \cdot \text{size}$$
A simple black and white icon of a solar panel with a grid pattern on its surface and a mounting bracket at the bottom.

$$\text{turbine\_CO}_2 = B \cdot \text{size}$$
A simple black and white icon of a wind turbine with three blades and a central tower.

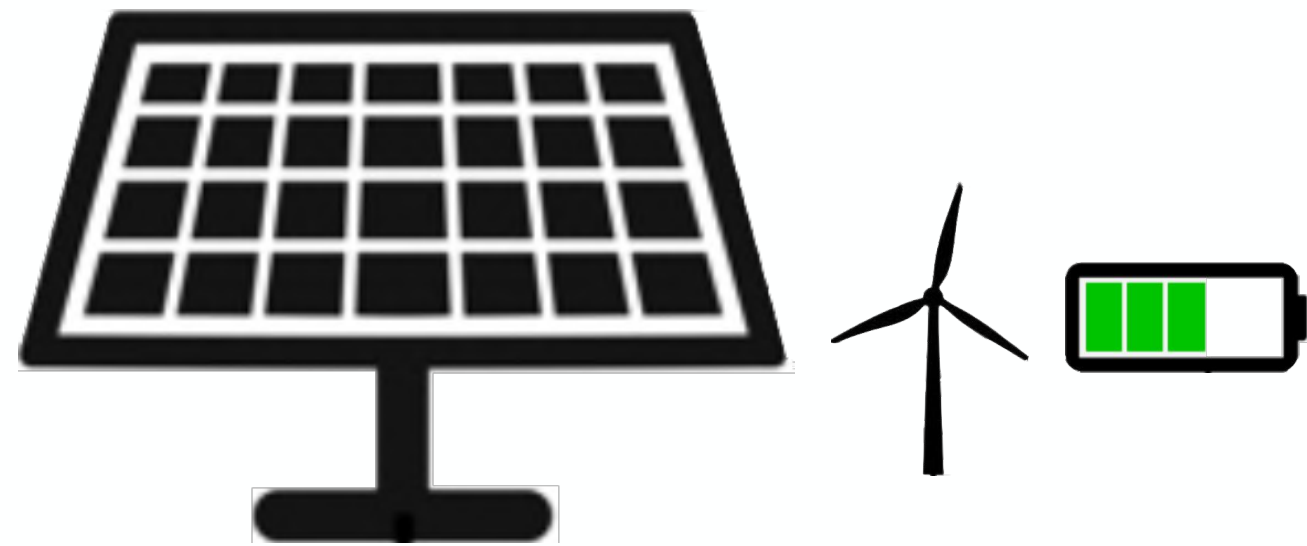
(A, B and C are constants)

$$\text{battery\_CO}_2 = C \cdot \text{size}$$
A simple black and white icon of a battery with a green bar inside, representing a charge level.

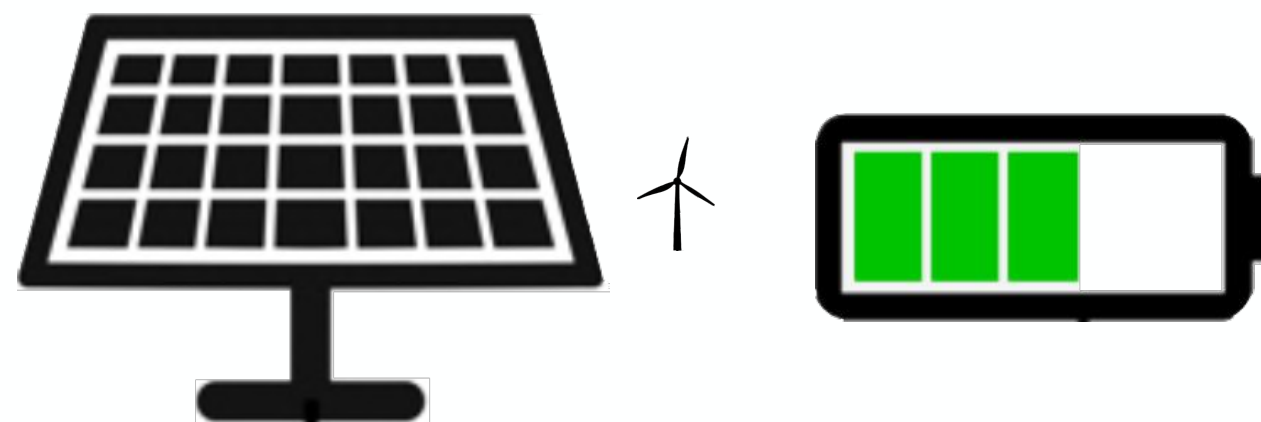
# Now we compute the uptime...



65 %



82 %



90 %

For a fixed CO<sub>2</sub> footprint, it gives the best uptime

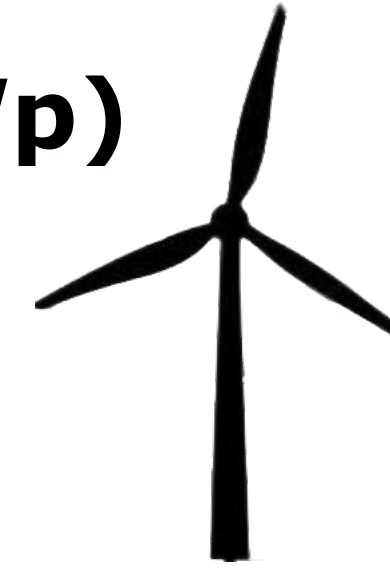
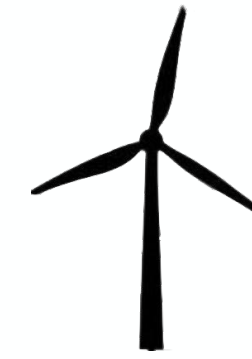
68 kgCO<sub>2</sub>e/year → 90 %

100 kgCO<sub>2</sub>e/year → 93 %

200 kgCO<sub>2</sub>e/year → 98 %

**Battery size** in function of panel and turbine size, with fixed carbon footprint (e.g. **68 kgCO<sub>2</sub>e/year**)

**Wind turbine size (Wp)**



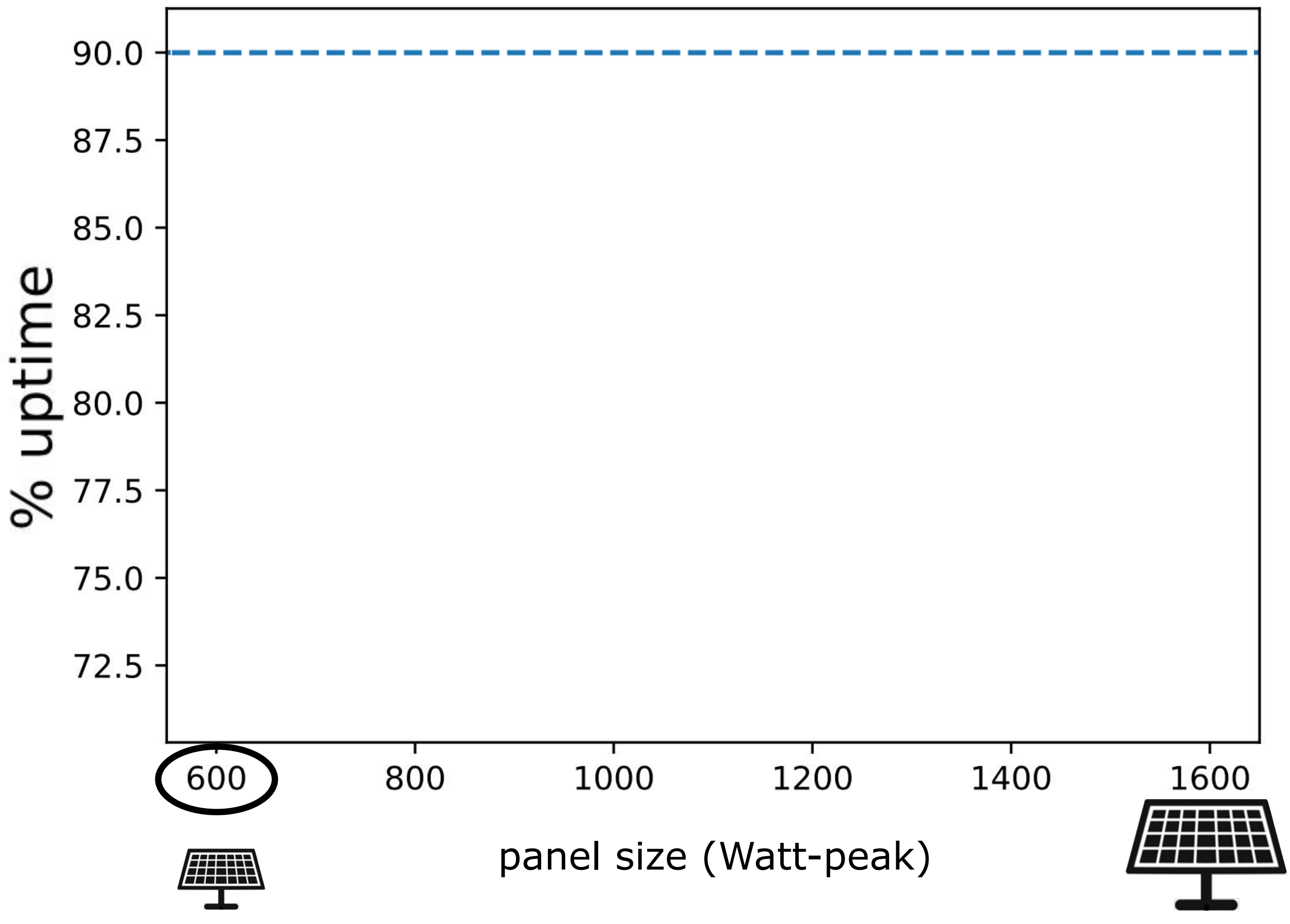
**Solar panel size (Wp)**



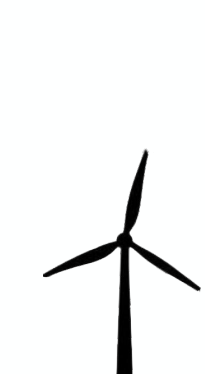
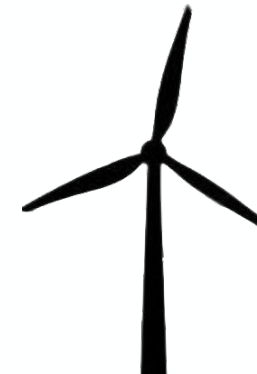


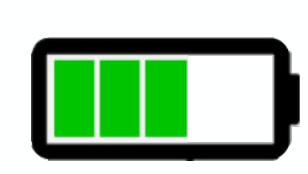
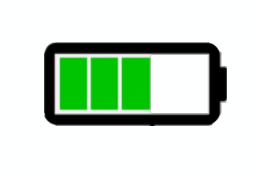


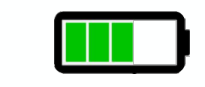






		0	200	350
<b>600</b>	4120	2925	2030	
<b>1000</b>	2701	1507	611	
<b>1400</b>	1283	89	/	

 no WT
 

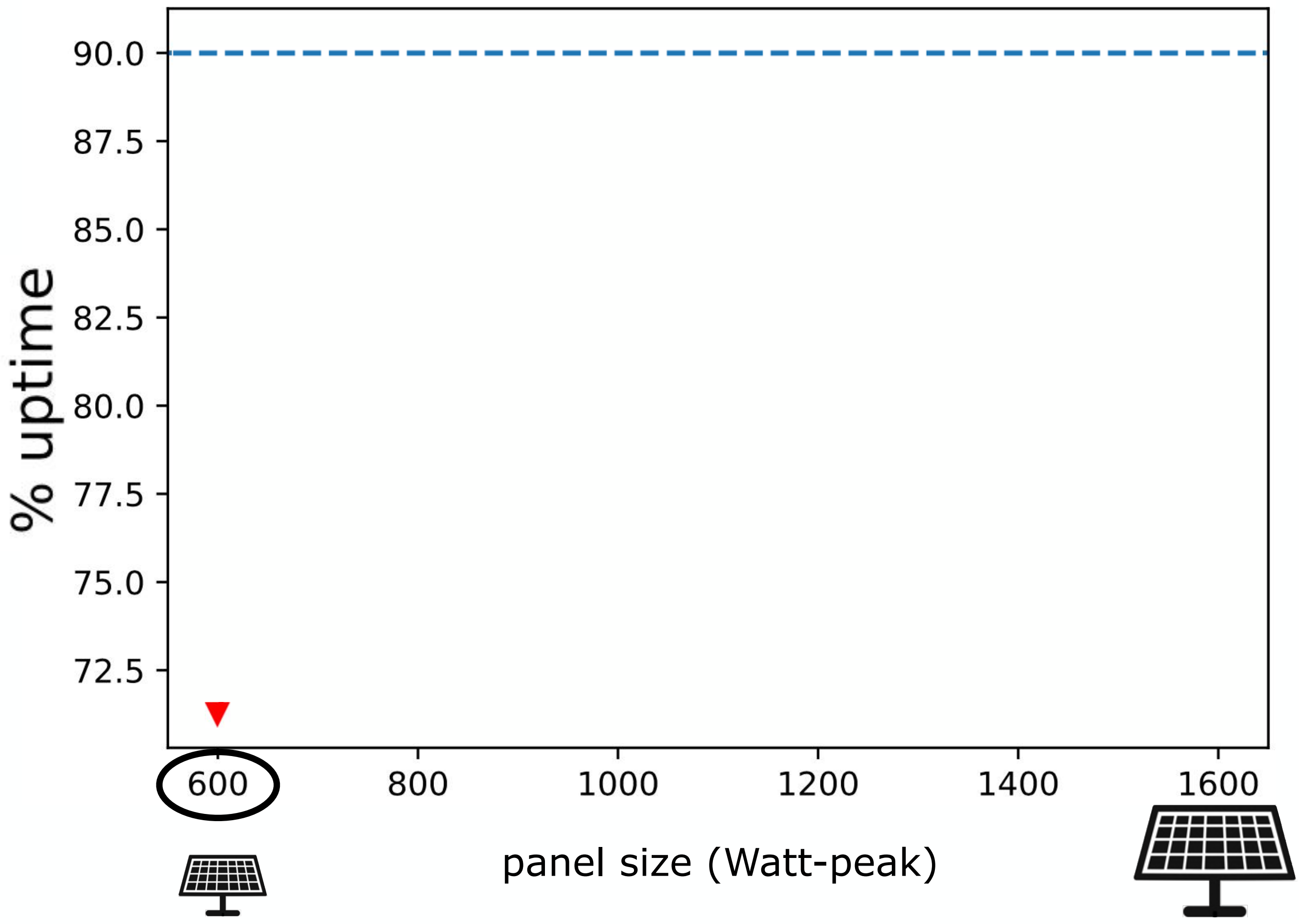
365 days (year 2021)  
 servers (200 W when idle)  
 68 kgCO<sub>2</sub>e/year


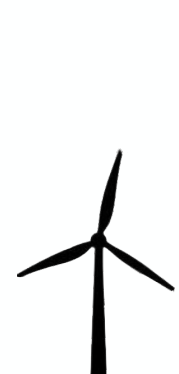
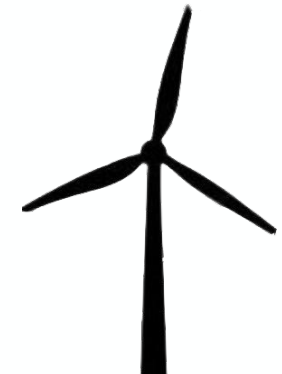


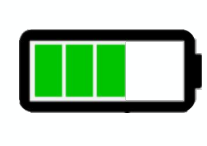








	 			
	0	200	350	
	600	4120 	2925 	2030 
	1000	2701 	1507 	611 
	1400	1283 	89 	/

no WT  

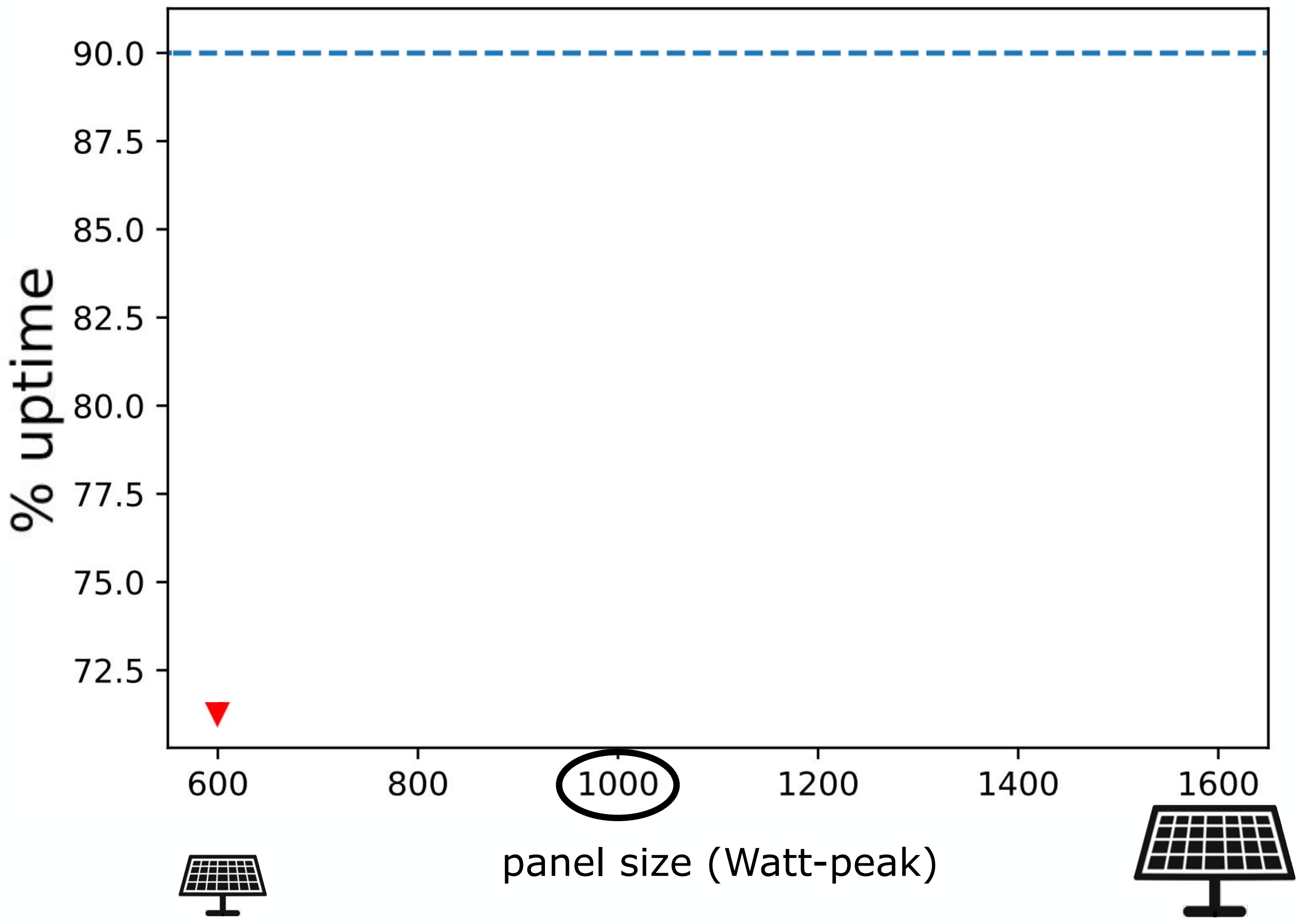
365 days (year 2021)  
 servers (200 W when idle)  
 68 kgCO<sub>2</sub>e/year



