Supporting Information

Resourcing the fairytale country with wind power: a dynamic material flow analysis

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1. Lifetime distribution

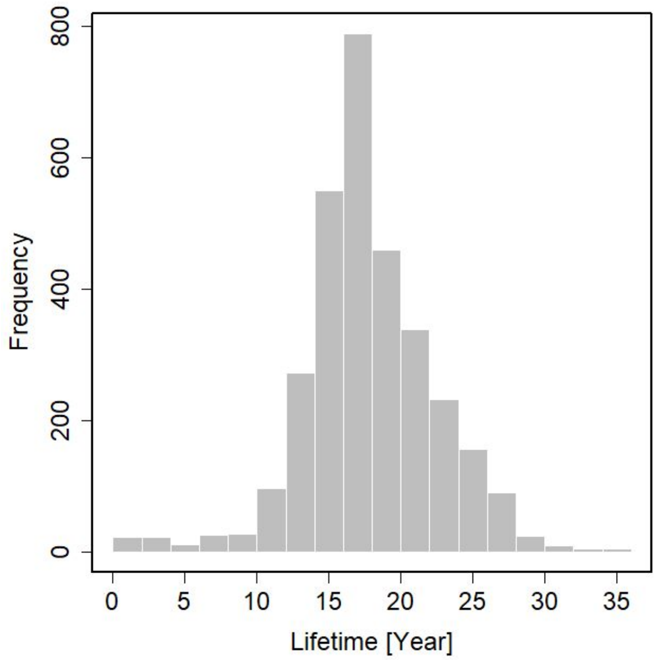


Figure S1. Lifetime dstribution of wind turbines derived from the decommissioned wind turbines' lifetime.

2. Uncertainties in lifetime distribution and empirical regressions

Table S1. Statistical uncertainties in lifetime distribution.

	Parameter/ coefficient	Onshore estimate (std. error)	Offshore estimate (std. error)
Lifetime: $\boldsymbol{S_{t-t'}} = \frac{\kappa}{\lambda}(\frac{t-t'}{\lambda})^{\kappa-1} e^{-(\frac{t-t'}{\lambda})^{\kappa}}$	Scale (λ)	19.48 (0.09)	19.48 (0.09)
	Shape (k)	4.07 (0.05)	4.07 (0.05)

Table S2. Statistical uncertainties in empirical regressions.

Regression	Parameter/ coefficient	Onshore			Offshore		
		Estimate	Std. error	p-value	Estimate	Std. error	p-value
Capacity (C) versus Rotor Diameter (D): $\boldsymbol{D = aC^b}$	Constant (a)	1.9137436	0.019089336	0.000	0.9465624	0.041687867	0.000
	Exponent (b)	0.4908309	0.001517153	0.000	0.5872416	0.005668181	0.000
Capacity (C) versus Hub Height (H): $\boldsymbol{D = aH^b}$	Constant (a)	3.5582026	0.037550605	0.000	5.0678762	0.52263451	0.000
	Exponent (b)	0.3906782	0.001596508	0.000	0.3372751	0.01327258	0.000

Rotor Diameter (D) versus Rotor Weight (W_D): $W_D = a\ D^b$	Constant (a)	0.005103532	0.0008179673	0.000	0.003501329	0.001456135	0.024
	Exponent (b)	2.013795269	0.0394237953	0.000	2.141169196	0.090727487	0.000
Rotor Diameter (D) versus Nacelle Weight (W_N): $W_N = a\ D^b$	Constant (a)	0.03538216	0.005330698	0.000	0.009089909	0.006908406	0.195
	Exponent (b)	1.69079068	0.037665550	0.000	2.045599174	0.164827460	0.000
Product of Swept Area (D^2) and Hub Height (H) versus Tower Weight (W_T): $W_T = a\ (D^2 \times H)^b$	Constant (a)	0.01755028	0.003942973	0.000	0.01755028	0.003942973	0.000
	Exponent (b)	0.68387935	0.019340208	0.000	0.68387935	0.019340208	0.000

