Facility-specific greenhouse gas footprints of wind and solar power at a global scale

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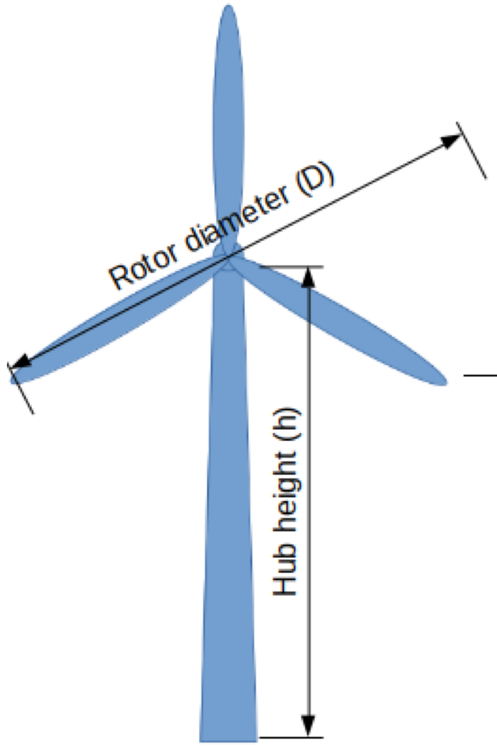
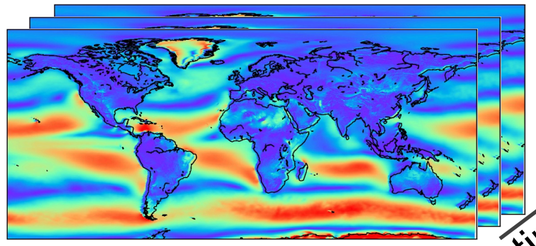
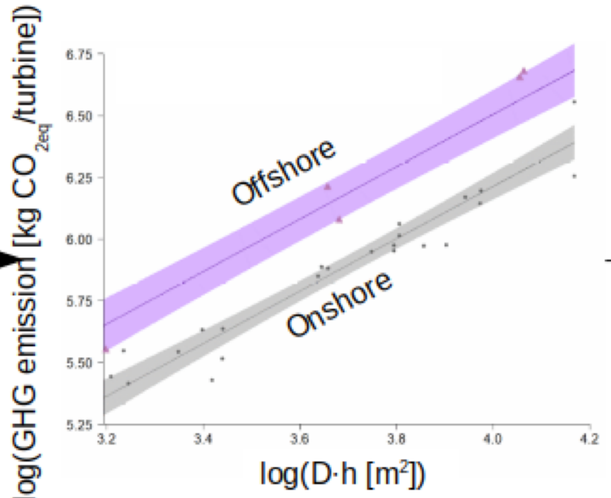
Overview – Wind power