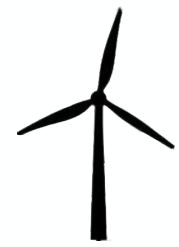
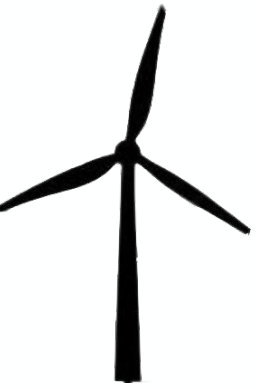













	 0	 200	 350
	<b>600</b>	2925 	2030 
	<b>1000</b>	2701 	611 
	<b>1400</b>	1283 	89 

 no WT
 

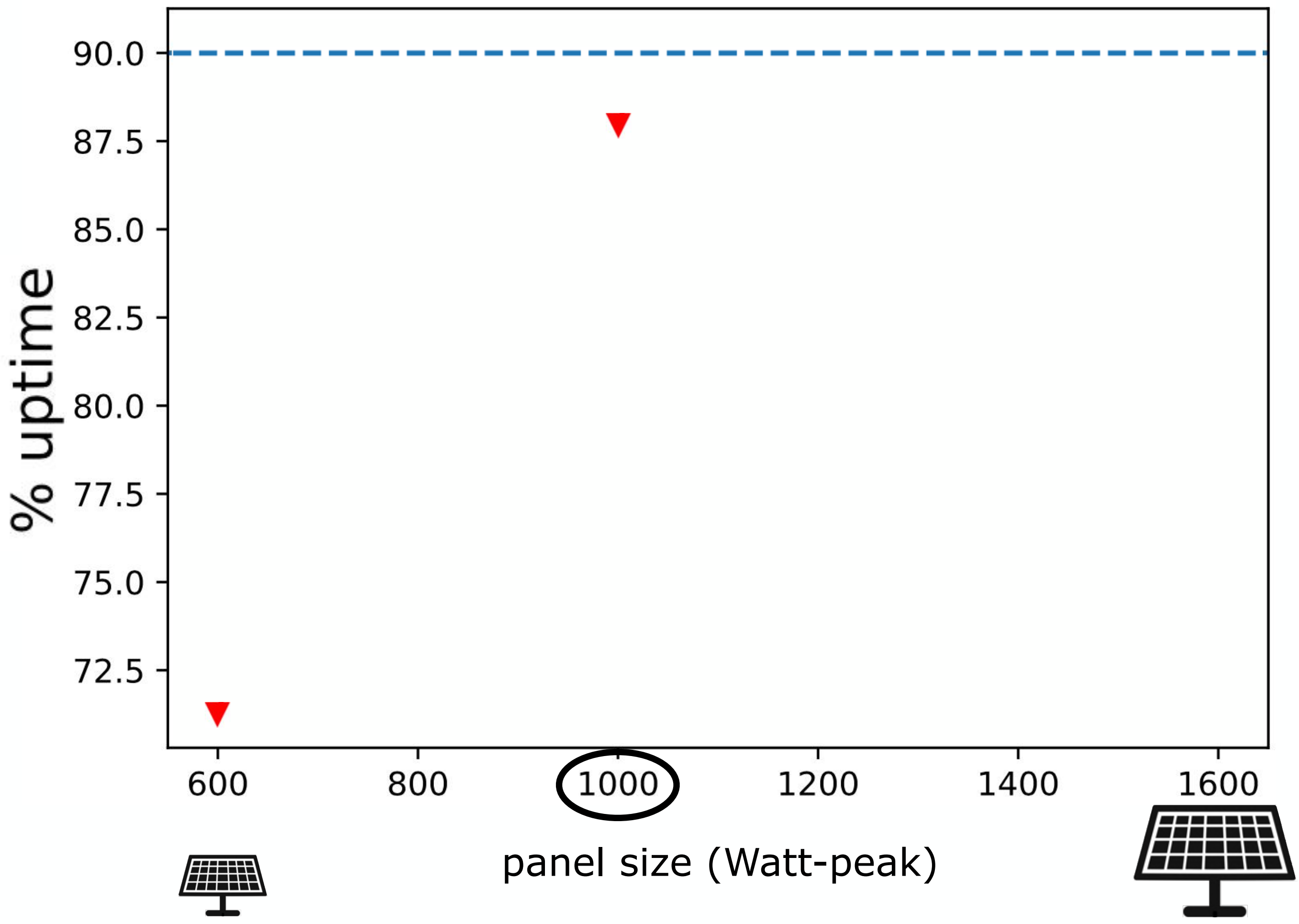
365 days (year 2021)  
 servers (200 W when idle)  
 68 kgCO<sub>2</sub>e/year


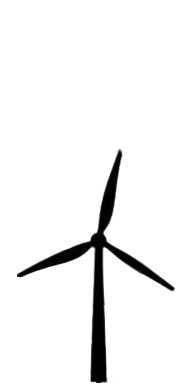
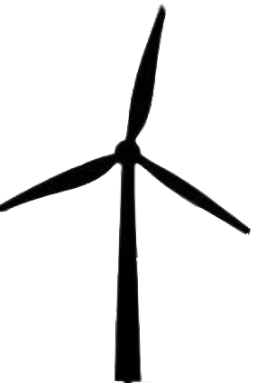






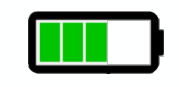





	 			
	0	200	350	
	600	4120 	2925 	2030 
	1000	2701 	1507 	611 
	1400	1283 	89 	/

no WT  

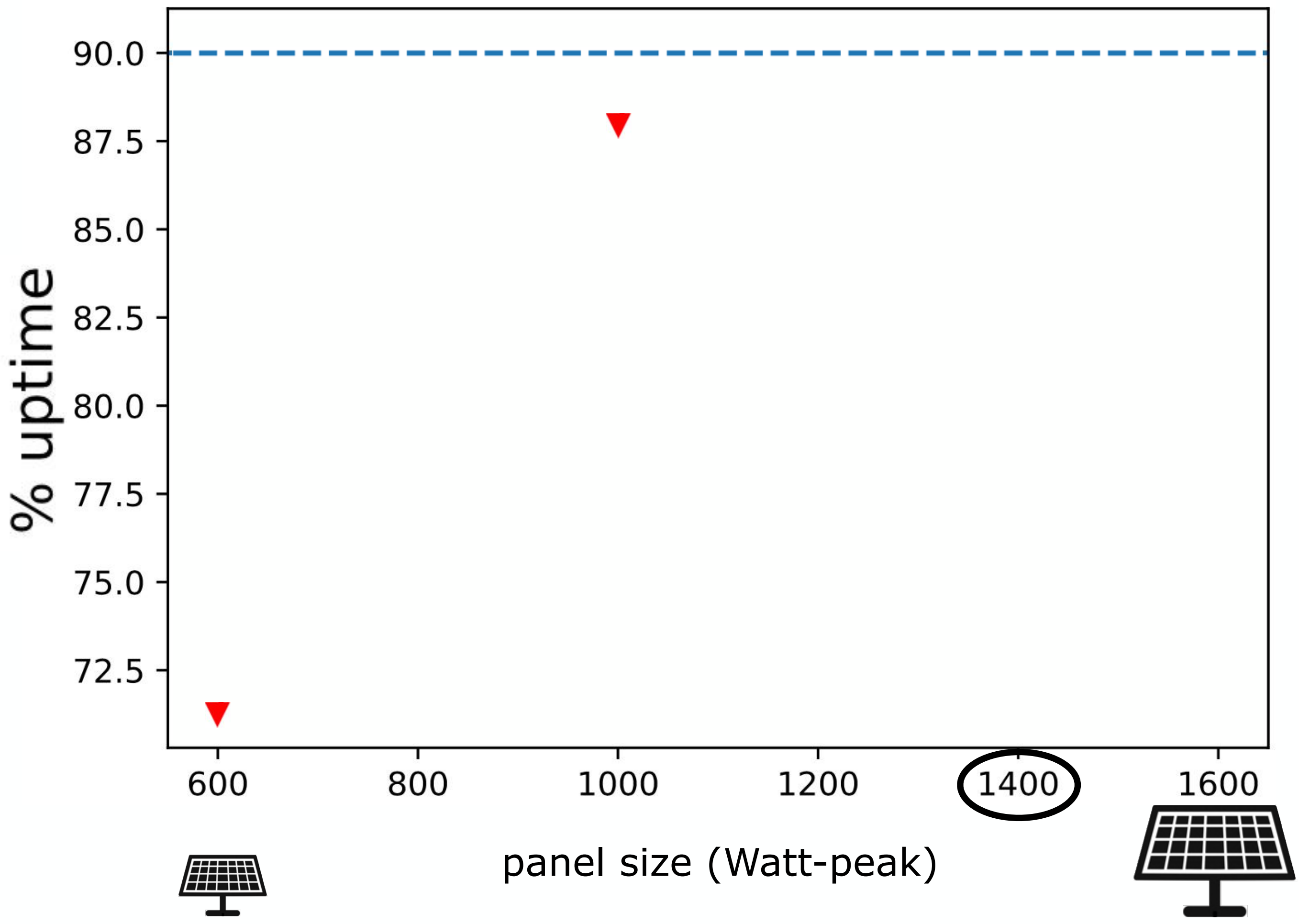
365 days (year 2021)  
 servers (200 W when idle)  
 68 kgCO<sub>2</sub>e/year



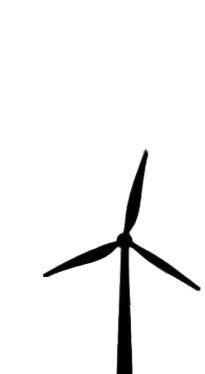
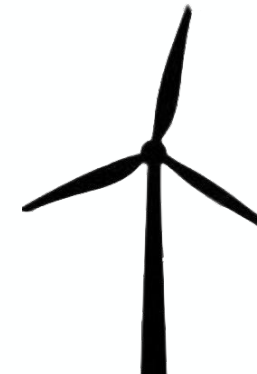


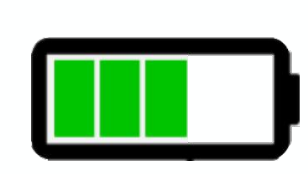
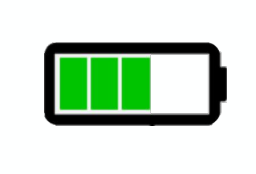

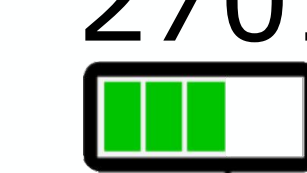
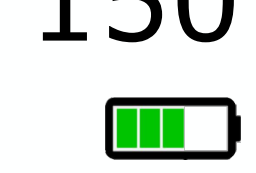

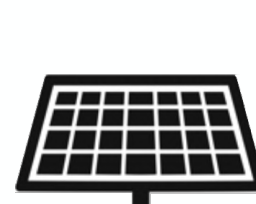
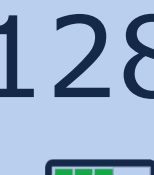



			
			
	<b>0</b>	<b>200</b>	<b>350</b>
	<b>600</b>	4120 	2925 
	<b>1000</b>	2701 	1507 
	<b>1400</b>	1283 	89 
			/

 no WT
 

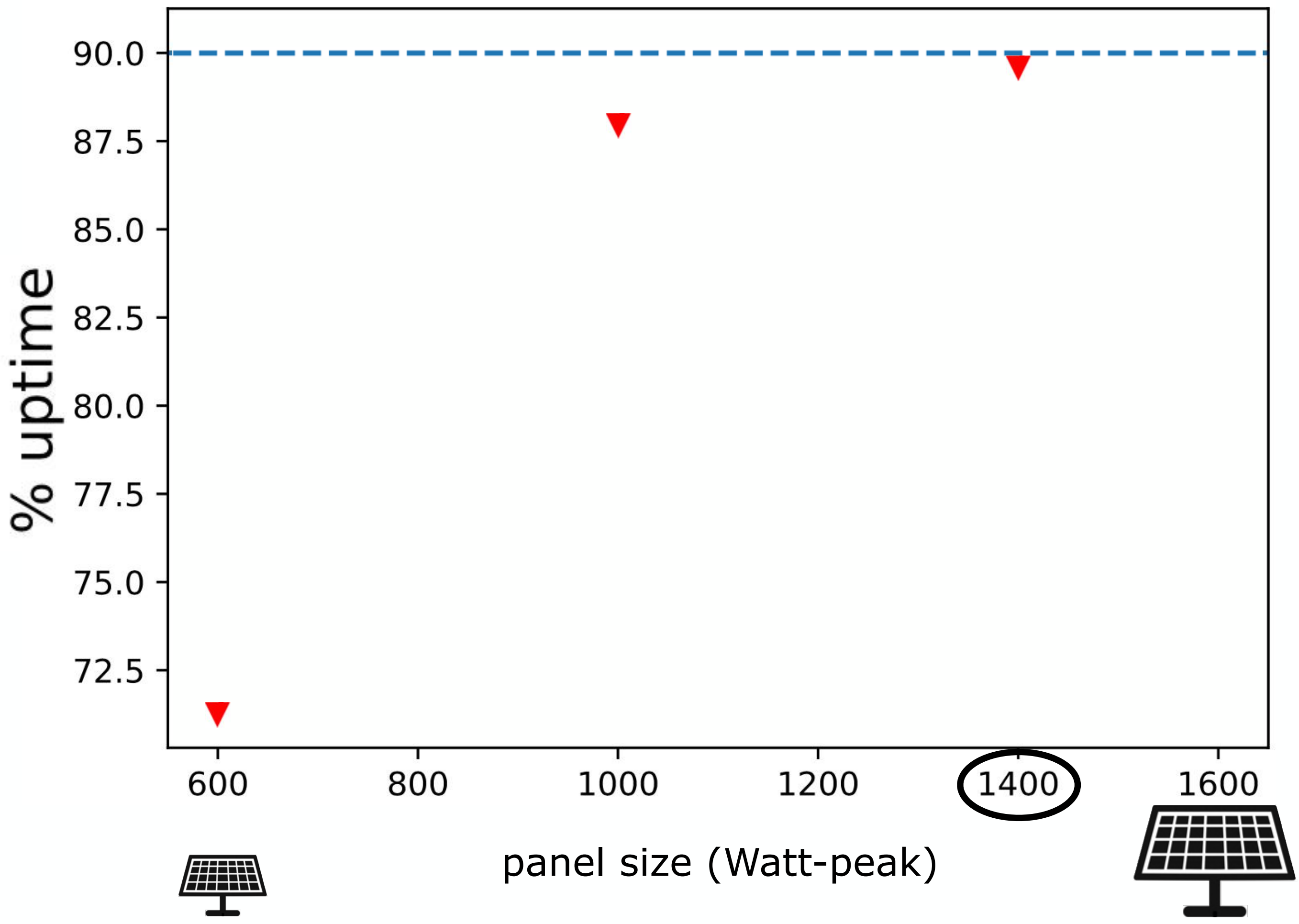
365 days (year 2021)  
 servers (200 W when idle)  
 68 kgCO<sub>2</sub>e/year



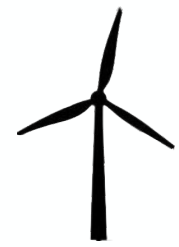
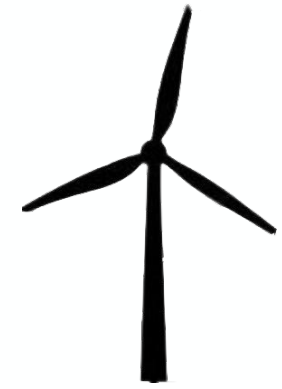






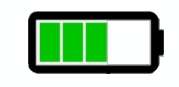






	 		
	0	200	350
 600	4120 	2925 	2030 
 1000	2701 	1507 	611 
 1400	1283 	89 	/

 no WT
 

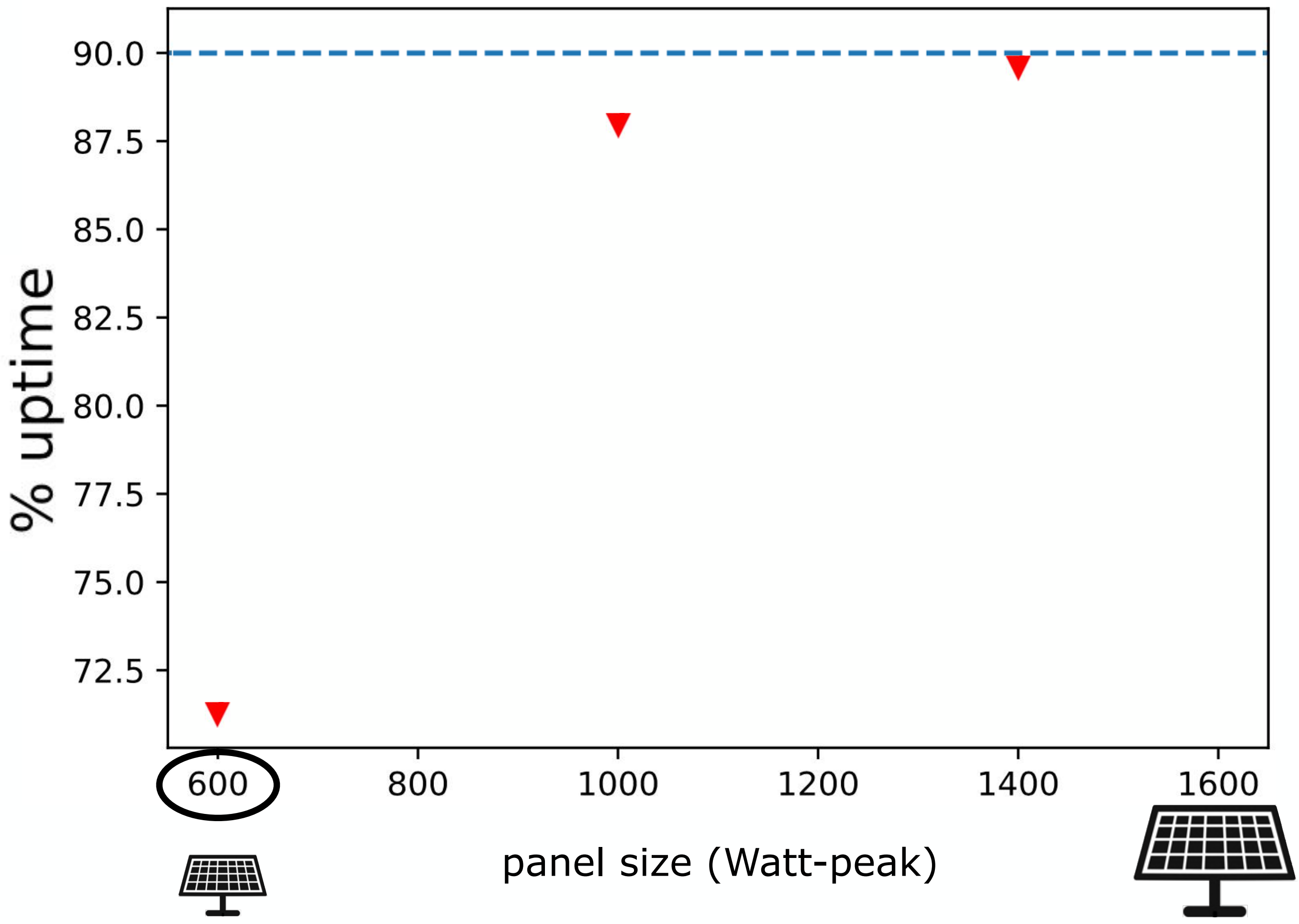
365 days (year 2021)  
 servers (200 W when idle)  
 68 kgCO<sub>2</sub>e/year