3. Mass intensities of wind turbine components

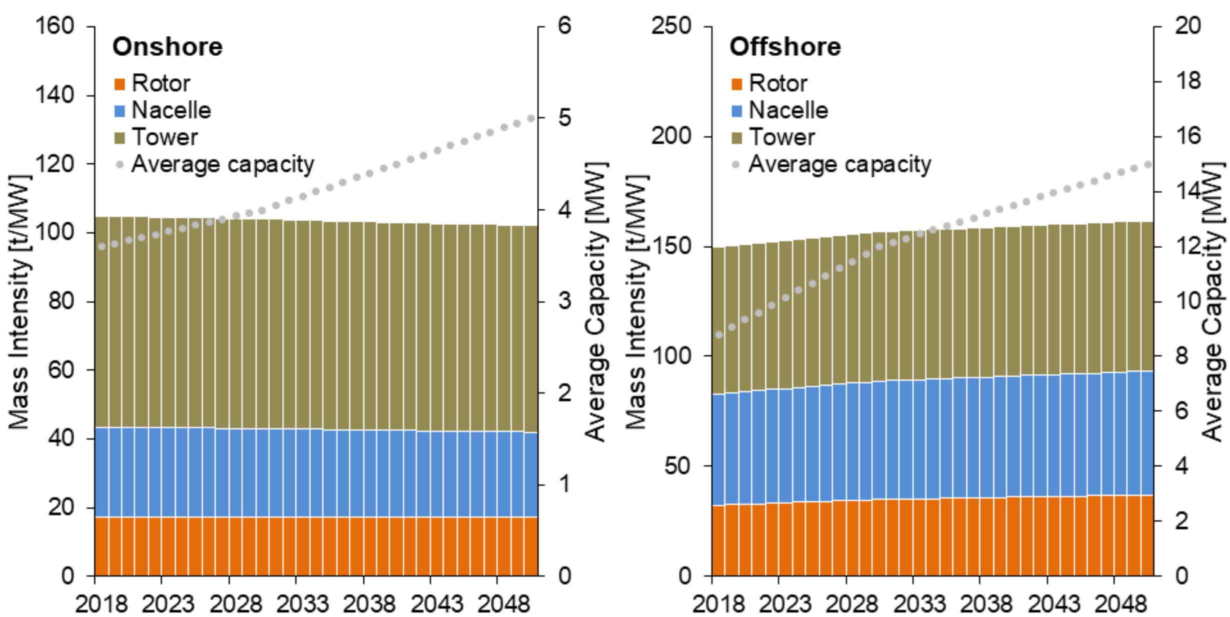


Figure S2. Mass intensities of wind turbine components corresponding to the average capacity of wind turbines over time. Note: mass presented here only includes three components, i.e., rotor, nacelle, and tower.

4. Material intensities of wind energy systems

We collected 20 LCA reports conducted by Vesta Sustainability, which can be accessed via the following link: https://www.vestas.com/en/about/sustainability#!available-reports.