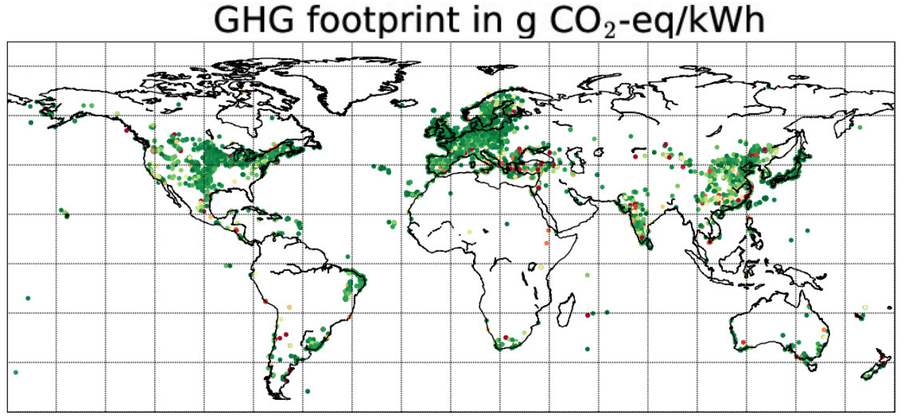
Wind speed 10, 100m



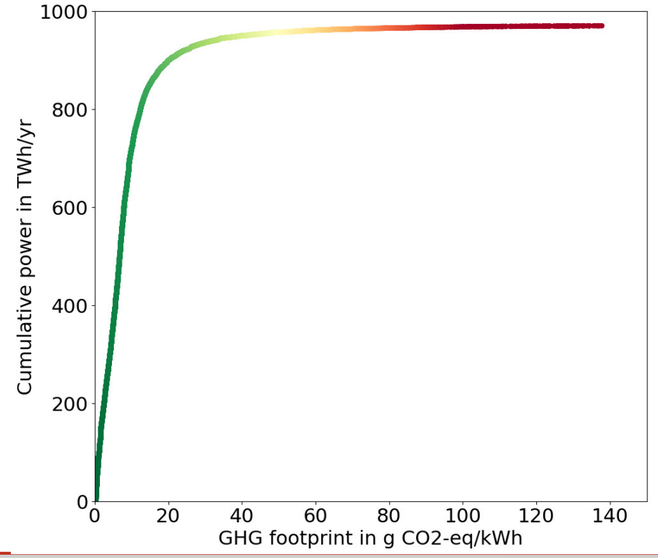
P: Lifetime power production
f (D, h, u_{hub}) [kWh]



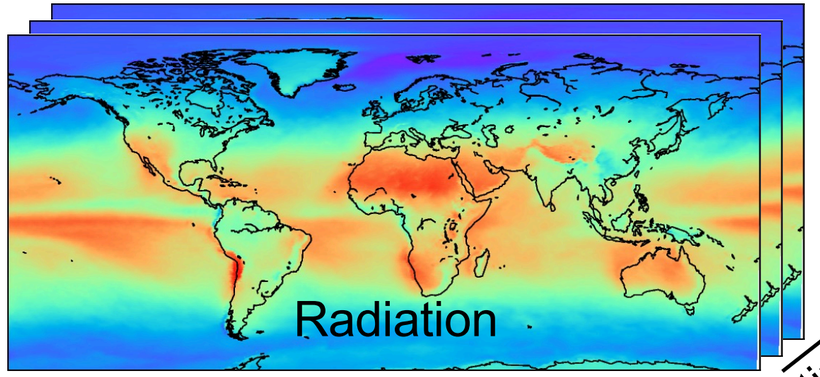
I: Lifetime emissions [g CO_2-eq]