	 		
	0	200	350
 600	4120 	2925 	2030 
 1000	2701 	1507 	611 
 1400	1283 	89 	/



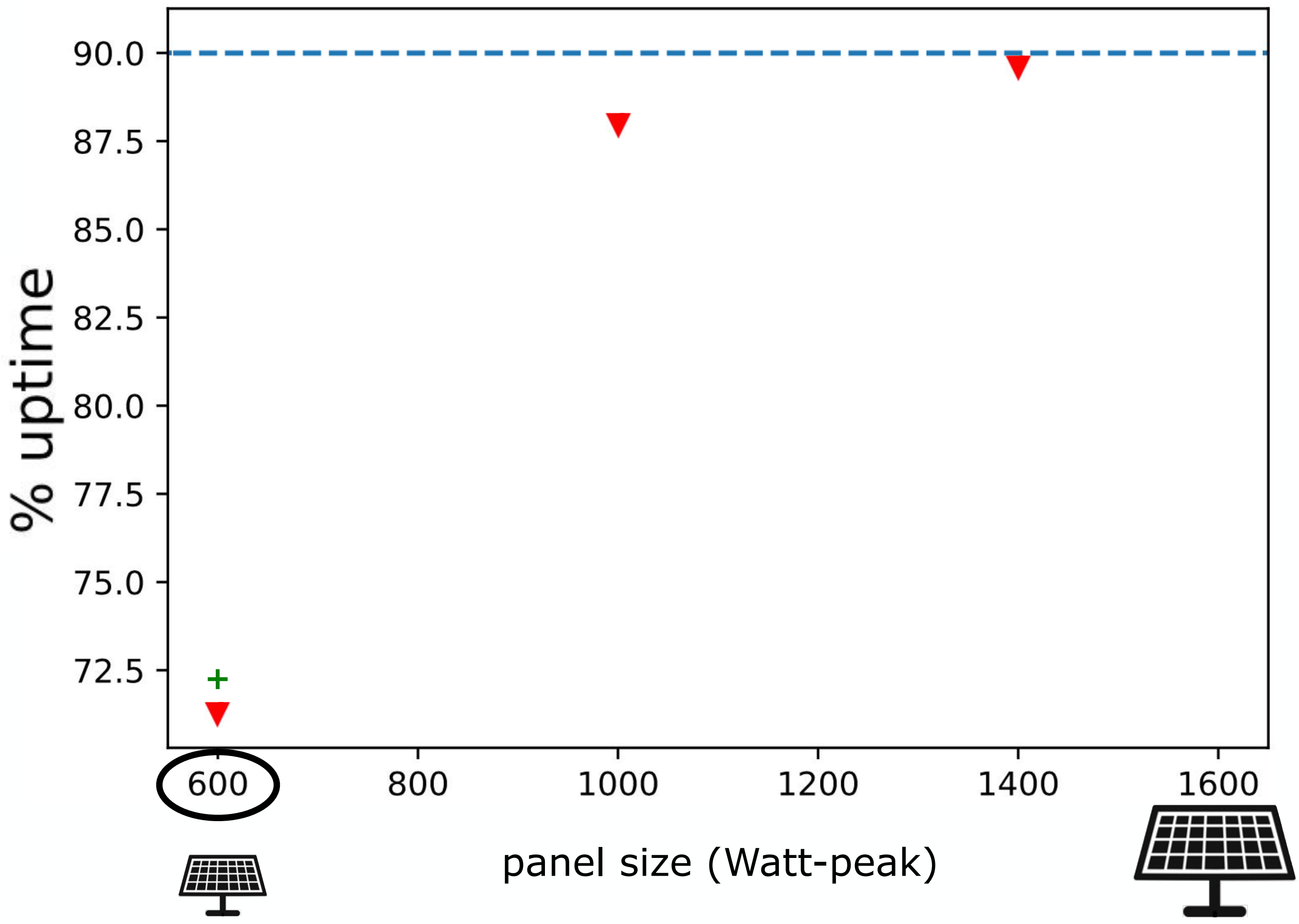
365 days (year 2021)  
 servers (200 W when idle)  
 68 kgCO<sub>2</sub>e/year



	0	200	350
600	4120 	2925 	2030 
1000	2701 	1507 	611 
1400	1283 	89 	/



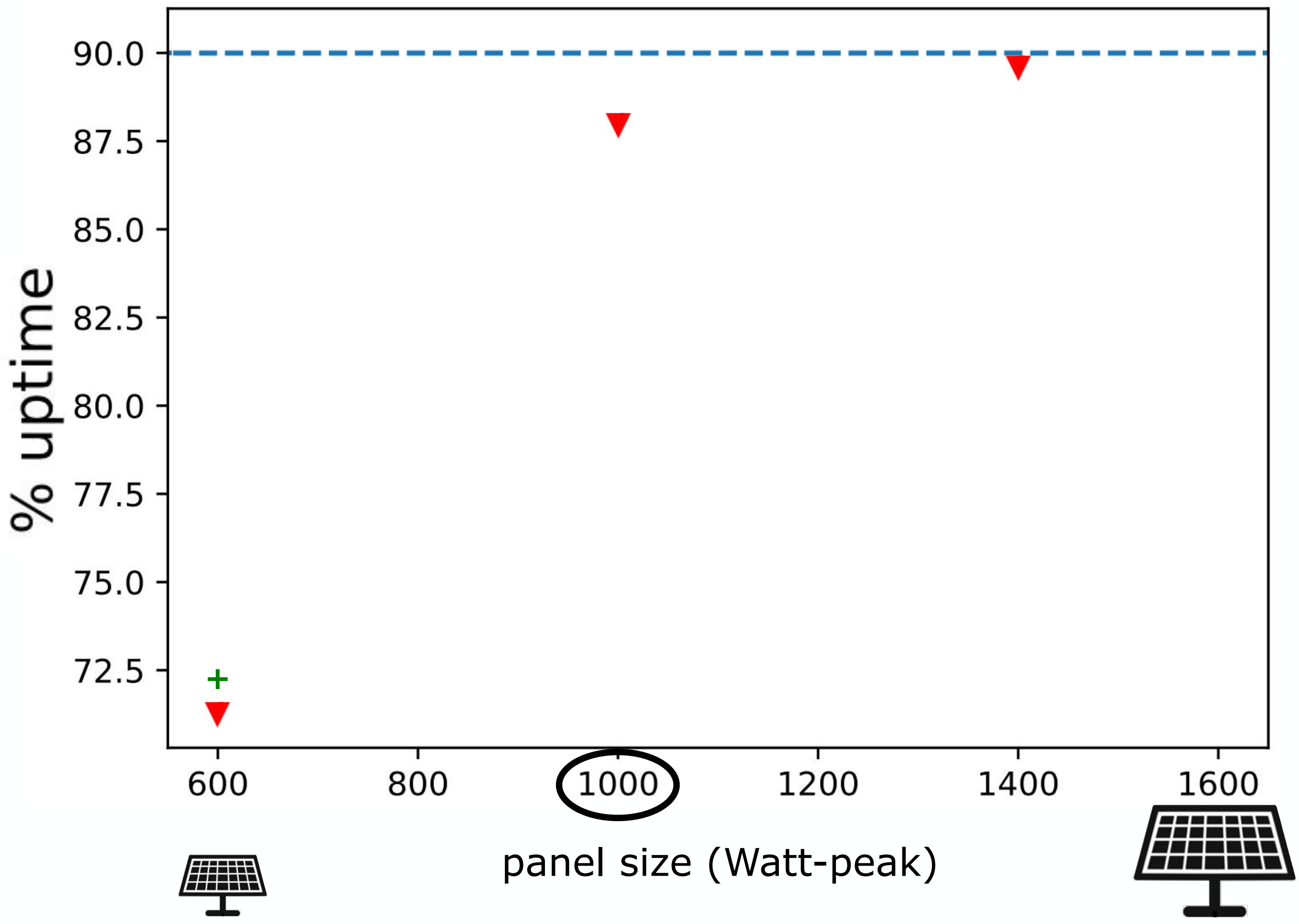
365 days (year 2021)  
 servers (200 W when idle)  
 68 kgCO<sub>2</sub>e/year



	0	200	350
	0	200	350
600	4120	2925	2030
1000	2701	1507	611
1400	1283	89	/



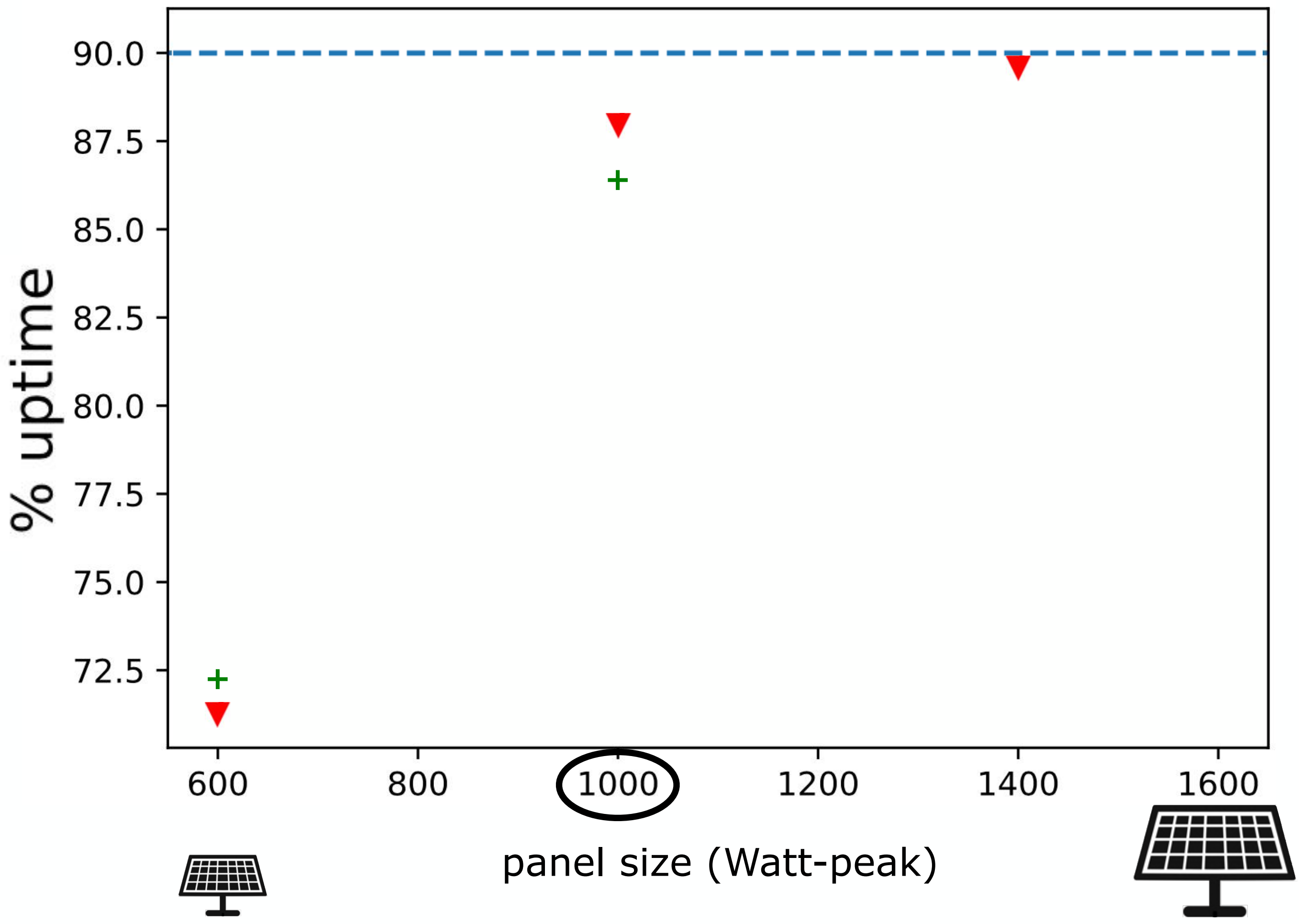
365 days (year 2021)  
 servers (200 W when idle)  
 68 kgCO<sub>2</sub>e/year



	0	200	350
600	4120 	2925 	2030 
1000	2701 	1507 	611 
1400	1283 	89 	/



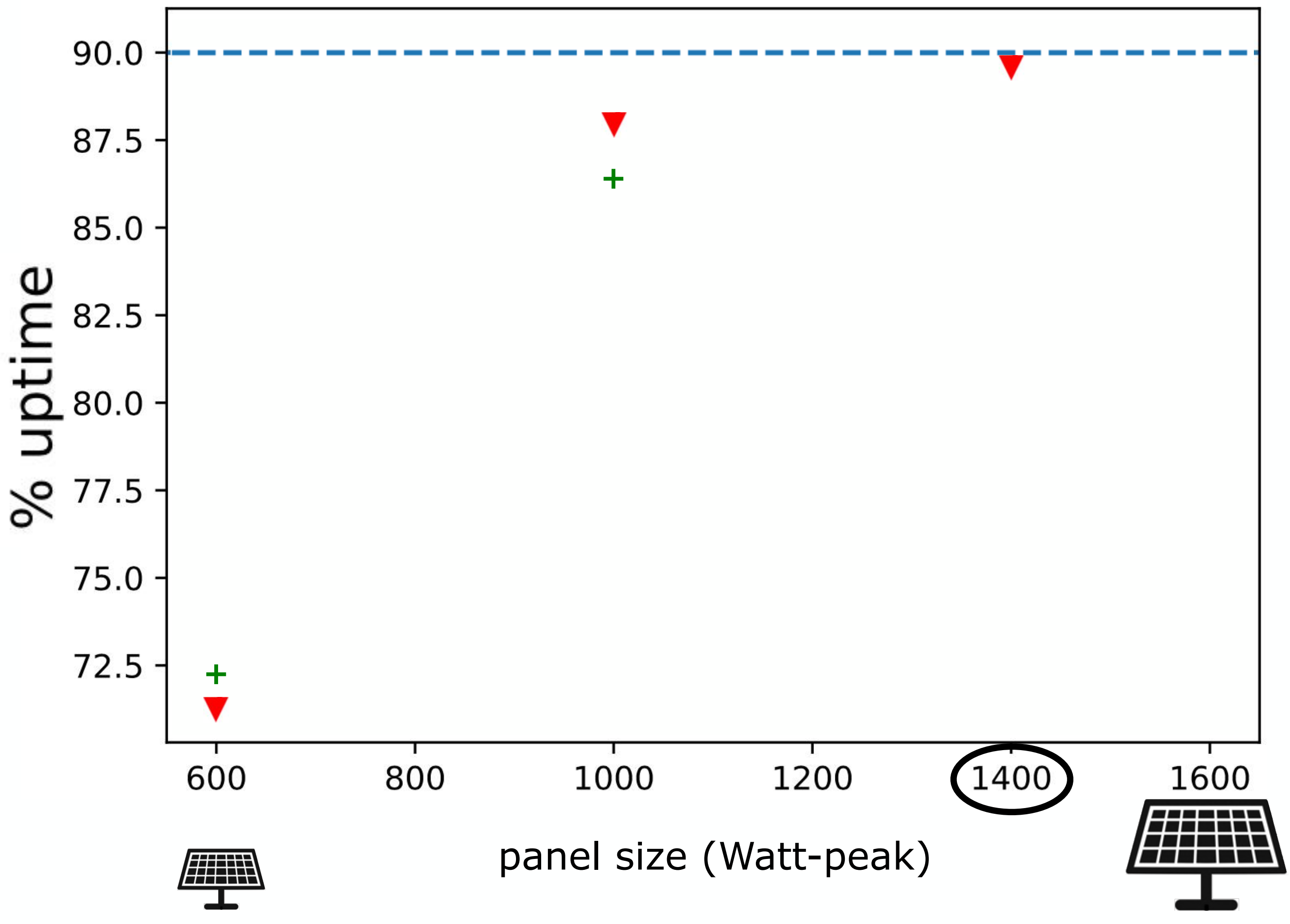
365 days (year 2021)  
 servers (200 W when idle)  
 68 kgCO<sub>2</sub>e/year



	0	200	350
600	4120 	2925 	2030 
1000	2701 	1507 	611 
1400	1283 	89 	/



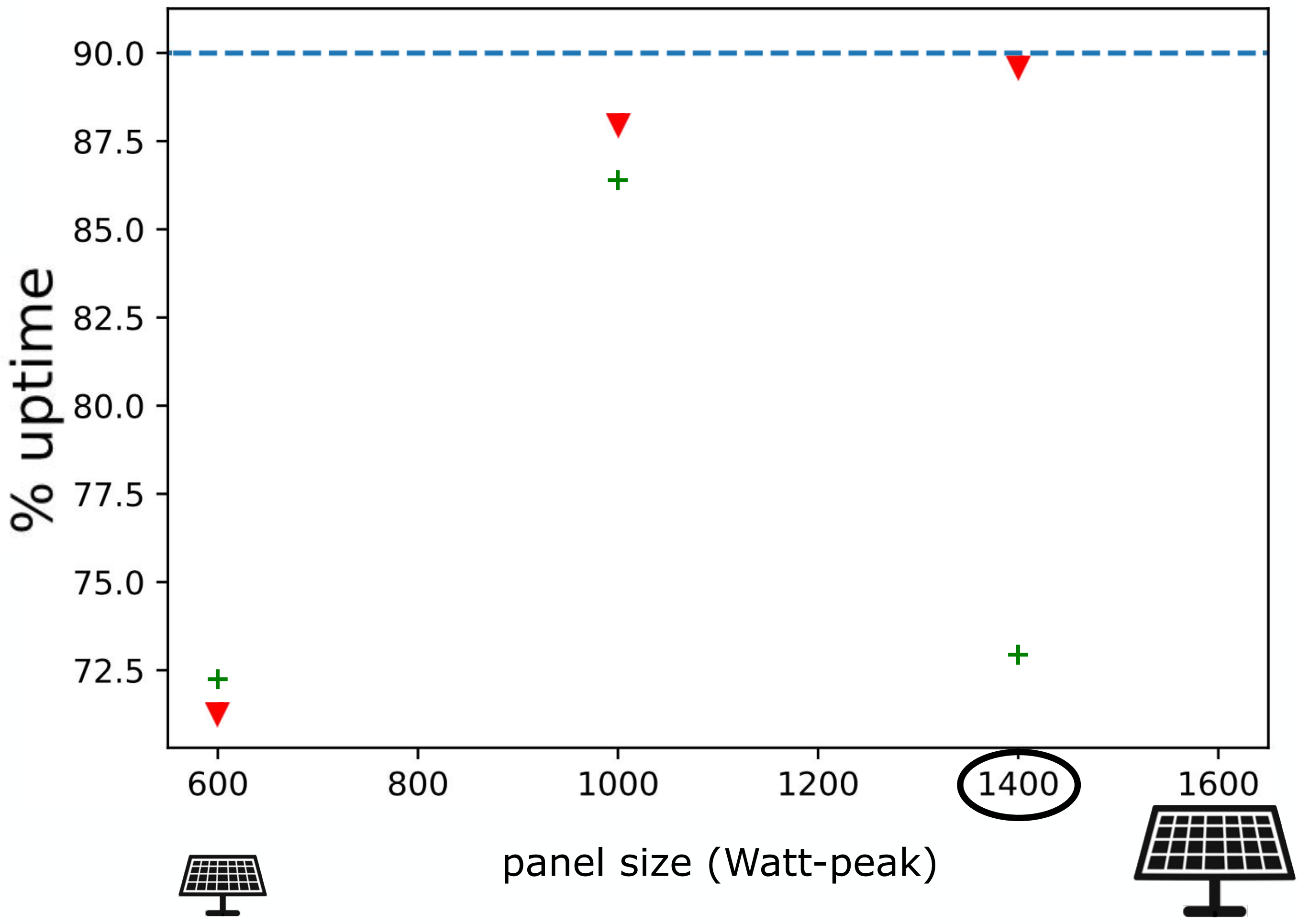
365 days (year 2021)  
 servers (200 W when idle)  
 68 kgCO<sub>2</sub>e/year



	no WT	200 Wp	200 Wp
	0	200	350
600	4120	2925	2030
1000	2701	1507	611
1400	1283	89	/