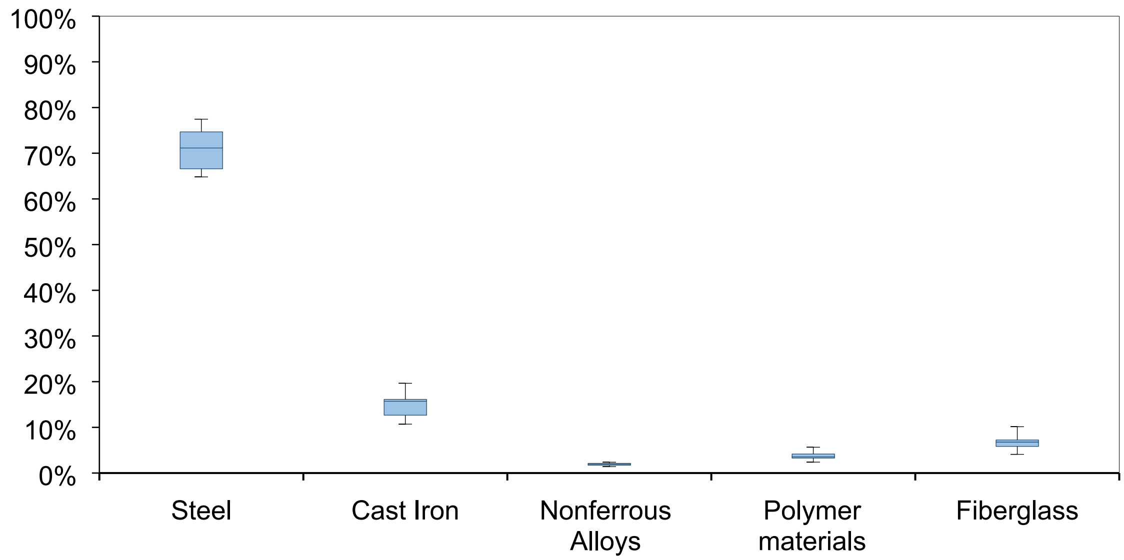


Figure S3. Material compositions of a wind turbine per se.

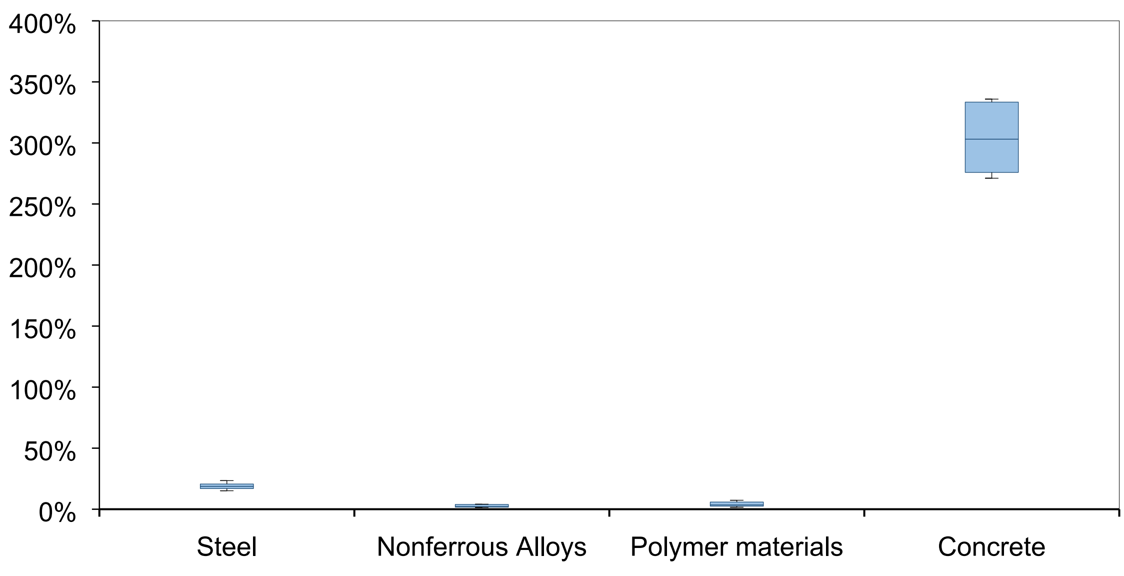


Figure S4. Material compositions of other parts of wind energy systems relative to the materials used in wind turbines.