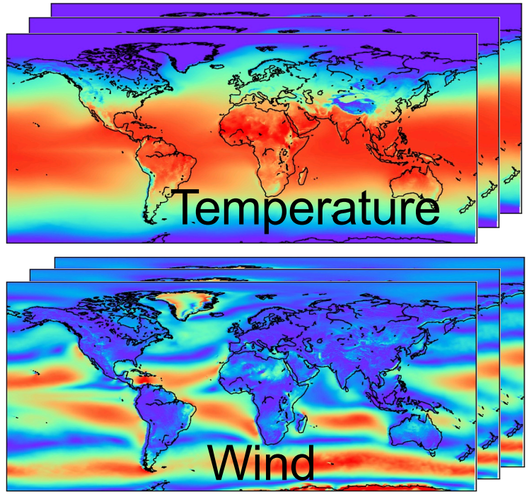


$EF_{GHG} = I / P$



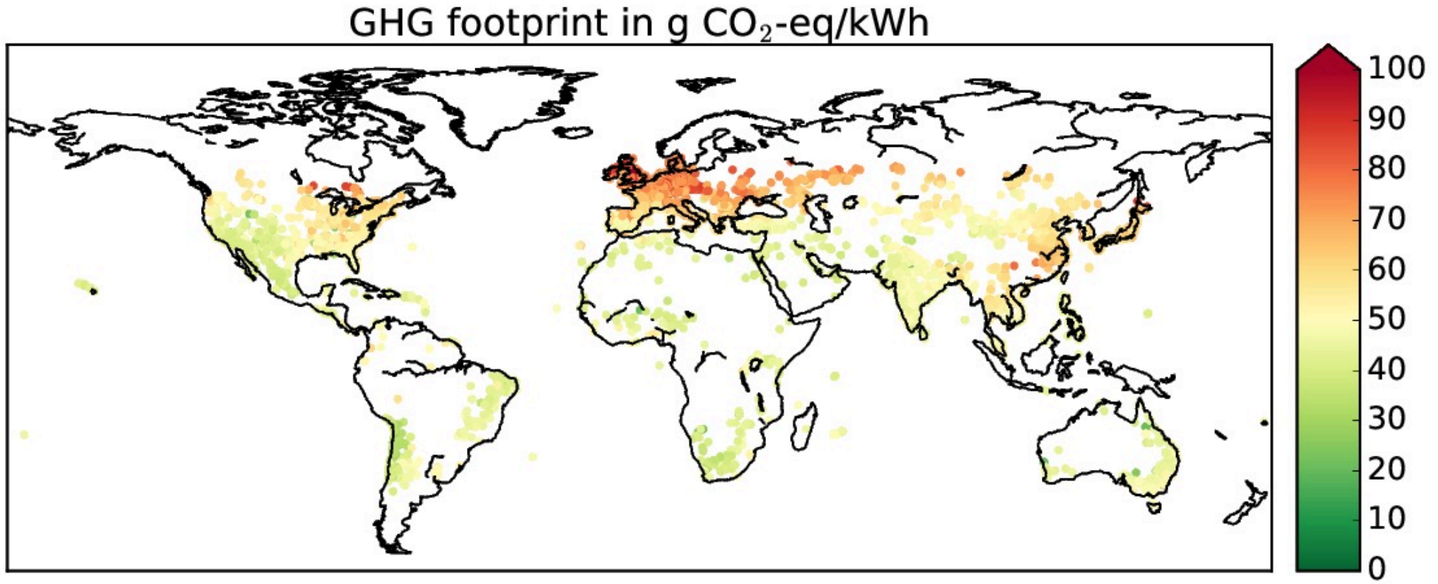
Overview – Utility-scale PV

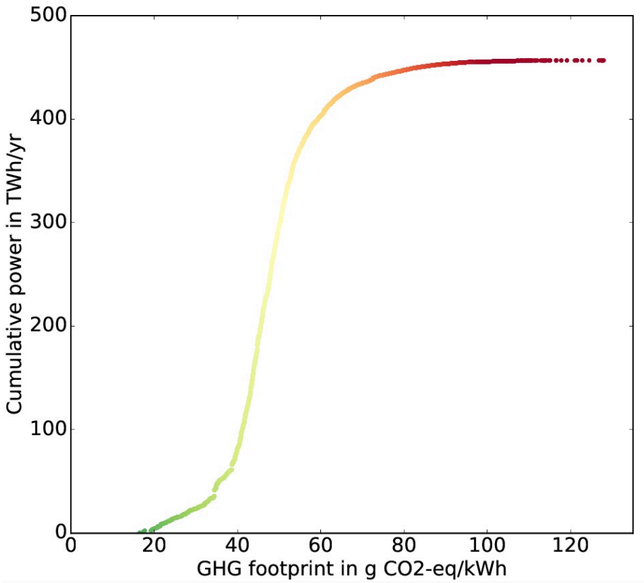




Construction year | Panel type | Capacity | Location

I: Lifetime emissions [g CO_2-eq] → $EF_{GHG} = I / P$ ← *P*: Lifetime power production [kWh]