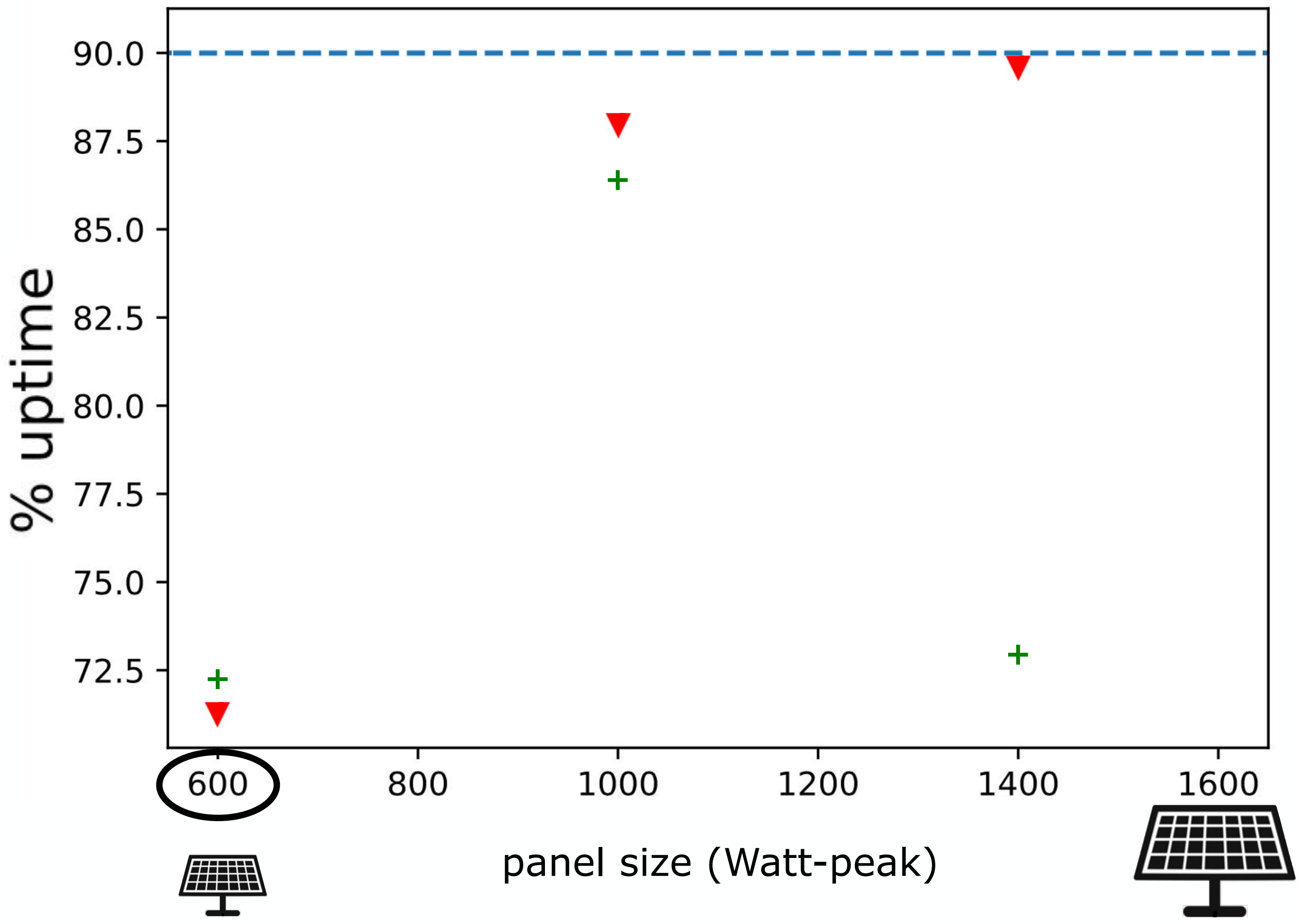
365 days (year 2021)  
 servers (200 W when idle)  
 68 kgCO<sub>2</sub>e/year



	0	200	350
600	4120 	2925 	2030 
1000	2701 	1507 	611 
1400	1283 	89 	/



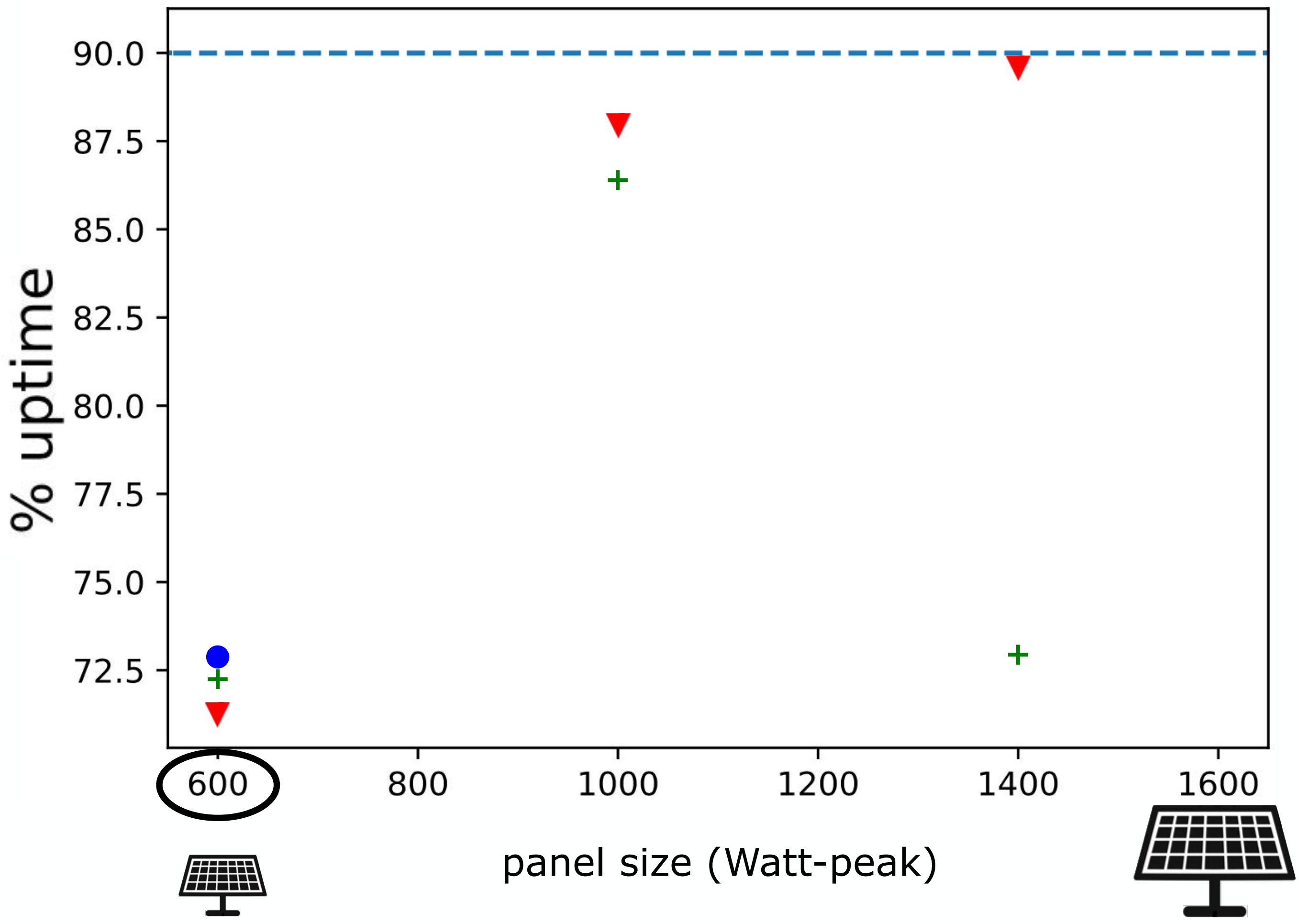
365 days (year 2021)  
 servers (200 W when idle)  
 68 kgCO<sub>2</sub>e/year



	0	200	350
600	4120	2925	2030
1000	2701	1507	611
1400	1283	89	/



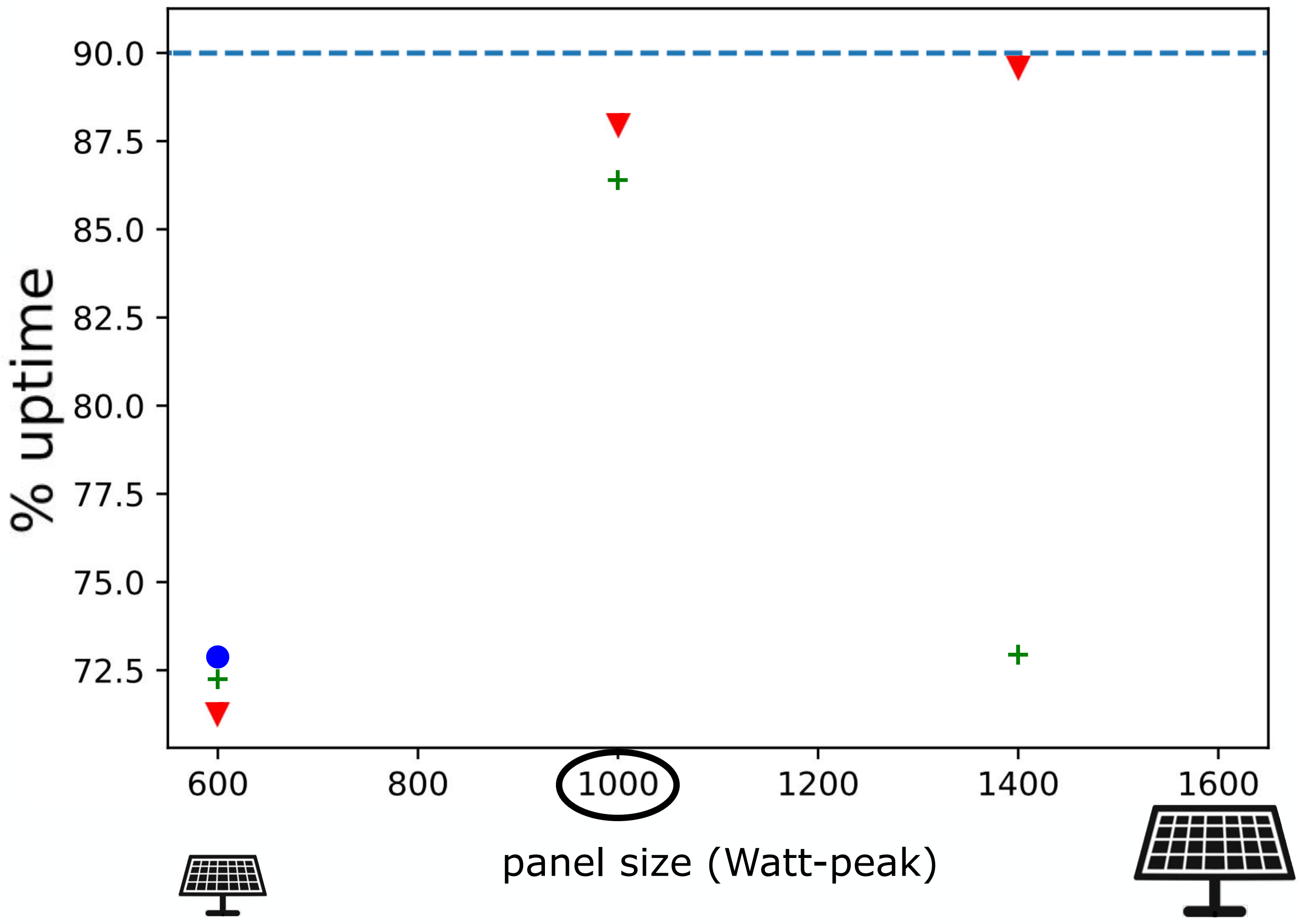
365 days (year 2021)  
 servers (200 W when idle)  
 68 kgCO<sub>2</sub>e/year



	0	200	350
600	4120 	2925 	2030 
1000	2701 	1507 	611 
1400	1283 	89 	/



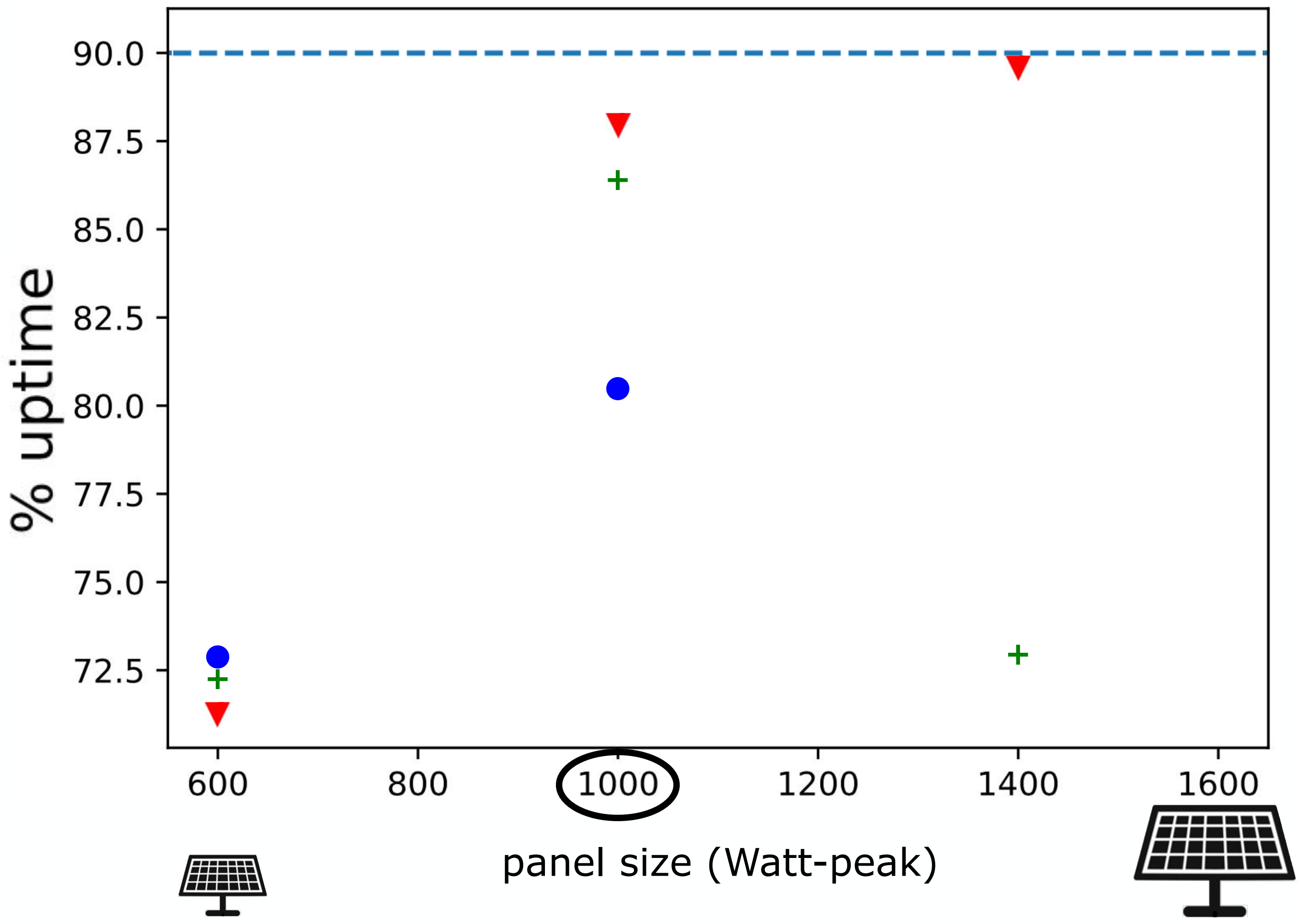
365 days (year 2021)  
servers (200 W when idle)  
68 kgCO<sub>2</sub>e/year