Table S3. Neodymium intensity and dysprosium intensity used in previous studies.

kg/MW	Nd%	Dy%	kg/MW	kg/MW	Reference
650	27.0%	3.0%	0.176	0.020	An assessment of U.S. rare earth availability for supporting U.S. wind energy growth targets[1]
560	29.0%	2.0%	0.162	0.011	Material Flows Resulting from Large Scale Deployment of Wind Energy in Germany[2]
571.4	29.0%	2.0%	0.166	0.011	
566.7	29.0%	2.0%	0.164	0.011	
400	31.0%	5.5%	0.124	0.022	Critical materials strategy 2010[3]
600	31.0%	5.5%	0.186	0.033	
800	27.0%		0.216		Wind Energy in the United States and Materials Required for the Land-Based Wind Turbine Industry From 2010 Through 2030[4]
642	30.8%	4.5%	0.198	0.029	Can a dysprosium shortage threaten green energy technologies?[5]
600	30.0%	4.0%	0.180	0.024	
600	31.0%	5.0%	0.186	0.030	Byproduct metal requirements for U.S. wind and solar photovoltaic electricity generation up to the year 2040 under various Clean Power Plan scenarios[6]
400	29%	3.0%	0.116	0.012	
			0.1704	0.0203	Average (used for material intensities in 2017)
			0.119	0.014	70% of the 2017 level[7] (used for material intensities in 2050)

5. Survival curves of lifetime extension

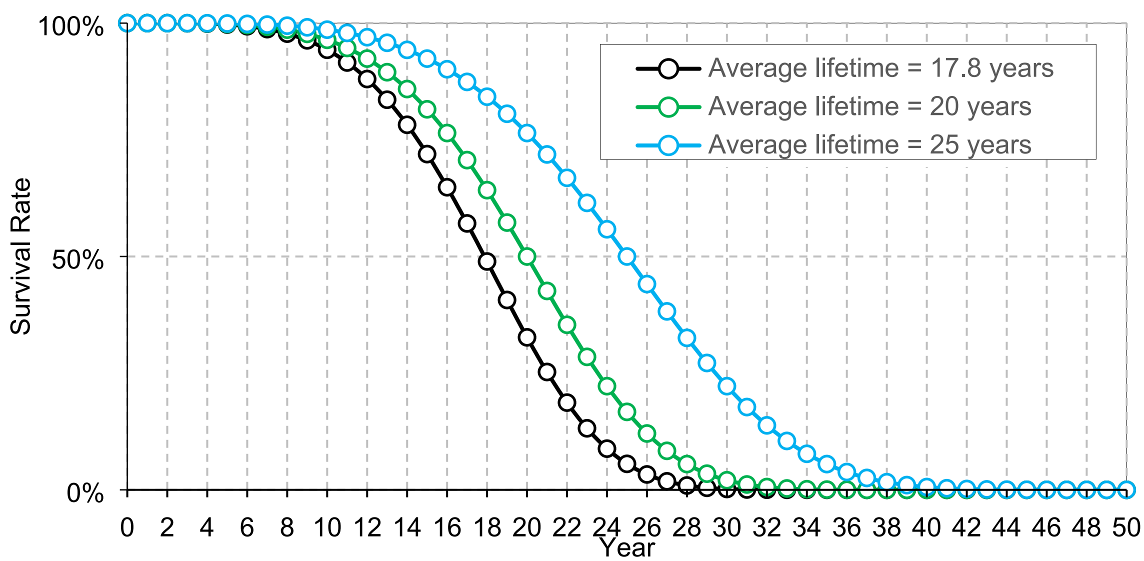


Figure S5. Survival curve of the lifetime function when average lifetime is 17.8 years, 20 years, or 25 years. Note: A survival curve presents the probability that previously installed turbines reach their lifetime, and thus average lifetime represents the duration between the time point when turbines were installed and the time point when half of them are still functioning. Based on the baseline lifetime function (average lifetime = 17.8 years), we generated new curves for two lifetime extension scenarios (20 years and 25 years), by adjusting the scale parameter of lifetime function while keeping the shape parameter unchanged. In a nutshell, the longer average lifetime is, the slower decommission of turbines is.