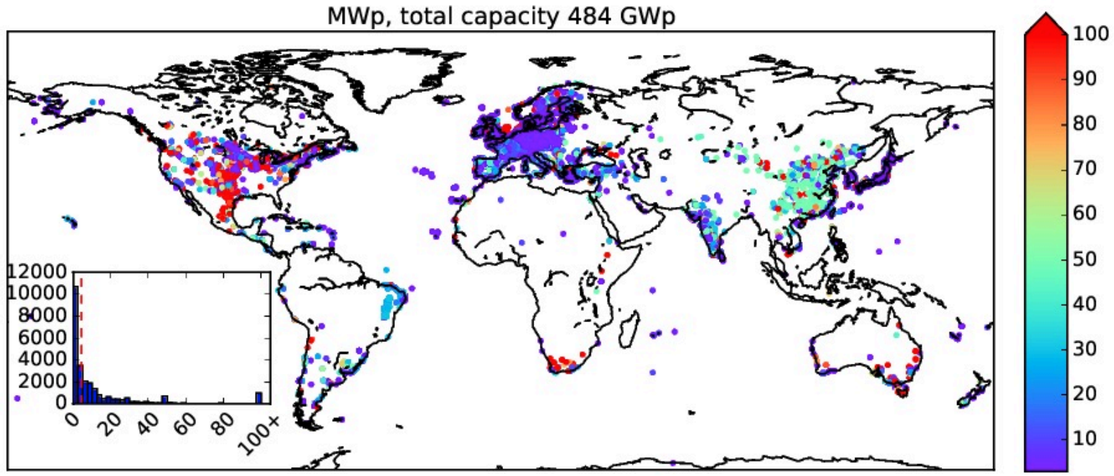


Methods – GHG emissions

Wind

- Windpower.net: 26,730 wind farms
- Hub height, diameter, location

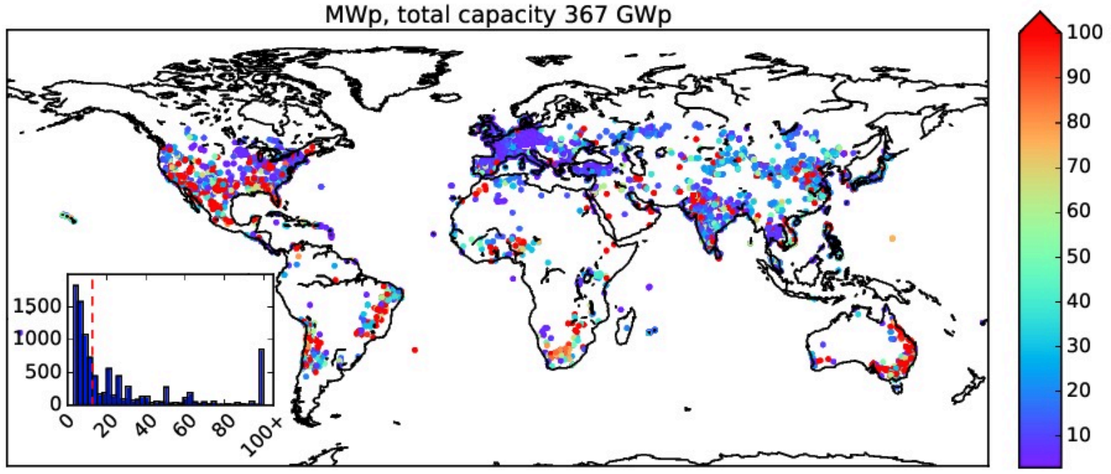
life-cycle GHG emissions per facility



Solar

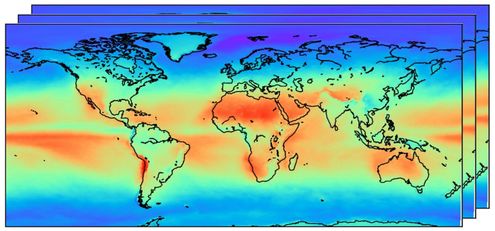
- Wiki-Solar.org: 9,992 utility-scale PV farms
- Year, capacity, panel type, location