	no WT	200 Wp	350 Wp
600	4120	2925	2030
1000	2701	1507	611
1400	1283	89	/

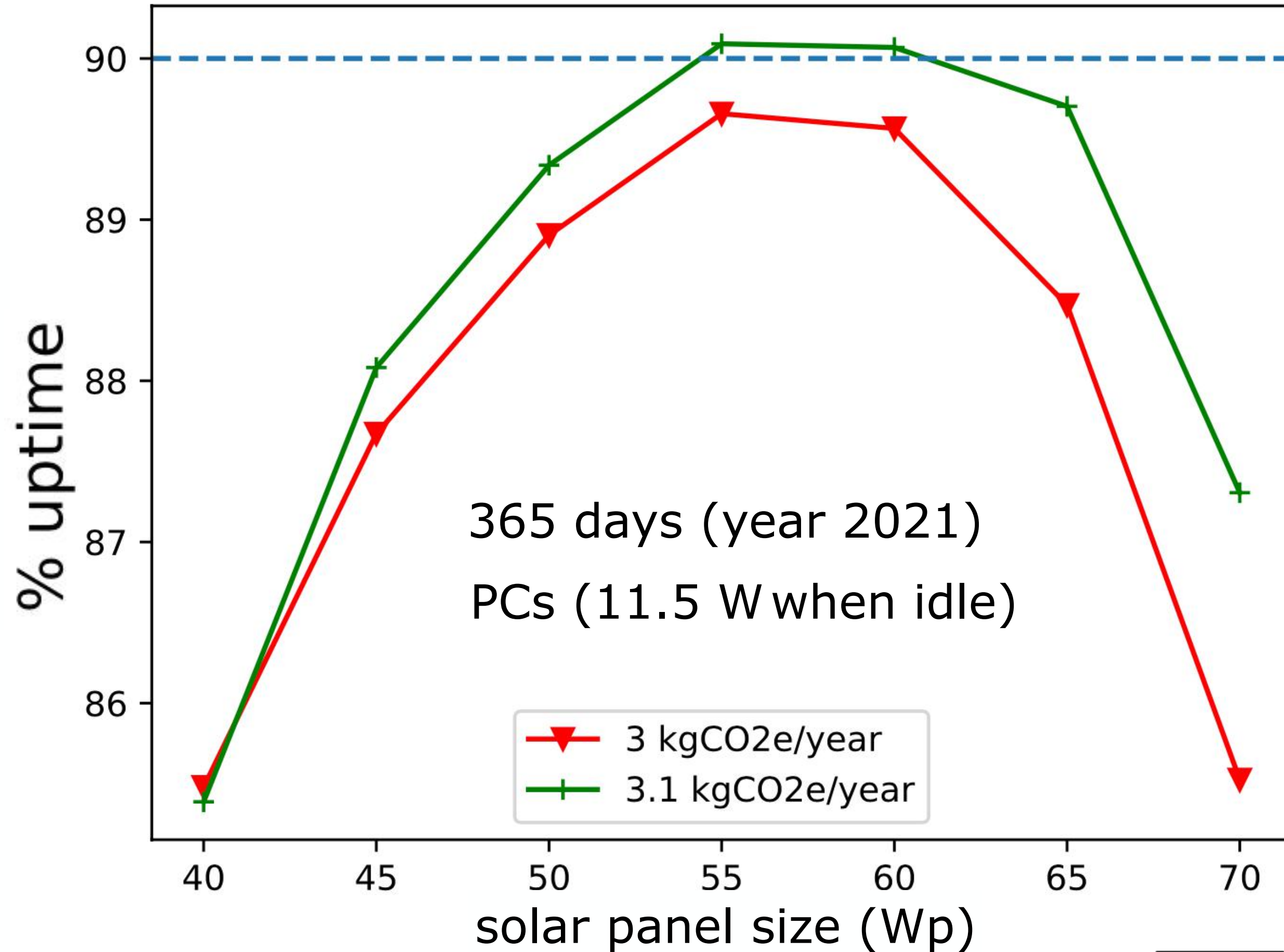
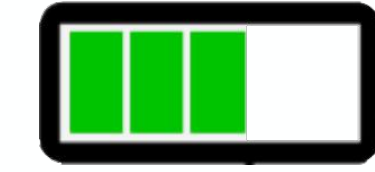
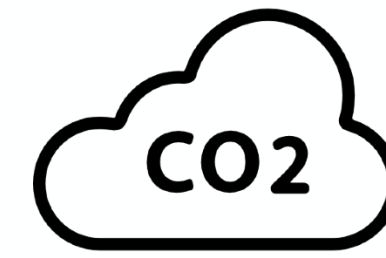


365 days (year 2021)  
servers (200 W when idle)  
68 kgCO<sub>2</sub>e/year



	0	200	350
600	4120	2925	2030
1000	2701	1507	611
1400	1283	89	/

# minimal footprint to reach 90% uptime

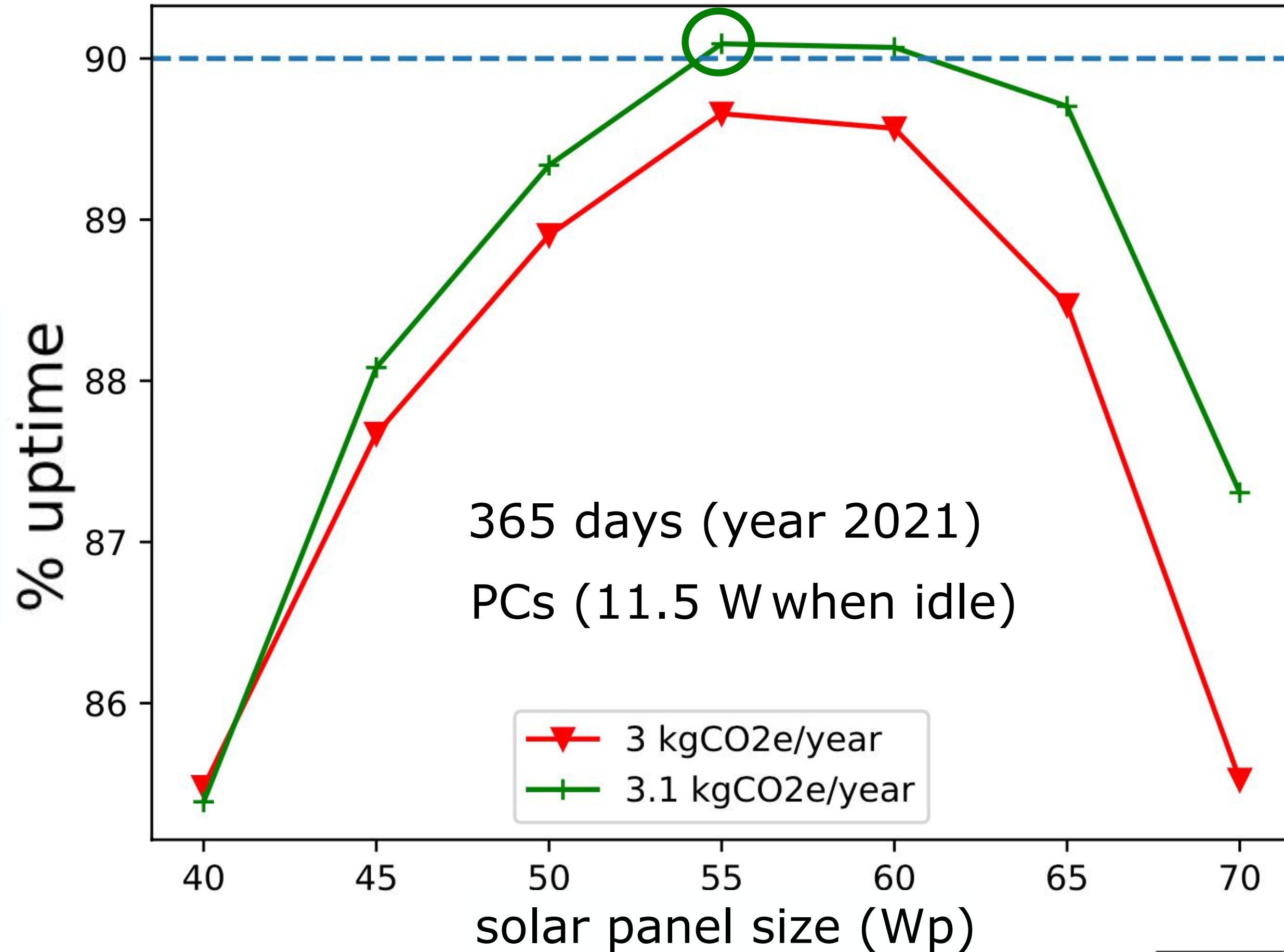
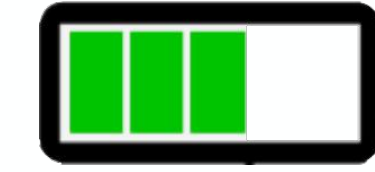
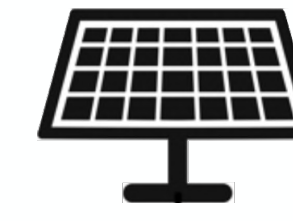
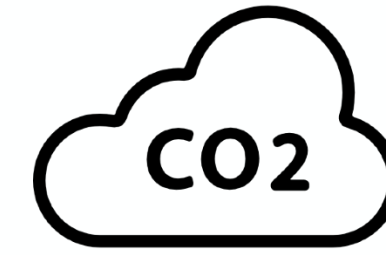


kgCO <sub>2</sub> e/year	PV size	battery size	uptime
3.0	40 Wp	133 Wh	85.48%
3.0	45 Wp	116 Wh	87.67%
3.0	50 Wp	98 Wh	88.90%
<b>3.0</b>	<b>55 Wp</b>	<b>80 Wh</b>	<b>89.66%</b>
3.0	60 Wp	62 Wh	89.57%
3.0	65 Wp	45 Wh	88.47%
3.0	70 Wp	27 Wh	85.53%
3.1	40 Wp	142 Wh	85.39%
3.1	45 Wp	125 Wh	88.08%
3.1	50 Wp	107 Wh	89.34%
3.1	55 Wp	89 Wh	90.09%
<b>3.1</b>	<b>60 Wp</b>	<b>72 Wh</b>	<b>90.07%</b>
3.1	65 Wp	54 Wh	89.70%
3.1	70 Wp	36 Wh	87.31%



Here, we use PCs.  
11.5 W when idle

# minimal footprint to reach 90% uptime

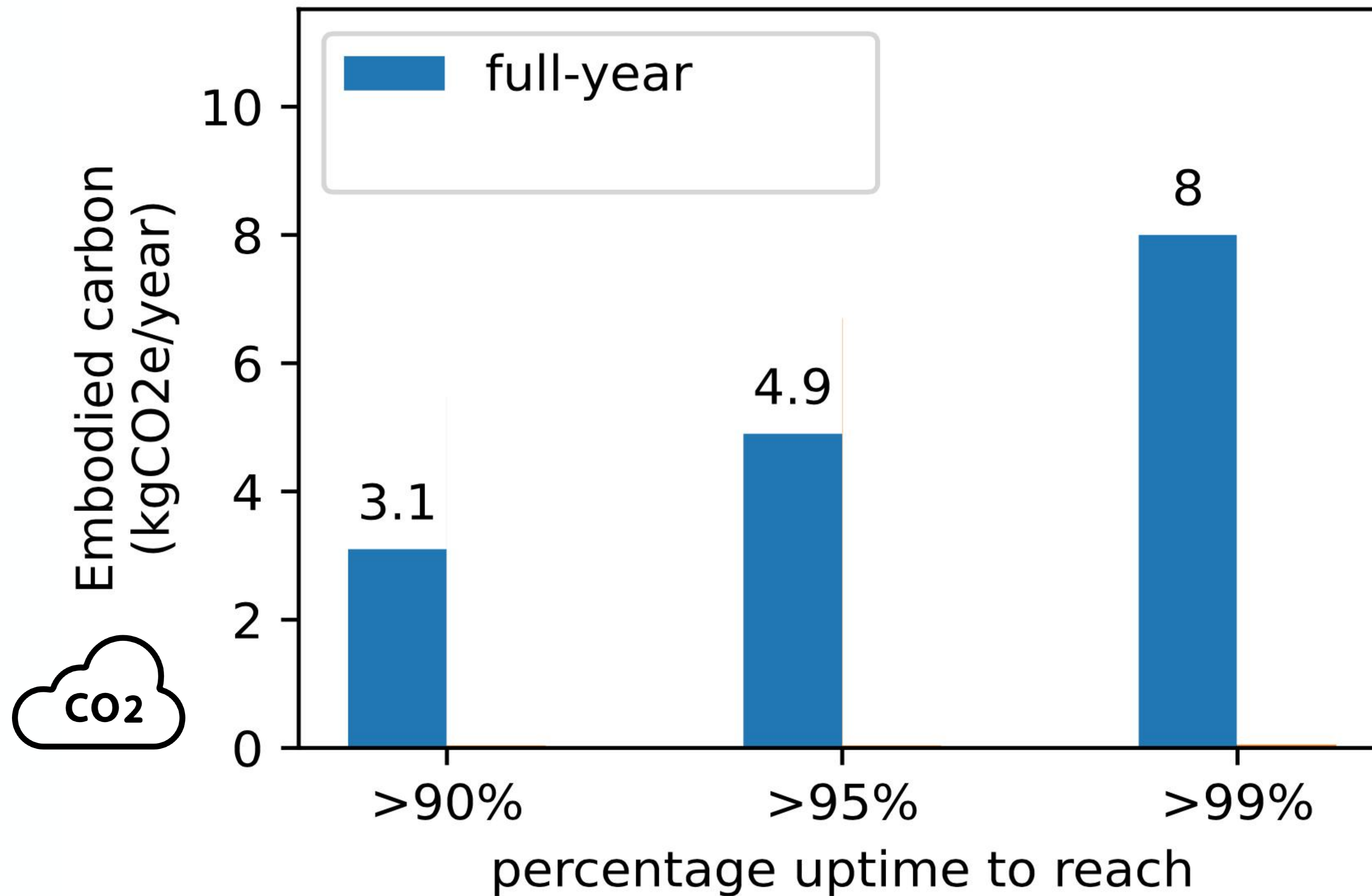


kgCO <sub>2</sub> e/year	PV size	battery size	uptime
3.0	40 Wp	133 Wh	85.48%
3.0	45 Wp	116 Wh	87.67%
3.0	50 Wp	98 Wh	88.90%
<b>3.0</b>	<b>55 Wp</b>	<b>80 Wh</b>	<b>89.66%</b>
3.0	60 Wp	62 Wh	89.57%
3.0	65 Wp	45 Wh	88.47%
3.0	70 Wp	27 Wh	85.53%
3.1	40 Wp	142 Wh	85.39%
3.1	45 Wp	125 Wh	88.08%
3.1	50 Wp	107 Wh	89.34%
3.1	55 Wp	89 Wh	90.09%
<b>3.1</b>	<b>60 Wp</b>	<b>72 Wh</b>	<b>90.07%</b>
3.1	65 Wp	54 Wh	89.70%
3.1	70 Wp	36 Wh	87.31%