6. Impacts of increasing market share on dysprosium flows

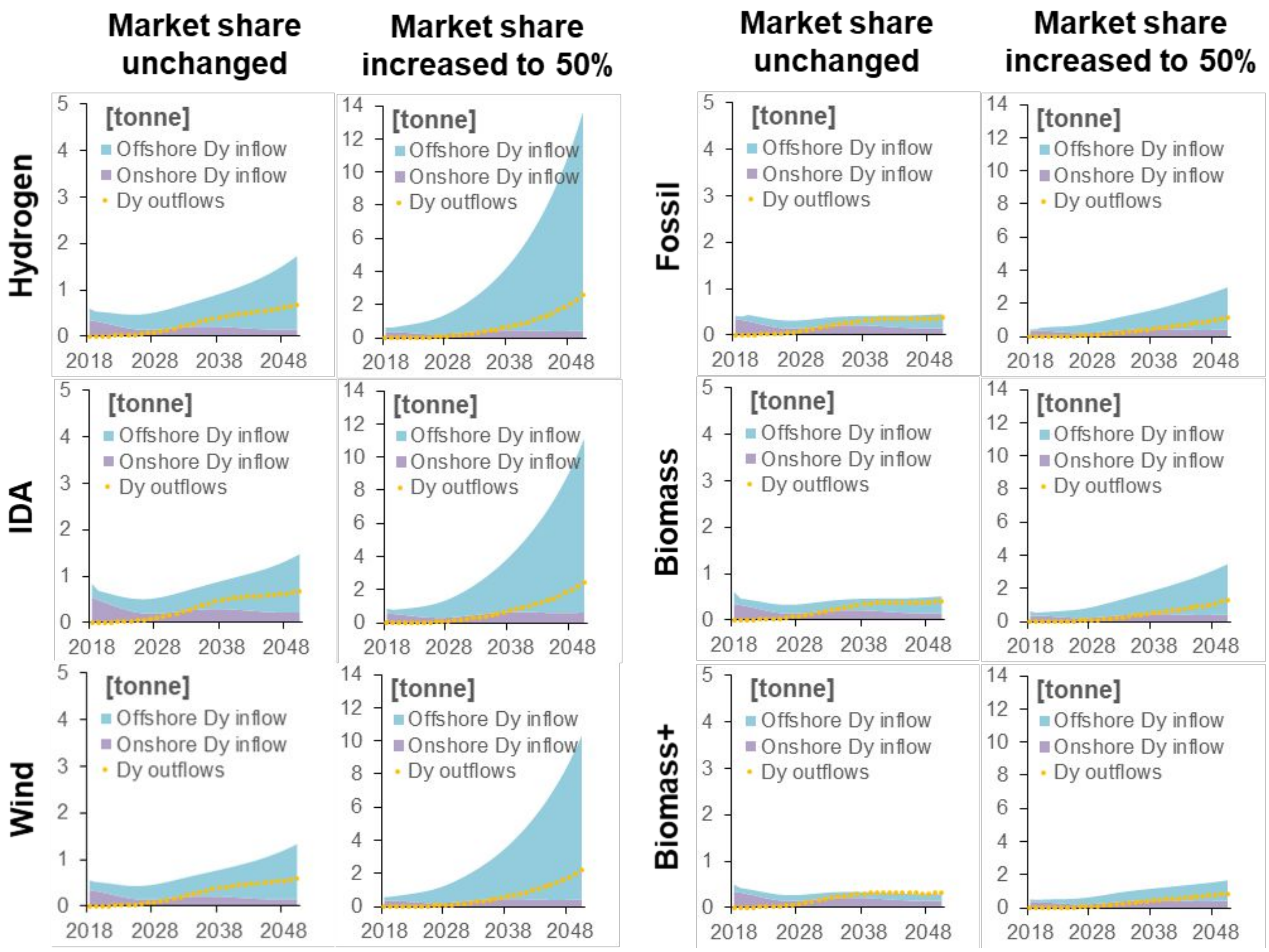
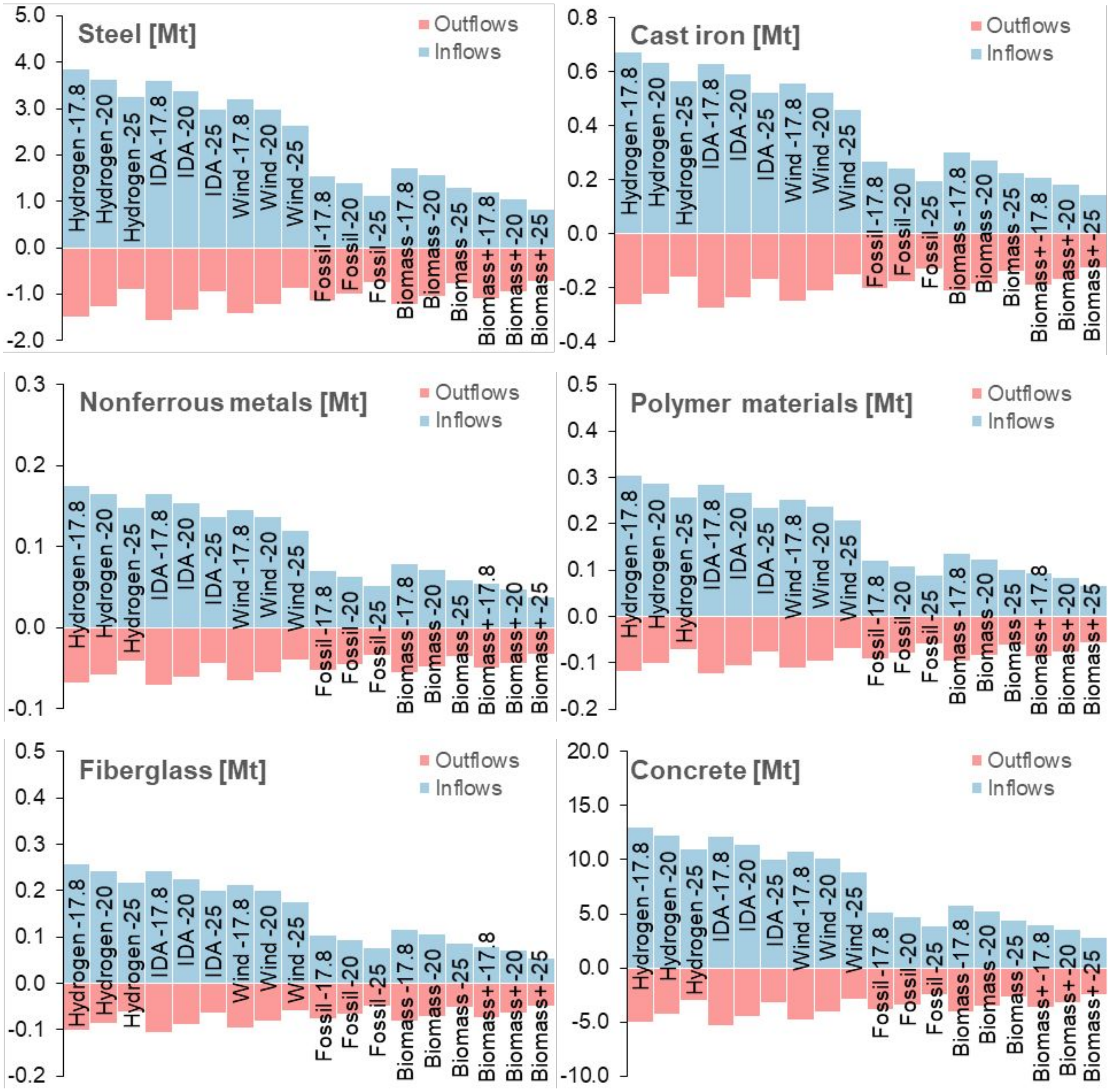