life-cycle GHG emissions per facility

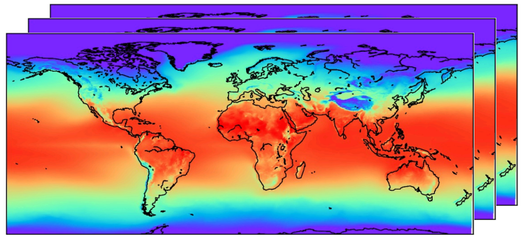


ERA5 reanalysis data, hourly, 0.25°x0.25 °, 1988-2017

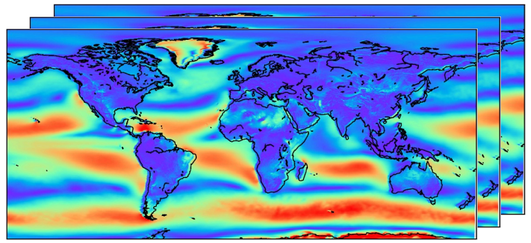
Methods – Power output



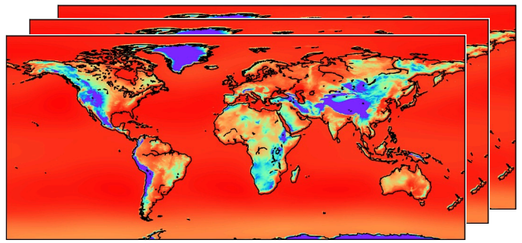
Irradiation



Temperature



Wind speed (10 & 100m)



Surface pressure

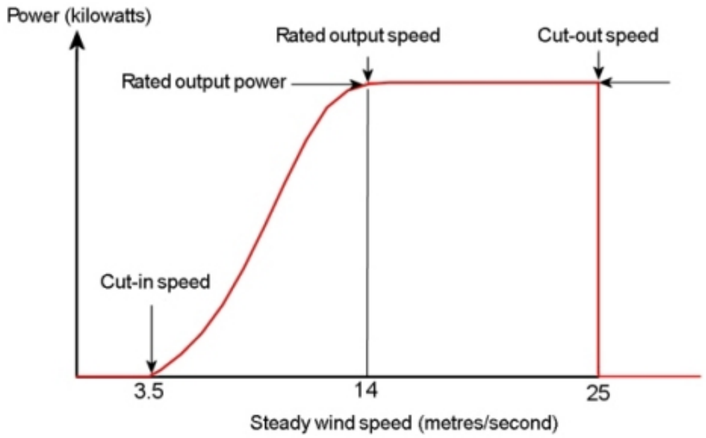
Solar:

- P = f(irr, temp, wind, capacity, panel type)
- Lifetime P (kWh) = $\sum_{1988}^{2017,h} P(t)$
- Loss due to panel degradation:

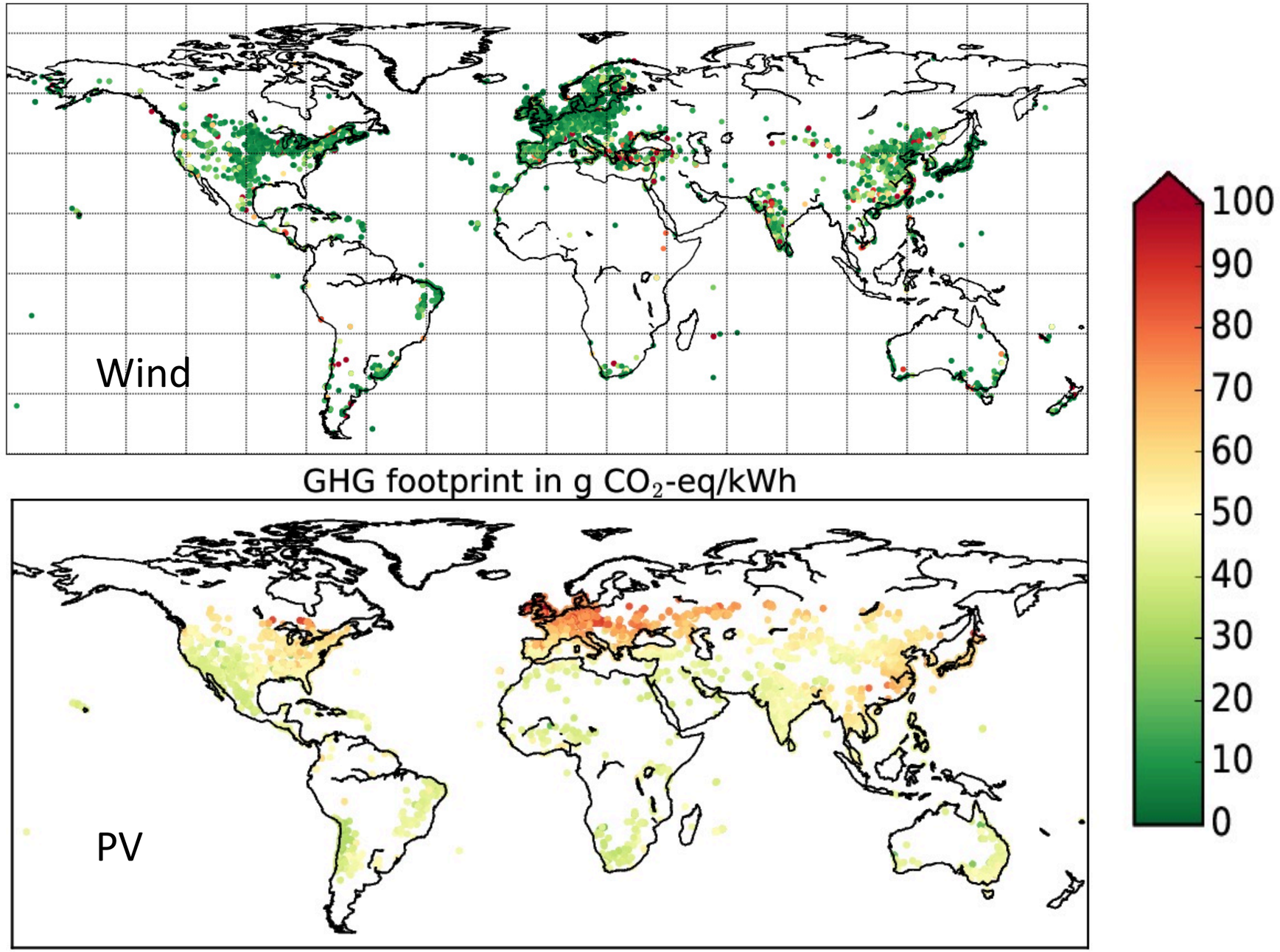
$$f_{\text{loss}} \cdot \sum_{1}^{y,h} P(t)$$

Wind:

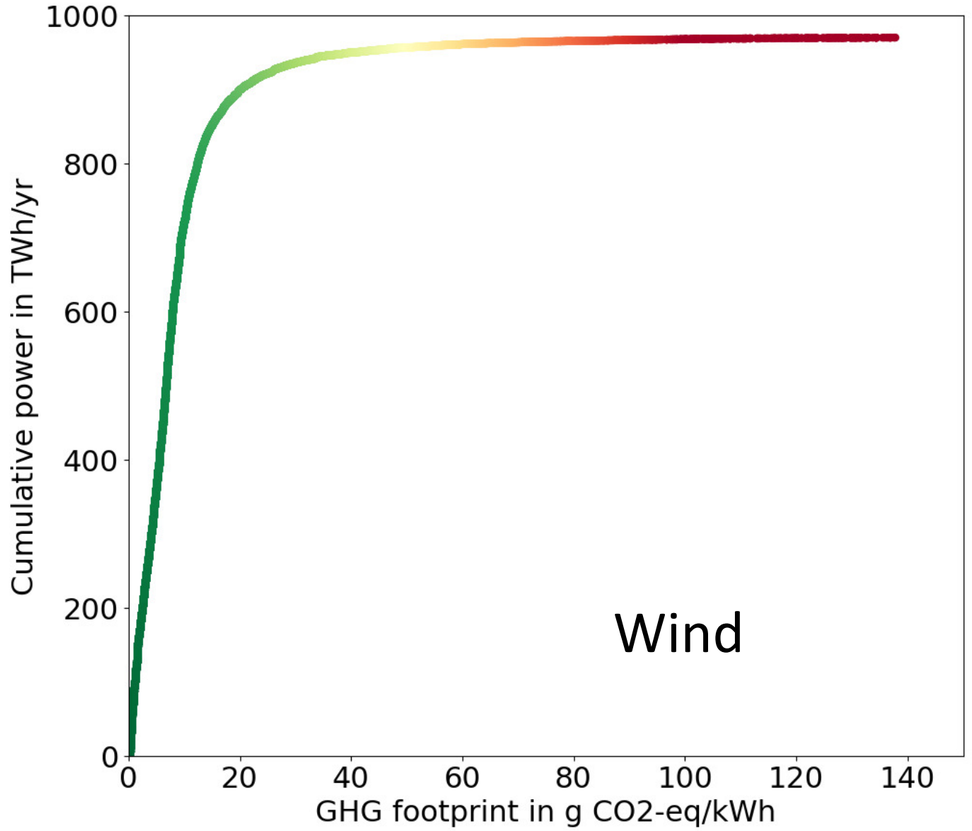
- $u_{hub} = f$ (u_{10}, u_{100}, $\boldsymbol{\rho}_{hub}$, power curve)
- Lifetime P (kWh) = $\sum_{1988}^{2017,h} \sum_{1}^{n_{turbines}} P(u_{hub})$
- Wake effect: $\mu(n_{turbines}) \cdot P$