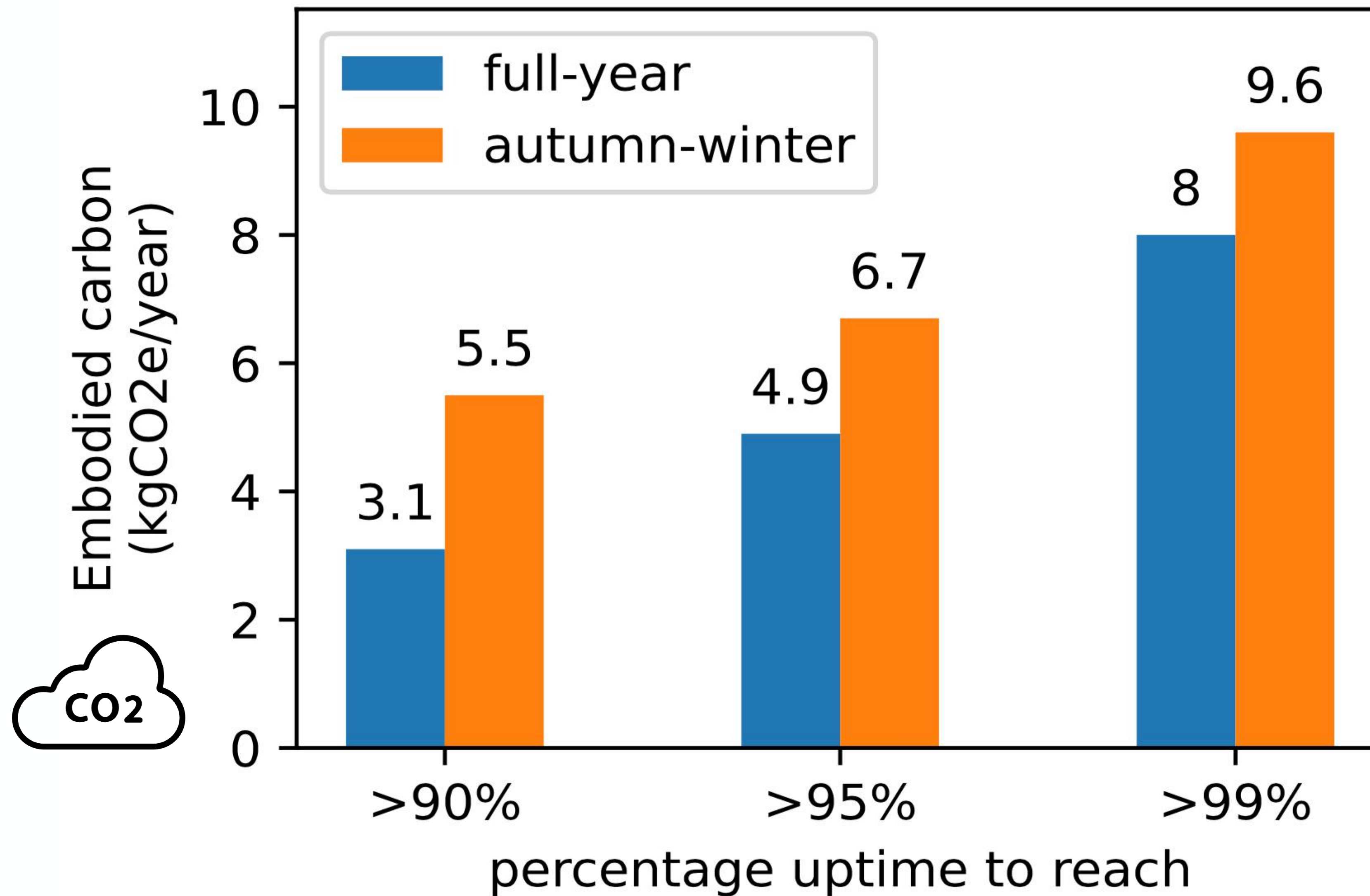
Here, we use PCs.  
11.5 W when idle

# Results

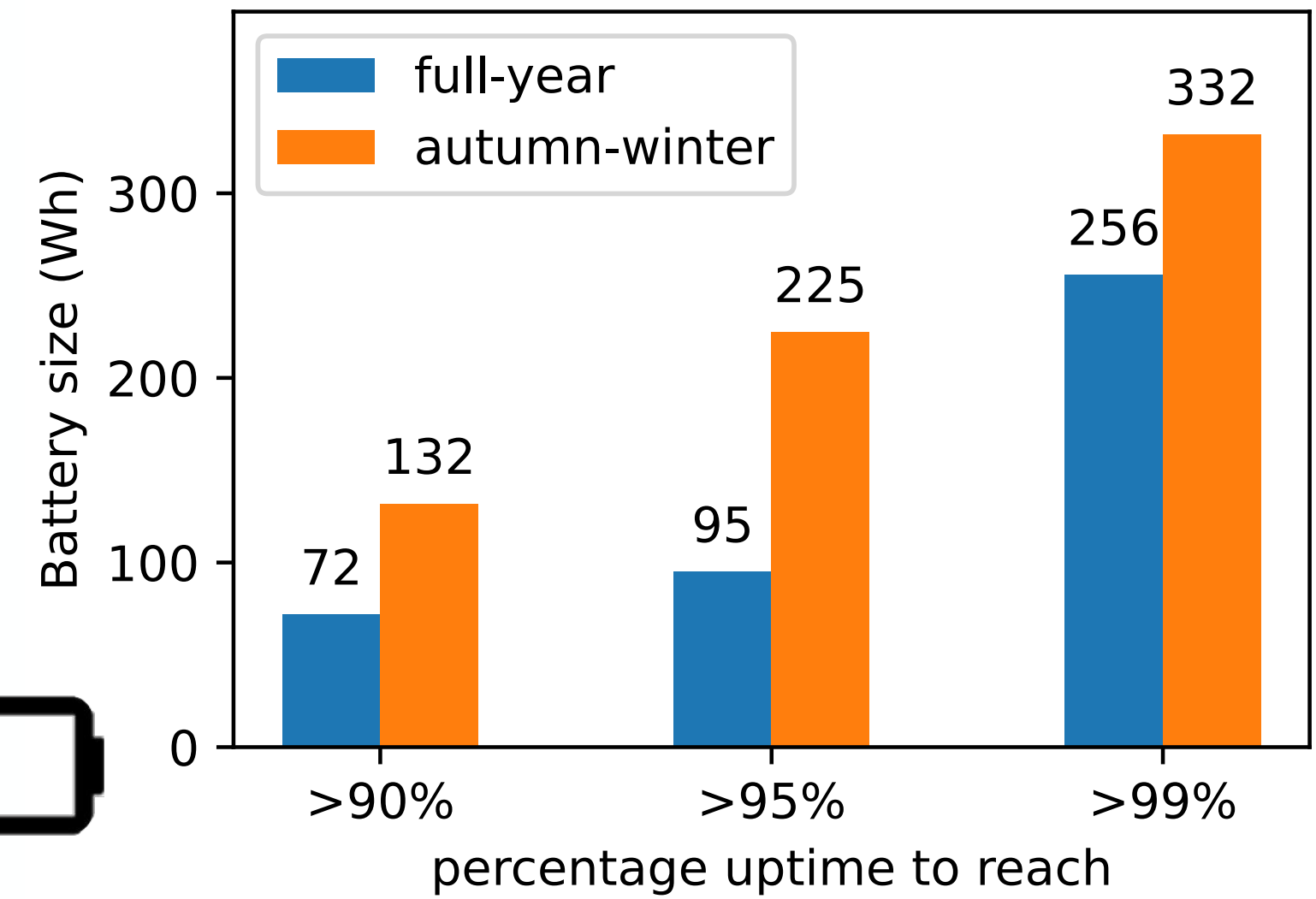
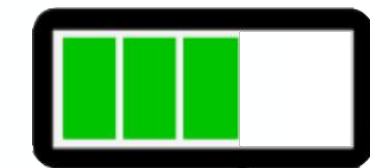
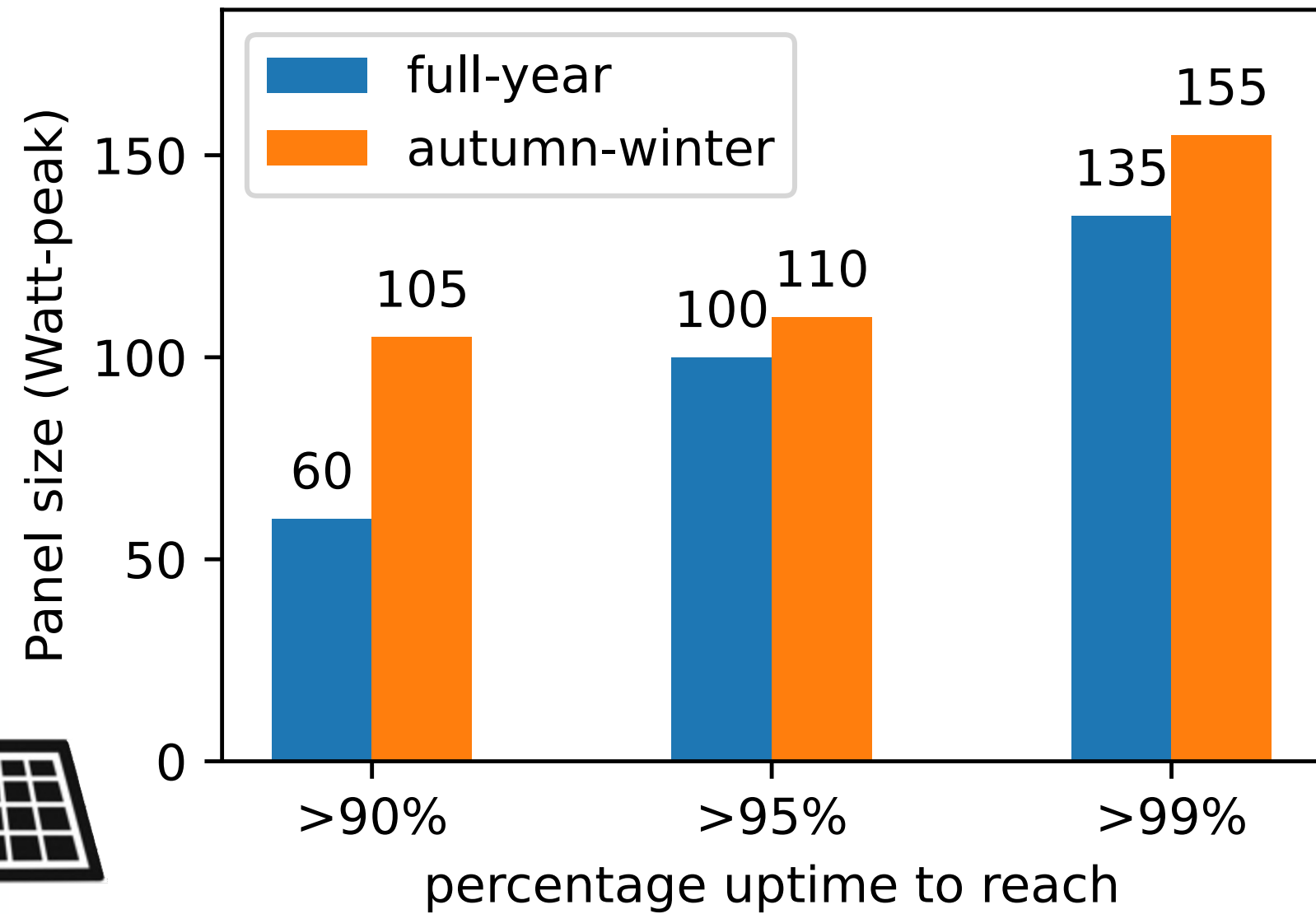
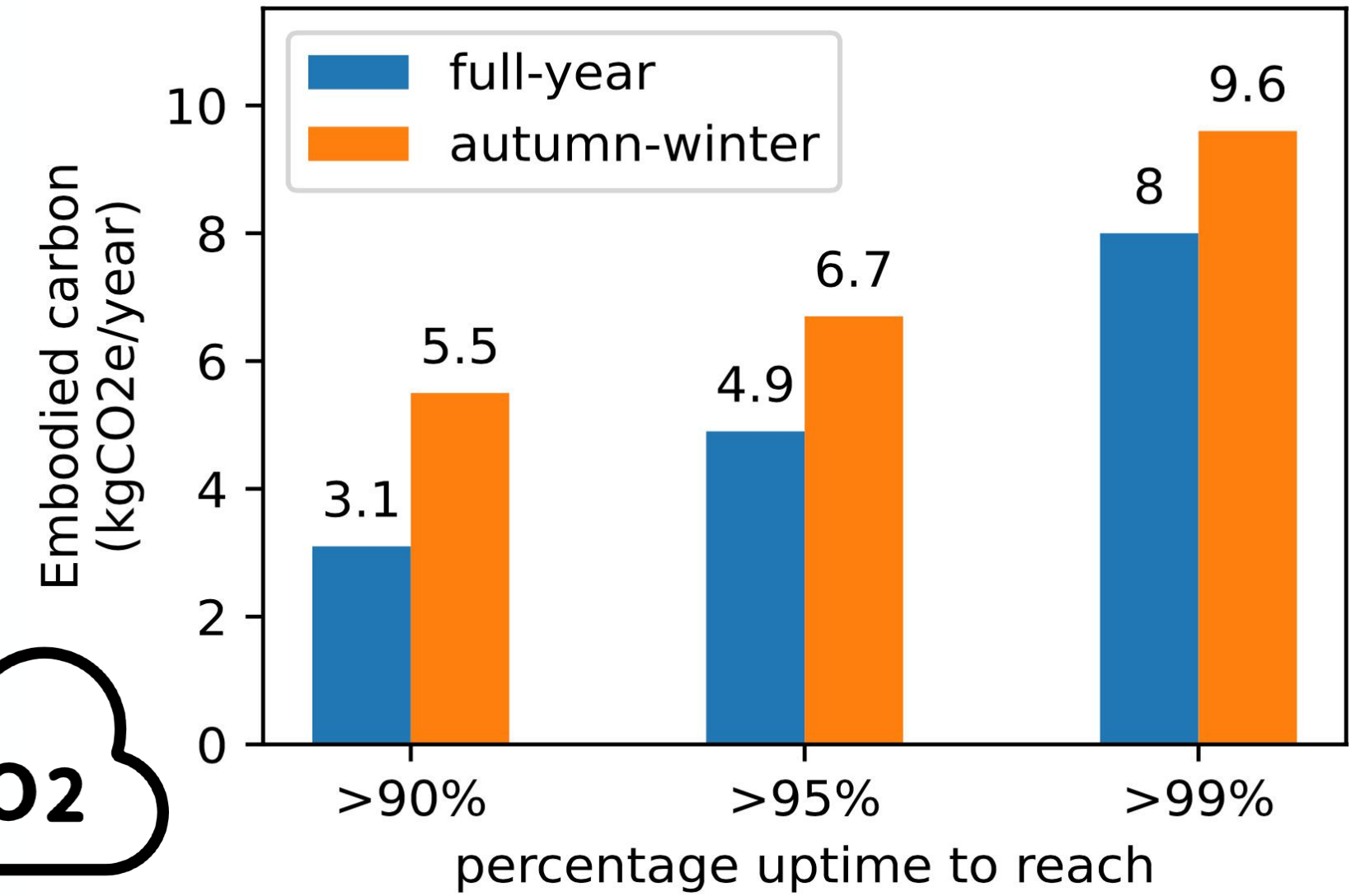
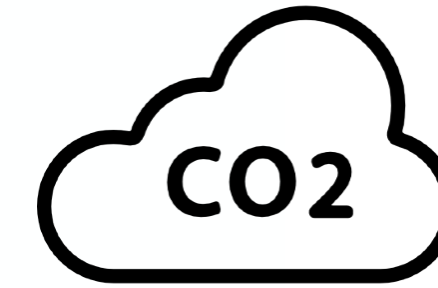