Figure S6. Impacts of increasing market share on annual dysprosium flows from 2018 to 2050.

7. Impacts of lifetime extension on material flows



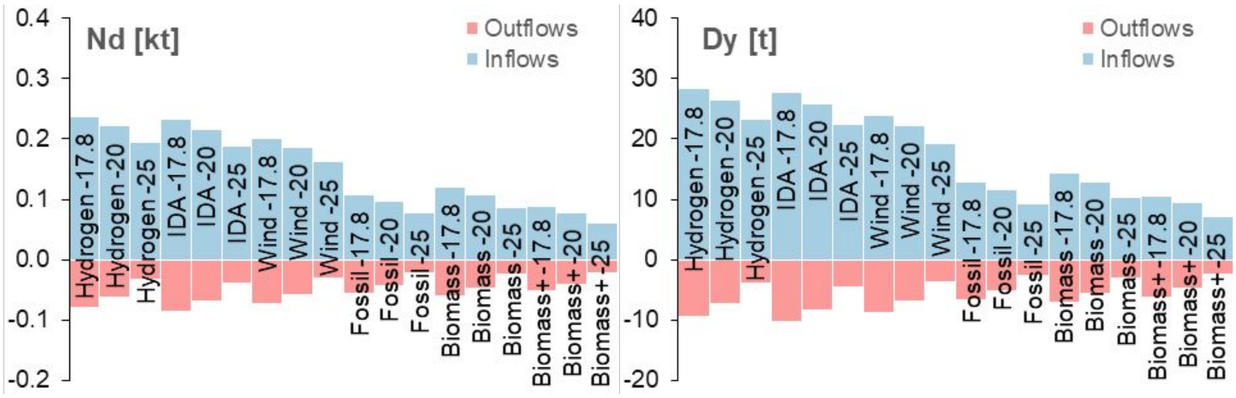


Figure S7. Impacts of lifetime extension on cumulative material flows during 2018-2050 in the *Hydrogen*, *IDA*, *Wind*, *Fossil*, *Biomass*, and *Biomass+* scenarios.

8. References cited in supporting information

(1) Imholte, D. D.; Nguyen, R. T.; Vedantam, A.; Brown, M.; Iyer, A.; Smith, B. J.; Collins, J. W.; Anderson, C. G.; O'Kelley, B. An Assessment of U.S. Rare Earth Availability for Supporting U.S. Wind Energy Growth Targets. *Energy Policy* **2018**, *113*, 294–305. https://doi.org/10.1016/j.enpol.2017.11.001.

(2) Zimmermann, T.; Rehberger, M.; Gößling-Reisemann, S. Material Flows Resulting from Large Scale Deployment of Wind Energy in Germany. *Resources* **2013**, *2* (3), 303–334. https://doi.org/10.3390/resources2030303.

(3) Sandalow, D.; Bauer, D.; Diamond, D.; Li, J.; McKittrick, M.; Telleen, P. Critical Materials Strategy. *US Department of Energy, USA* **2010**.

(4) Wilburn, D. R. *Wind Energy in the United States and Materials Required for the Land-Based Wind Turbine Industry From 2010 Through 2030*; U.S. Geological Survey: Reston, Virginia, 2011.

(5) Hoenderdaal, S.; Tercero Espinoza, L.; Marscheider-Weidemann, F.; Graus, W. Can a Dysprosium Shortage Threaten Green Energy Technologies? *Energy* **2013**, *49*, 344–355. https://doi.org/10.1016/j.energy.2012.10.043.

(6) Nassar, N. T.; Wilburn, D. R.; Goonan, T. G. Byproduct Metal Requirements for U.S. Wind and Solar Photovoltaic Electricity Generation up to the Year 2040 under Various Clean Power Plan Scenarios. *Applied Energy* **2016**, *183*, 1209–1226. https://doi.org/10.1016/j.apenergy.2016.08.062.

(7) Fishman, T.; Graedel, T. E. Impact of the Establishment of US Offshore Wind Power on Neodymium Flows. *Nature Sustainability* **2019**. https://doi.org/10.1038/s41893-019-0252-z.