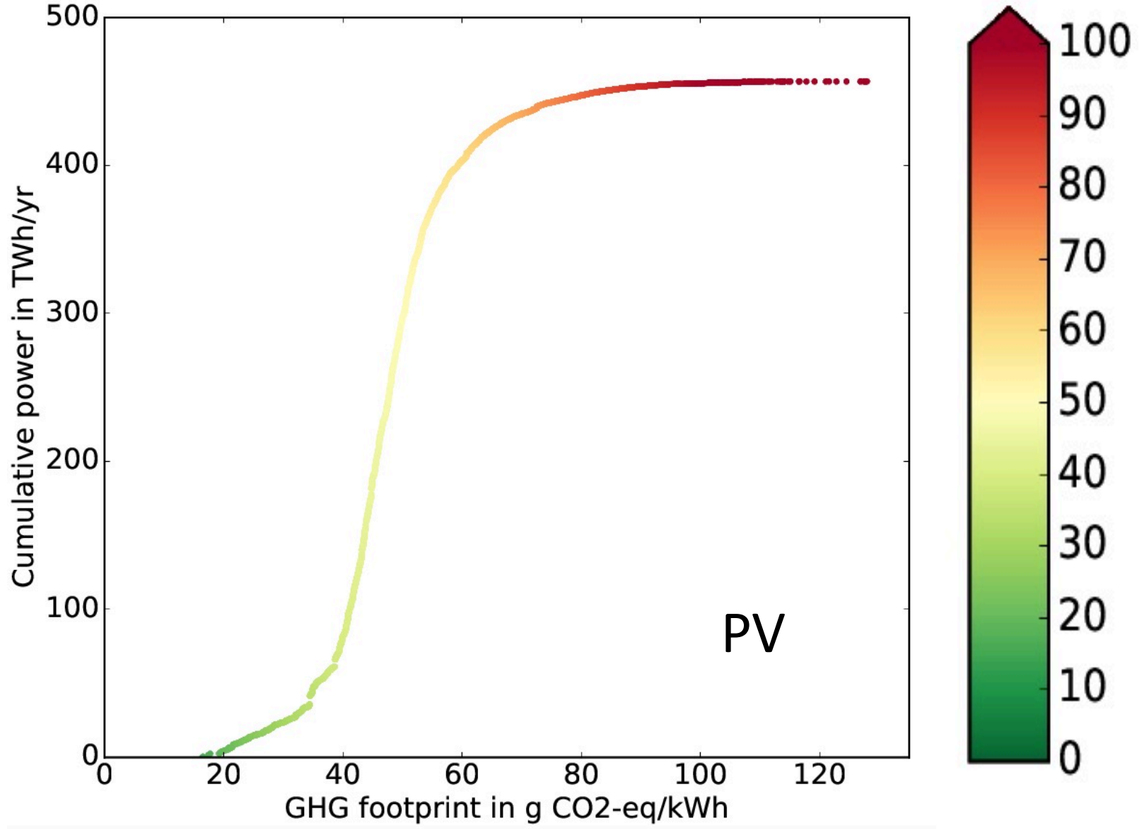
Results – GHG footprints



Results – Cumulative power



- 6.4 [0.7 – 66.5][1] g CO_2-eq /kWh
- 99.1% facilities < 100 g CO_2-eq /kWh



- 56.7 [31.9 – 92.6][1] g CO_2-eq /kWh
- 98.5% facilities < 100 g CO_2-eq /kWh

[1]: 2.5th – 97.5th percentiles

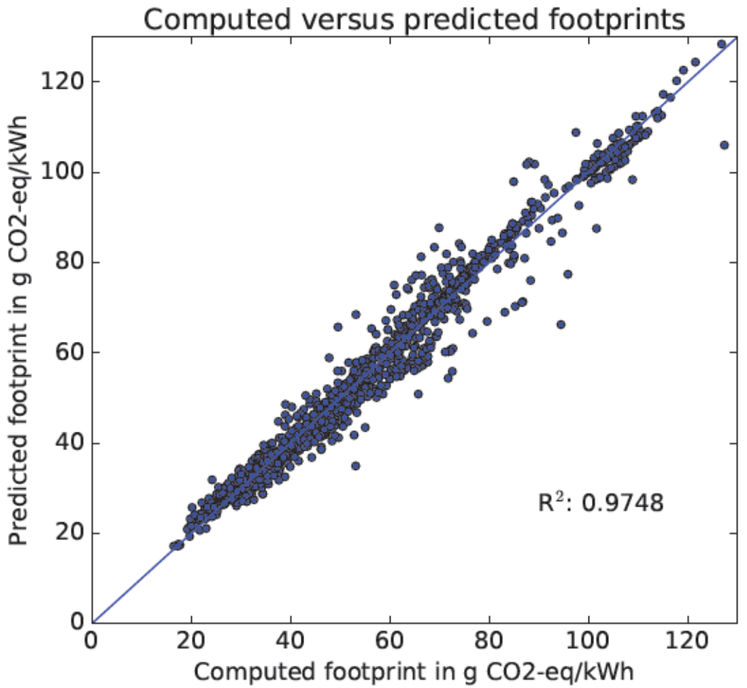
Results – Regression PV

- Linear regression model on PV GHG footprints to find most important predictors
- Best model:

$$EF_{GHG} = 10^{\beta_0} \cdot 10^{\beta_Y Year} \cdot 10^{\beta_{type}} \cdot 10^{\beta_I I_{mean}} \cdot 10^{\beta_T T_{mean}} \cdot 10^{\beta_u u_{mean}} \cdot 10^{\beta_{ICV} I_{CV}}$$

- R^2 = 0.9748, AIC = -5766
- Most important predictors[1]:
  - panel type
  - irradiation

Coefficient	value
β_0	1.739
β_Y	-0.050
β_{type}, mono-Si	0.080
β_{type}, poly-Si	0.036
β_{type}, CdTe	-0.180
β_{type}, CI(G)S	-0.045
β_{type}, a-Si	0
β_I	-0.095
β_T	0.010
β_u	-0.003
β_{ICV}	0.009



[1]Also based on randomizing predictors

Summary and Outlook

- Utility-scale PV: 56.7 [31.9-92.6][1] g CO_2-eq/kWh
- Wind farms: 6.4 [0.7-66.5][1] g CO_2-eq/kWh
- Footprints are much lower than for fossils[2]:
  - coal: ~ 800-900 g CO_2-eq/kWh
  - gas: ~ 500 g CO_2-eq/kWh
  - with CCS: ~ 200-260 g CO_2-eq/kWh

- Panel type and irradiation most important predictors of PV GHG footprint

- Footprints of future facilities:
  - lower lifecycle emissions?
  - higher lifetime power output?
  - effect of climate change on power output?
- Other impact categories:
  - metal depletion / resource scarcity?

Thanks for your interest! I look forward to the chat session, and feel free to email me at:
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[1]: 2.5th – 97.5th percentiles

[2]: Hertwich et al, 2015, PNAS