year 2021  
full-year = 365 days

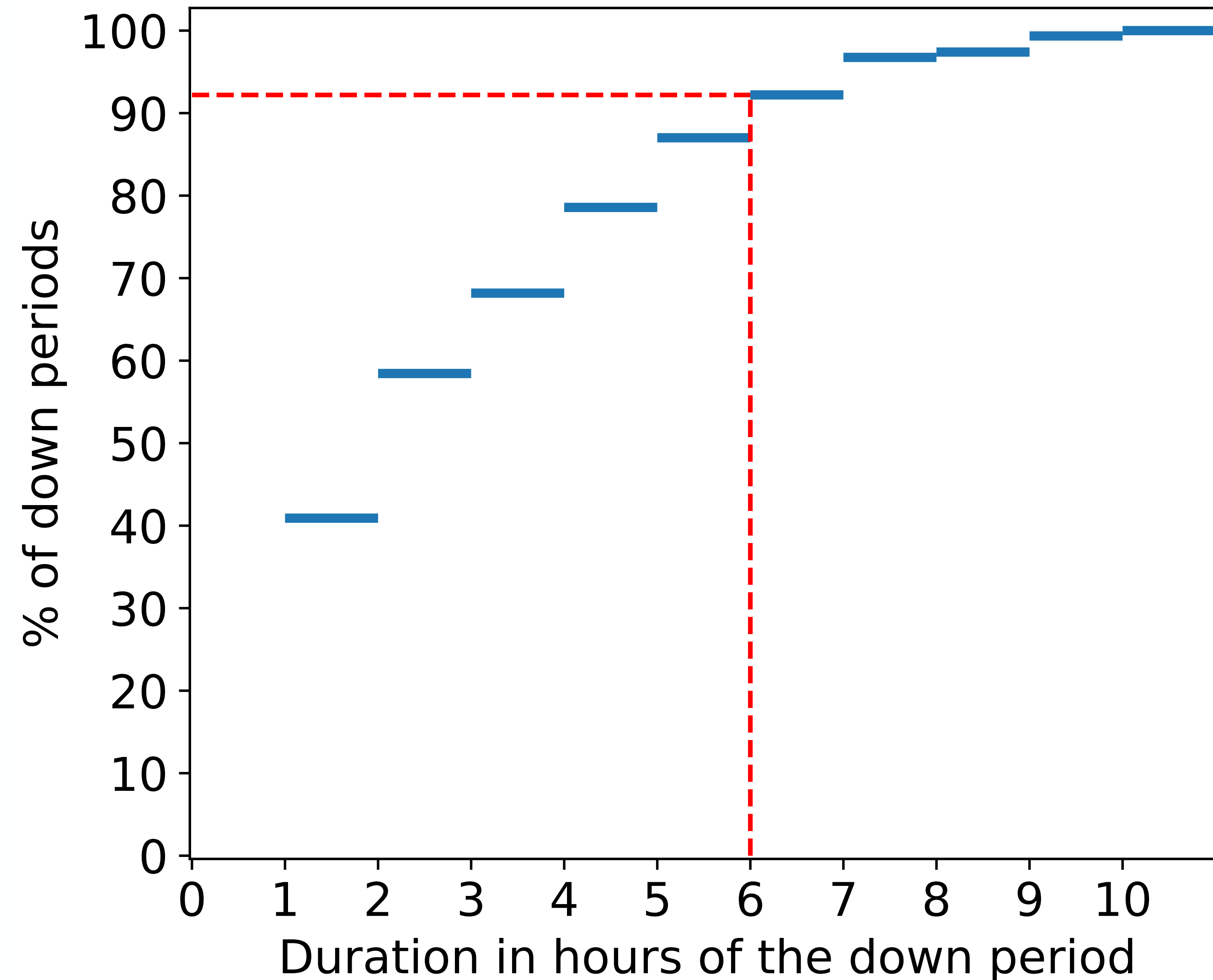
# Results



year 2021  
full-year = 365 days  
autumn-winter =  
October to February



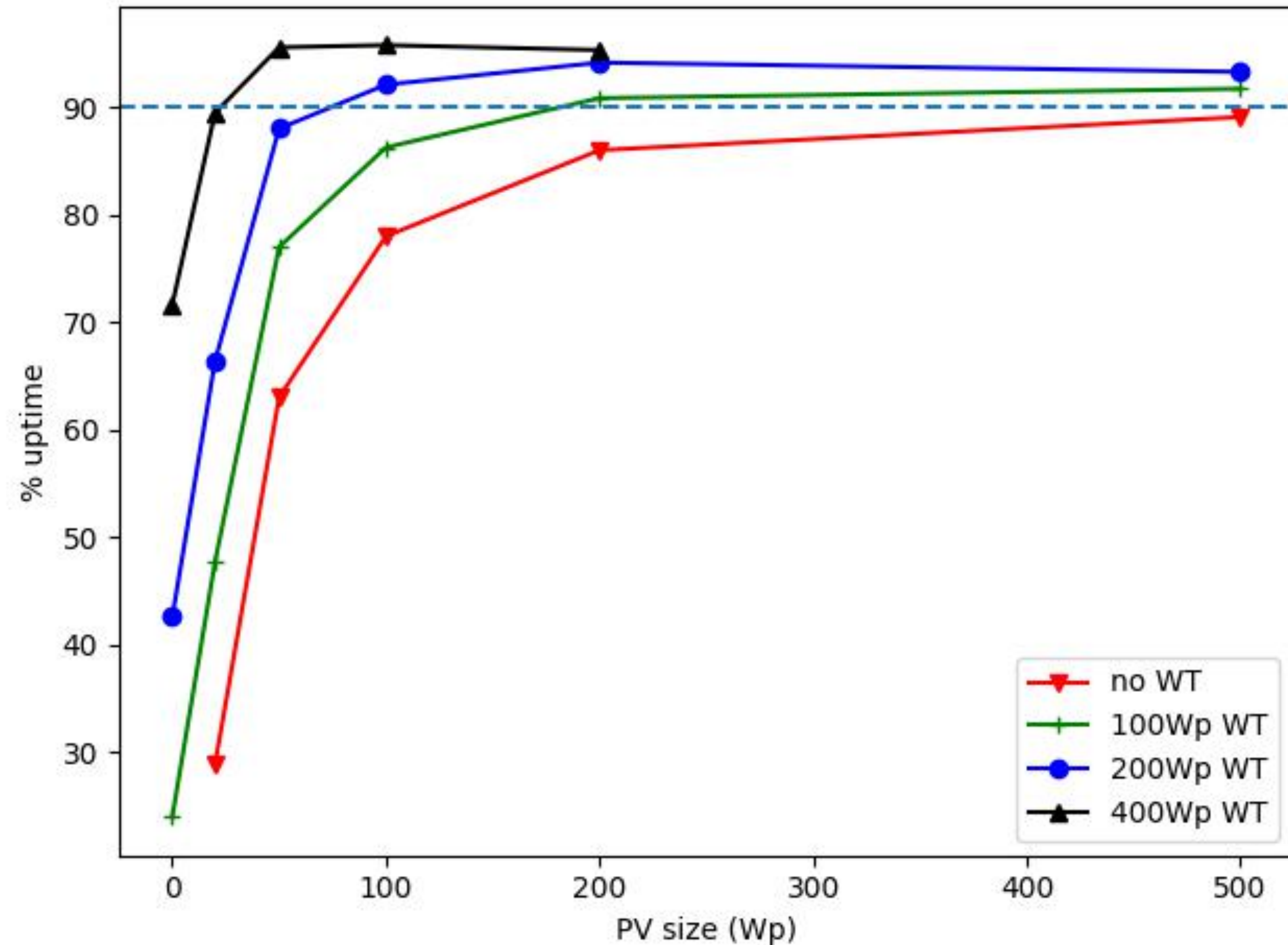
# Cumulative Distribution Function



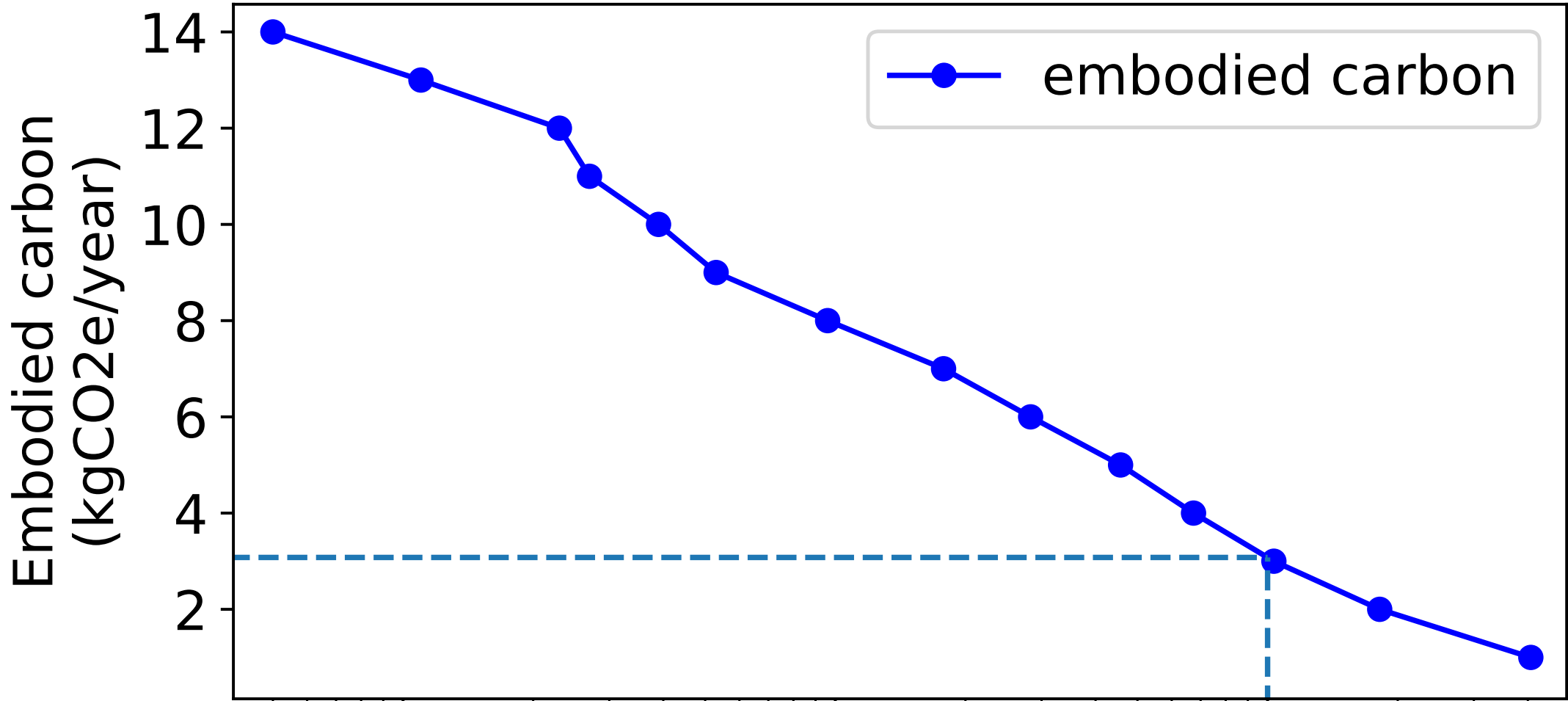
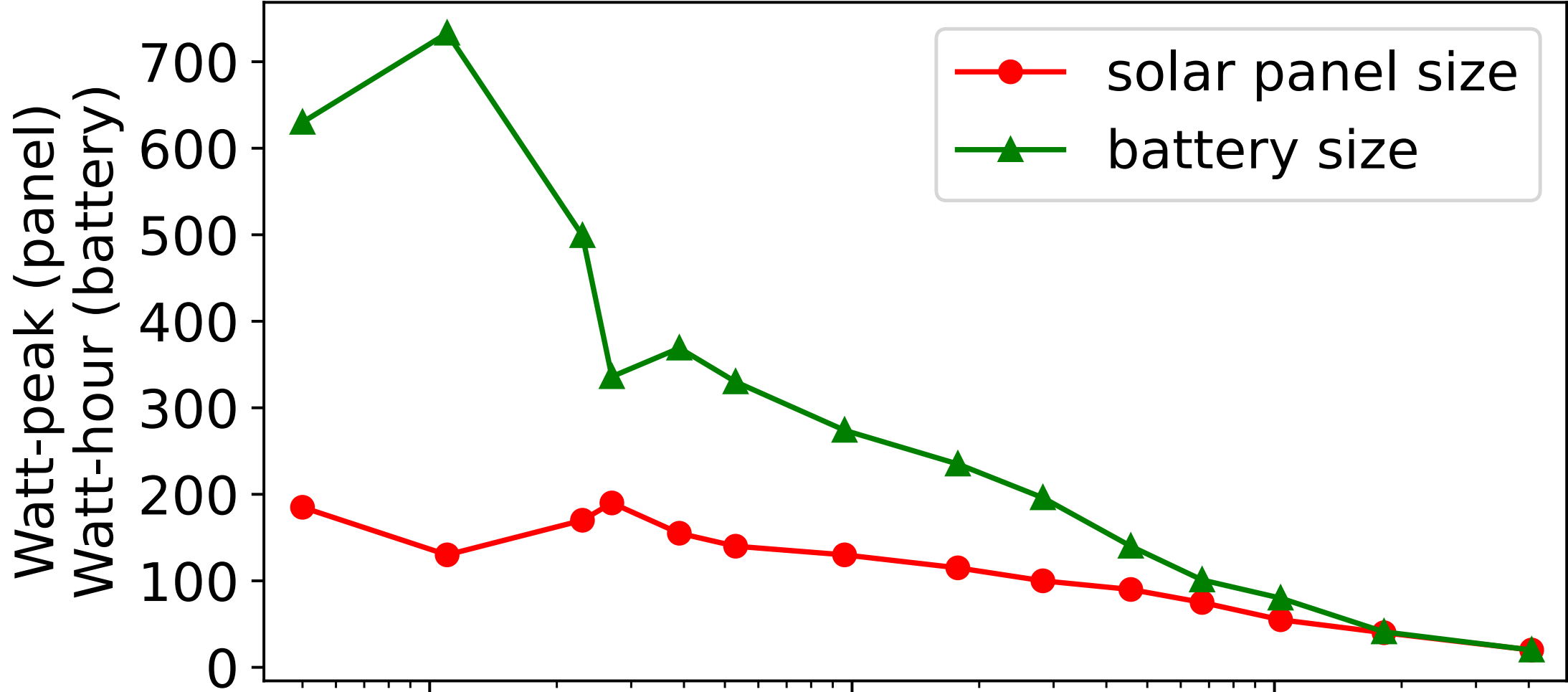
more than 92%  
of the blackouts  
last less than 6  
hours

No blackout last  
more than 11 hours,  
meaning that  
**everyday there is  
at least one  
moment when the  
service is up.**

# Wind turbines can be useful (here in Reykjavik)



# Carbon footprint is exponential with the downtime

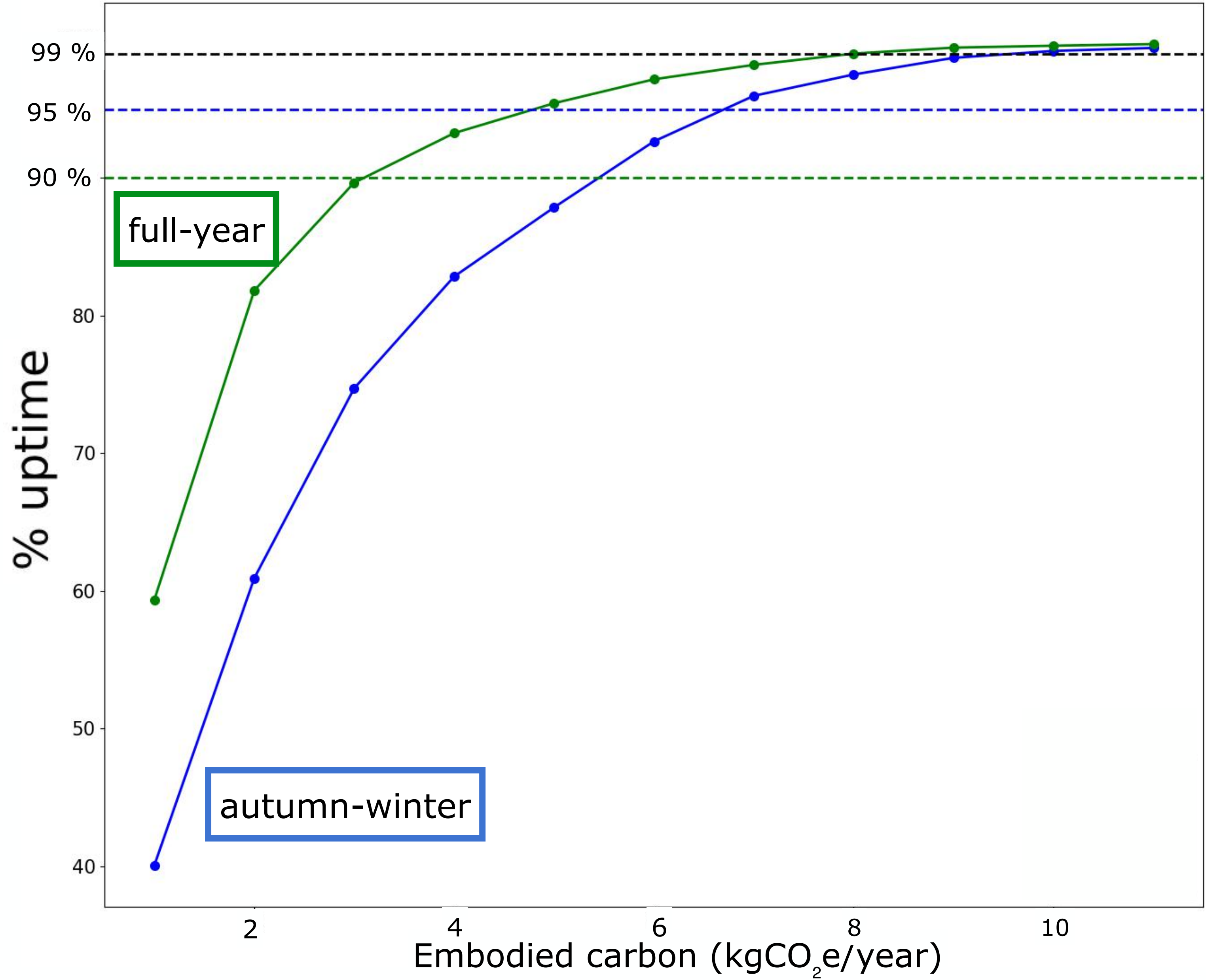


% downtime, logscale

downtime

uptime

# What about winter period ?

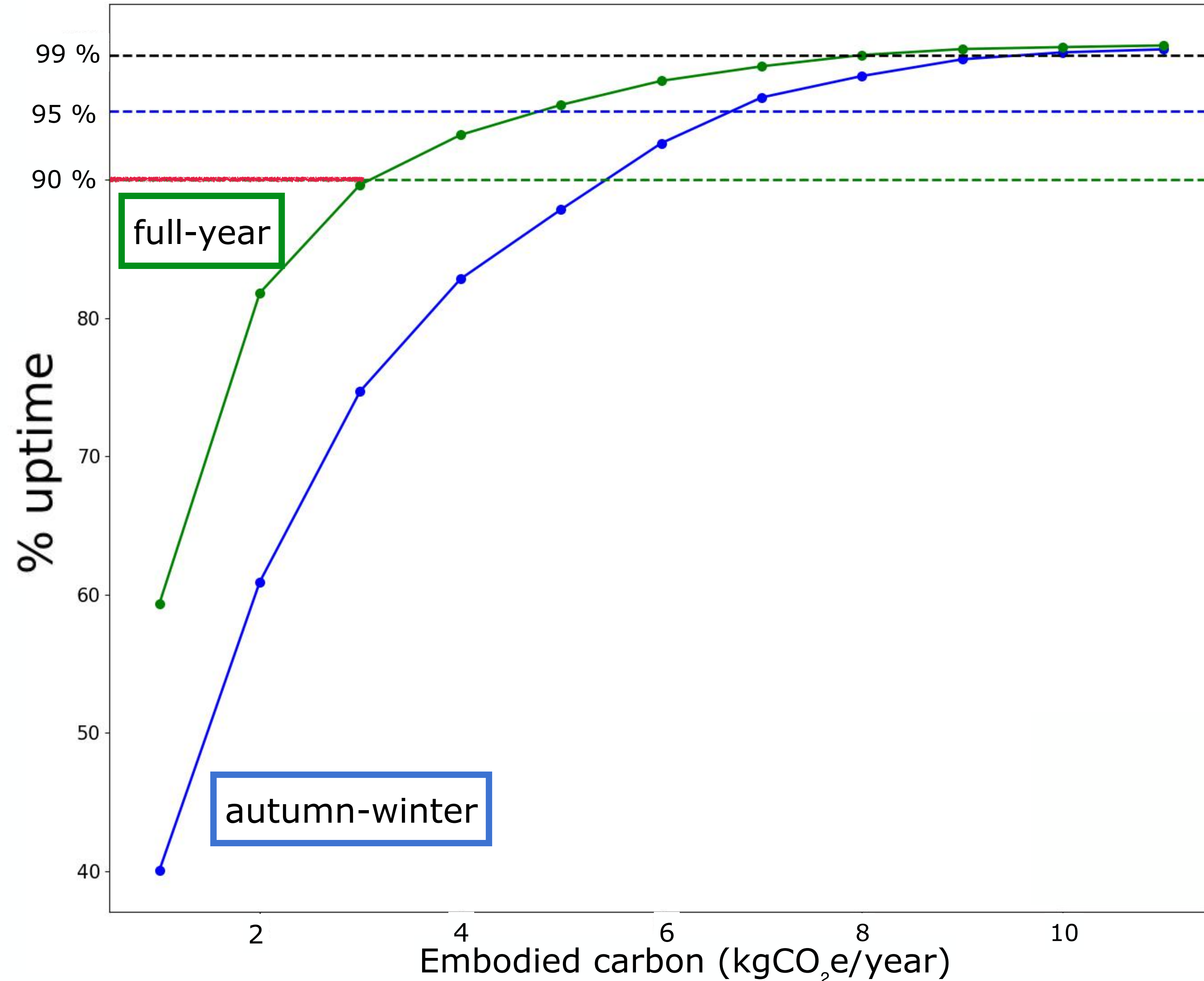


full-year 365 days

autumn-winter 5 months

(Oct, Nov, Dec, Jan, Feb)

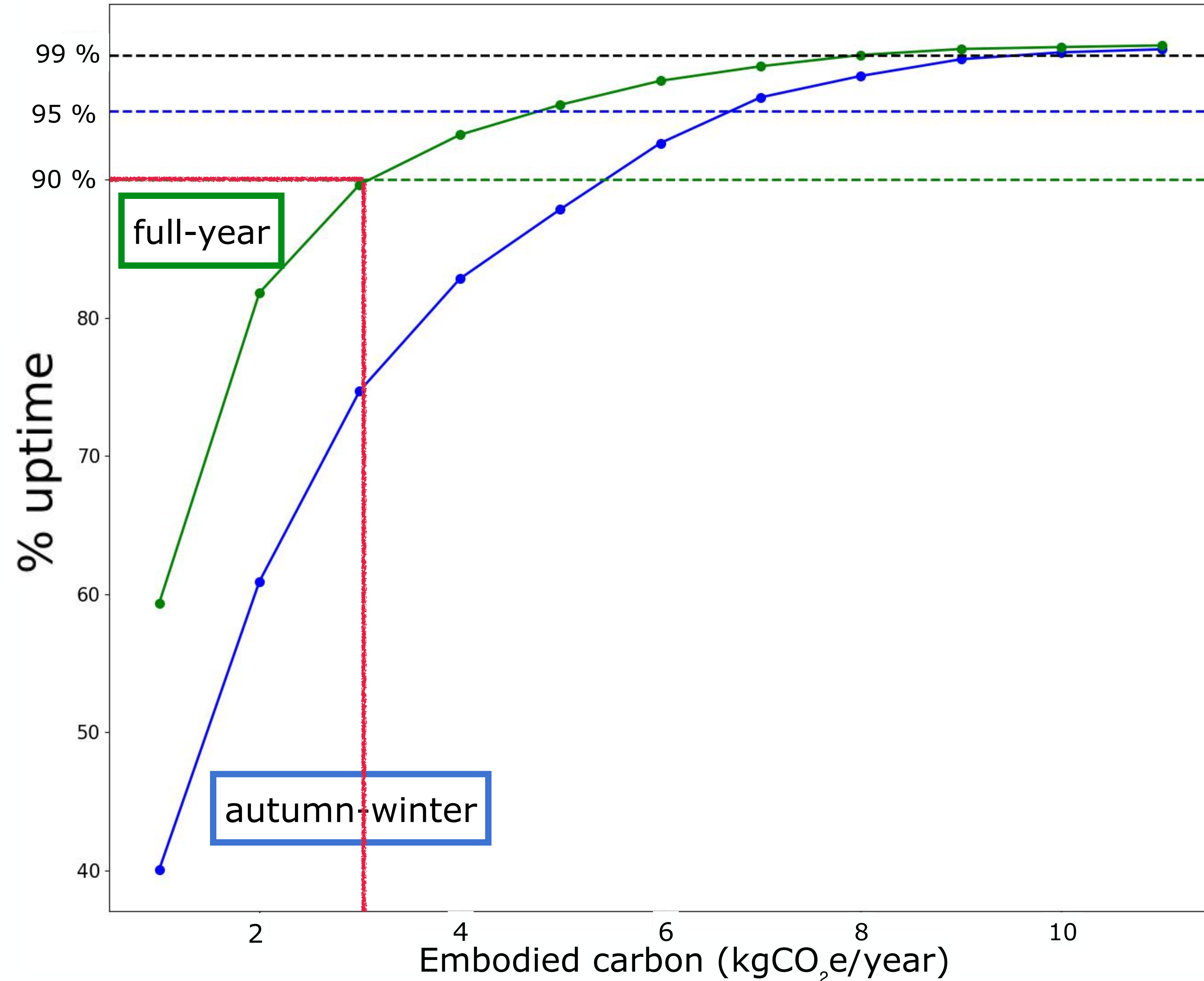
# What about winter period ?



full-year 365 days

autumn-winter 5 months  
(Oct, Nov, Dec, Jan, Feb)

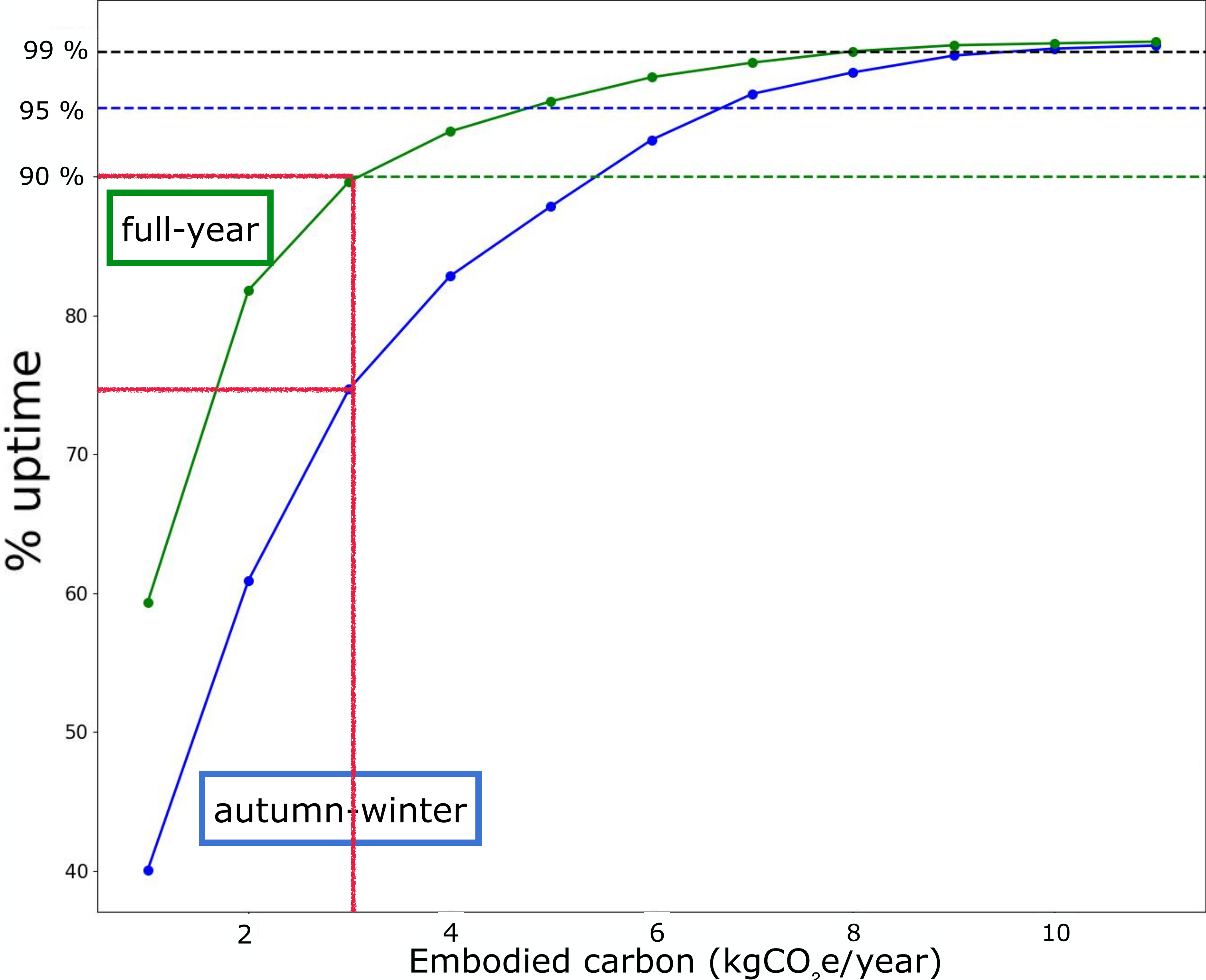
# What about winter period ?



full-year 365 days

autumn-winter 5 months  
(Oct, Nov, Dec, Jan, Feb)

# What about winter period ?

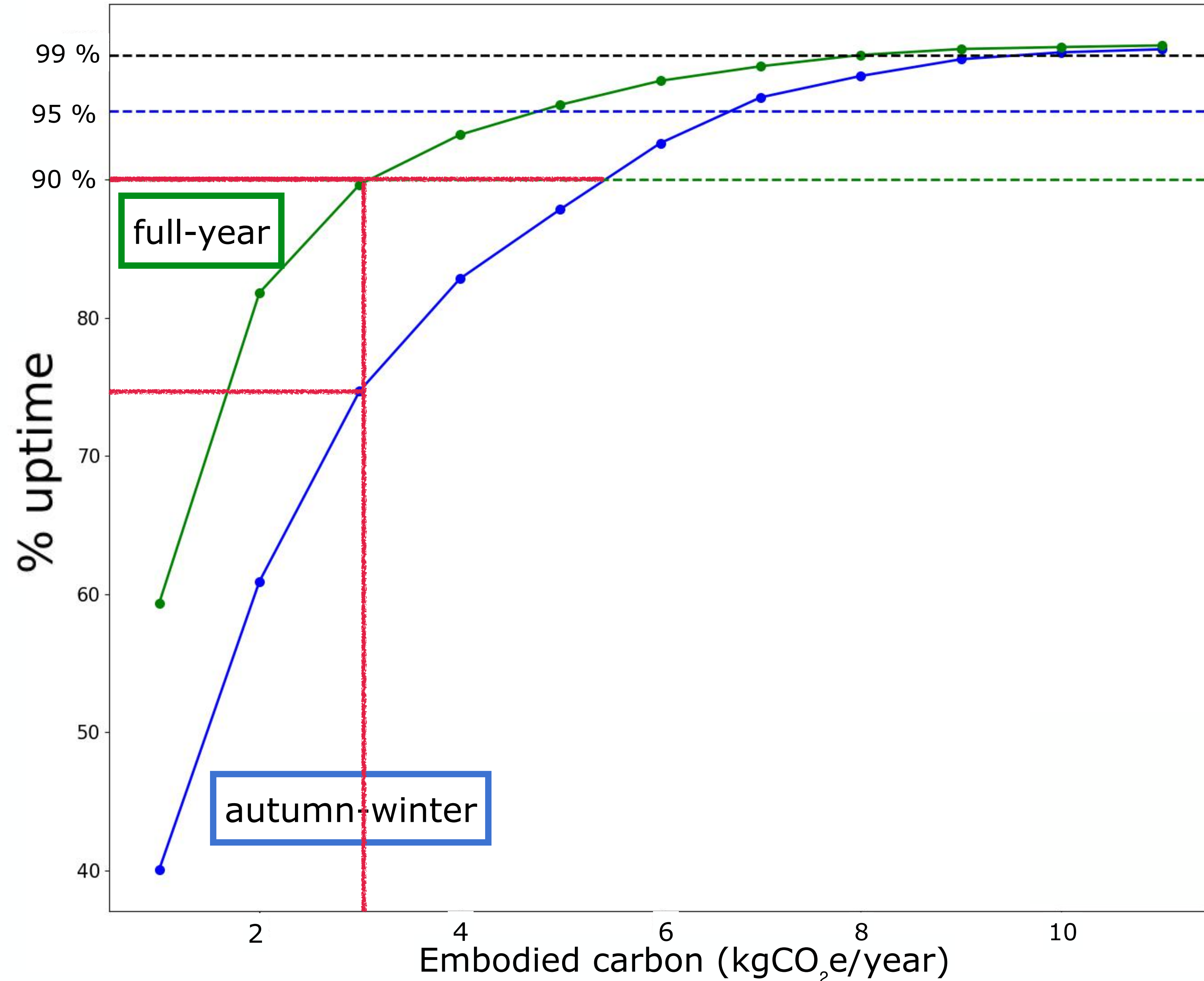


full-year 365 days

autumn-winter 5 months

(Oct, Nov, Dec, Jan, Feb)

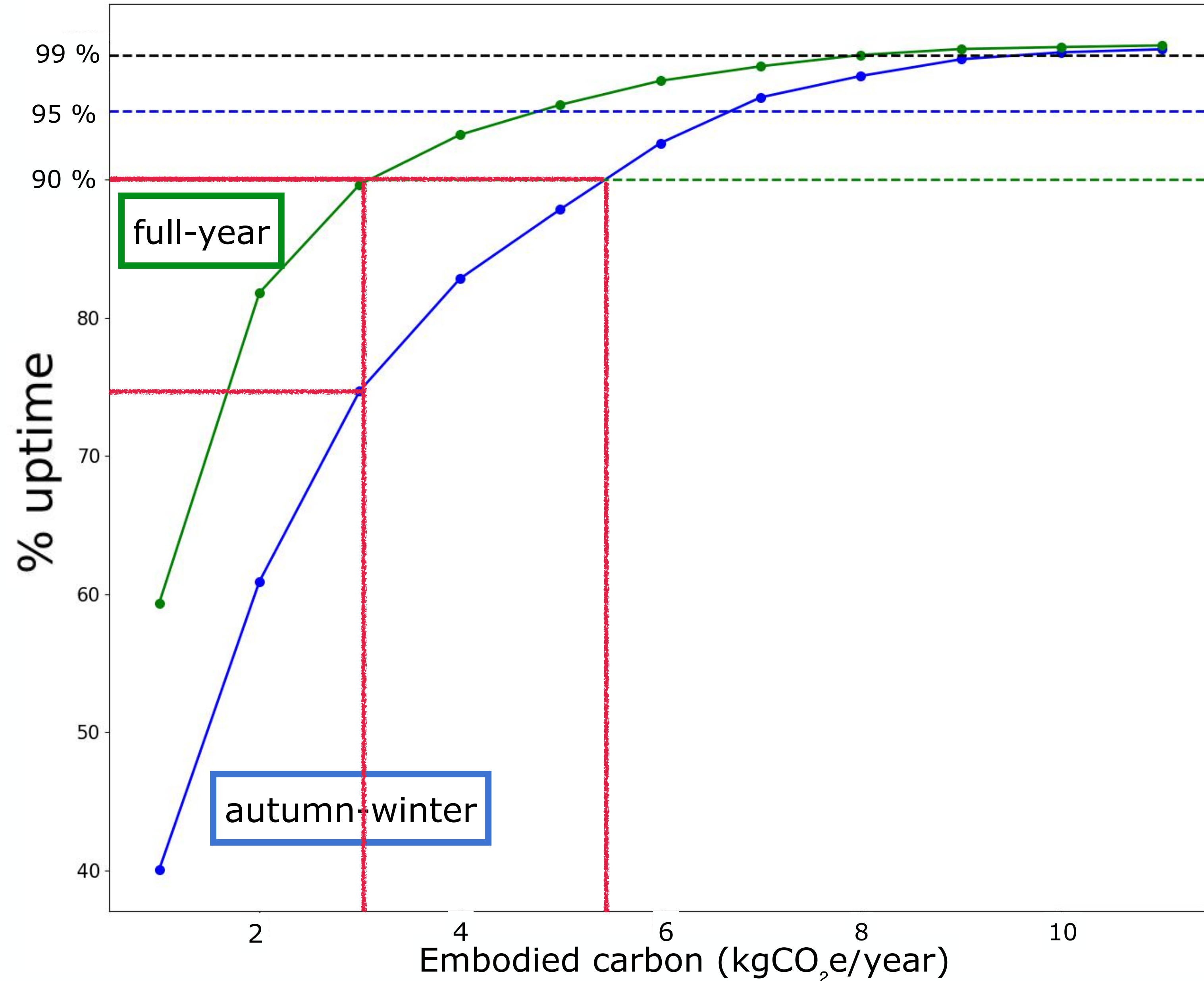
# What about winter period ?



full-year 365 days

autumn-winter 5 months  
(Oct, Nov, Dec, Jan, Feb)

# What about winter period ?

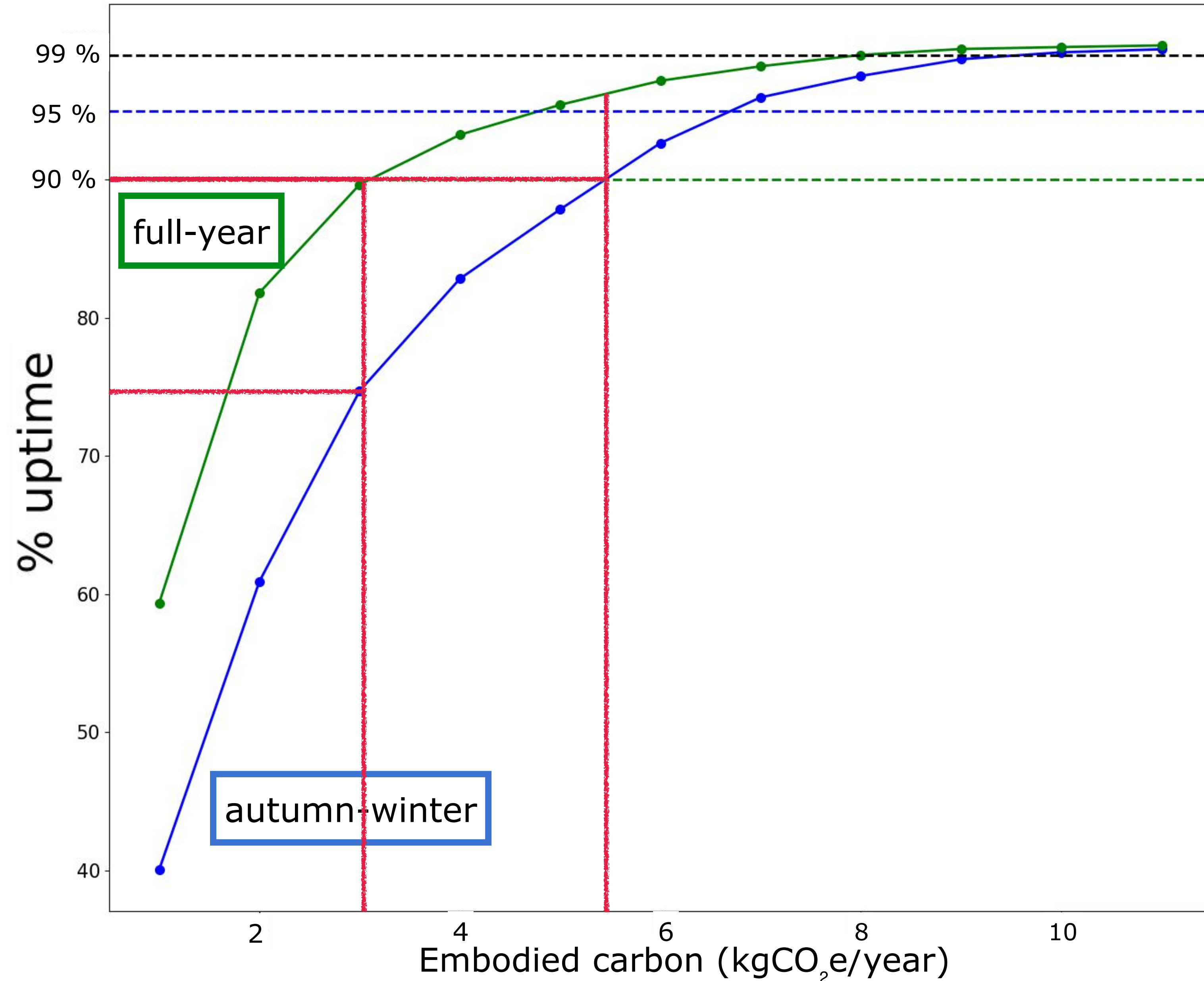


full-year 365 days

autumn-winter 5 months

(Oct, Nov, Dec, Jan, Feb)

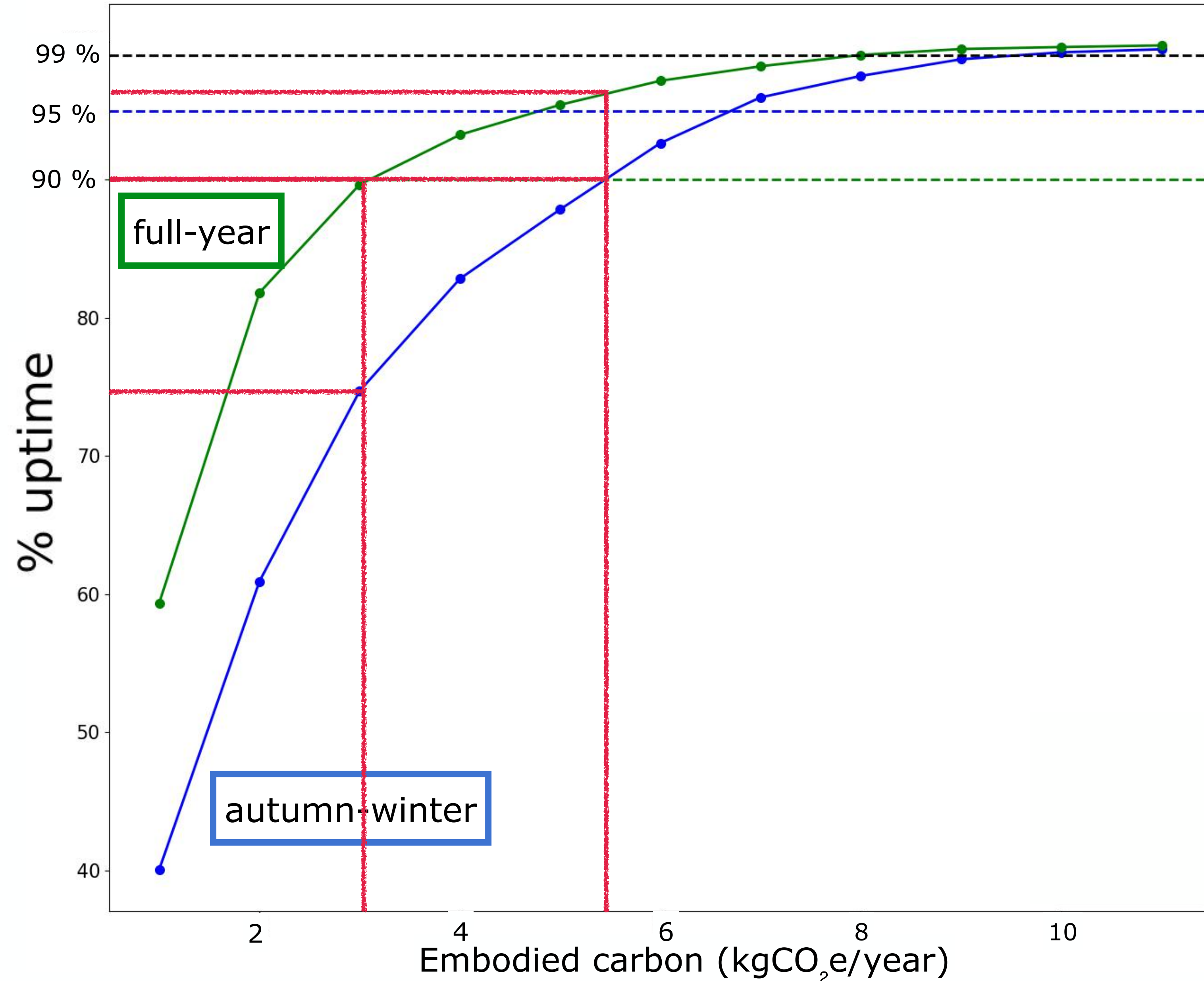
# What about winter period ?



full-year 365 days

autumn-winter 5 months  
(Oct, Nov, Dec, Jan, Feb)

# What about winter period ?



full-year 365 days

autumn-winter 5 months  
(Oct, Nov, Dec, Jan, Feb)

# Turning off servers during the night

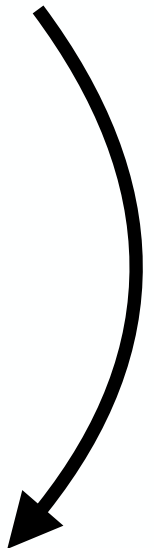
**carbon footprint to reach 90 %**

Work hours	<b>7am - 7pm</b>	3.1 kgCO <sub>2</sub> e/year
	<b>24/7</b>	7.7 kgCO <sub>2</sub> e/year

# Turning off servers during the night

**carbon footprint to reach 90 %**

Work hours	<b>7am - 7pm</b>	3.1 kgCO <sub>2</sub> e/year
	<b>24/7</b>	7.7 kgCO <sub>2</sub> e/year

 x2

...

# Bruxelles, Rennes, Toulouse

global % uptime between 7h-19h (72.16 % - 90.43 %)  
starting from 2021-01-01, for 365 days.

