

## Energy Transition

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The challenge of stabilizing Earth's climate system constitutes one of the most analytically complex policy problems of the modern era. It demands the simultaneous satisfaction of objectives that frequently conflict: economic efficiency, technological feasibility, intergenerational equity, geopolitical cooperation, and the preservation of natural systems. The leading proposals that have emerged from decades of climate science, economics, and international negotiation can be grouped into four broad categories:

1. Carbon pricing mechanisms — internalizing the social cost of carbon through taxes or markets;
2. Renewable energy transition — replacing fossil fuel combustion with zero-emission energy sources;
3. Carbon capture and storage (CCS) — removing CO<sub>2</sub> from the atmosphere or at point of emission;
4. Geoengineering — deliberate, large-scale manipulation of Earth systems to counteract warming.

Each proposal rests on a distinct set of assumptions—scientific, economic, and ethical—and each has generated a substantial body of supportive as well as critical literature. This analysis examines them in turn. This article covers the first two categories.

### The Physical Basis

Before critiquing specific interventions, it is necessary to establish the quantitative frame within which they operate.

The fundamental driver of anthropogenic warming is the enhancement of the greenhouse effect. Greenhouse gases (primarily CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, and fluorinated gases) trap outgoing longwave radiation. The resulting radiative forcing  $\Delta F$  (measured in watts per square meter, W m<sup>-2</sup>) attributable to CO<sub>2</sub> is approximated by:

$$\Delta F = 5.35 \ln\left(\frac{C}{C_0}\right) \quad [\text{W m}^{-2}]$$

where  $C$  is the current atmospheric CO<sub>2</sub> concentration and  $C_0 = 278$  ppm is the pre-industrial reference value (*Myhre et al.*, 1998). As of 2024,  $C \approx 422$  ppm, yielding:

$$\Delta F \approx 5.35 \ln\left(\frac{422}{278}\right) \approx 5.35 \times 0.417 \approx 2.23 \text{ W m}^{-2}$$

This forcing, combined with climate sensitivity  $\lambda$  (the equilibrium temperature change per unit forcing), produces the expected warming:

$$\Delta T = \lambda \cdot \Delta F$$

The Equilibrium Climate Sensitivity (ECS) — defined as the warming resulting from a doubling of CO<sub>2</sub> — is assessed by the *IPCC Sixth Assessment Report* (AR6, 2021) as likely in the range 2.5°C to 4.0°C, with a best estimate of 3.0°C.

A carbon budget is the total cumulative quantity of CO<sub>2</sub> that can be emitted while retaining a given probability of remaining below a specified temperature threshold. The IPCC AR6 estimates that, as of January 2020, the remaining budget to limit warming to 1.5°C with 50% probability was approximately 500 GtCO<sub>2</sub>, and with 67% probability approximately 400 GtCO<sub>2</sub>. Global annual emissions currently run at approximately 37 GtCO<sub>2</sub> per year, implying that — at current trajectories — the 1.5°C budget could be exhausted within approximately a decade:

$$t^* = \frac{B_{\text{remaining}}}{E_{\text{annual}}} \approx \frac{400 \text{ GtCO}_2}{37 \text{ GtCO}_2 \text{ yr}^{-1}} \approx 10.8 \text{ years}$$

This stark arithmetic underpins the urgency attached to all the proposals examined below.

### Carbon Pricing Mechanisms

Carbon pricing seeks to correct a market externality — a cost imposed on third parties (present and future generations) that is not reflected in the market price of fossil fuels. Two principal instruments exist:

- Carbon taxes (Pigouvian taxes): A tax equal to the marginal external damage is levied per tonne of CO<sub>2</sub>-equivalent emitted. Named after economist *Arthur Pigou*, who formalized the concept of correcting externalities through taxation.
- Cap-and-trade systems (Emissions Trading Schemes, ETS): A regulatory cap is placed on total permitted emissions; emitters receive or purchase allowances (permits), which they may trade. The price of carbon emerges endogenously from the market.

*Fundamental Assumptions.* The theoretical optimal tax is equal to the Social Cost of Carbon (SCC), defined as the present discounted value of all future damages caused by emitting one additional tonne of CO<sub>2</sub> today. Formally:

$$\text{SCC} = -\frac{\partial W / \partial E}{\partial W / \partial C} = \int_t^\infty e^{-r(\tau-t)} \cdot \frac{\partial D(\tau)}{\partial E(t)} d\tau$$

where  $W$  is social welfare,  $E$  is cumulative emissions,  $C$  is consumption,  $r$  is the discount rate, and  $D(\tau)$  is economic damage at time  $\tau$ .

The SCC is extraordinarily sensitive to three assumptions:

1. The discount rate  $r$ : A higher discount rate makes future damages appear smaller in present-value terms. *Nordhaus* (2017, DICE model) employs  $r \approx 4\%$ , yielding an SCC near \$31/tCO<sub>2</sub>. *Stern* (2006) employs  $r \approx 1.4\%$ , yielding an SCC exceeding \$85/tCO<sub>2</sub>. The 2022 US EPA estimate ranges from \$51 to \$190 per tonne at discount rates of 3% to 1.5%.

2. Damage functions: These map temperature increase to economic loss, typically as a polynomial:

$$D(T) = \alpha T^2 + \beta T^3$$

Critics argue that existing damage functions inadequately capture tipping points, non-linearities, and non-market damages (e.g., biodiversity loss, cultural heritage, human mortality).

3. Equity weighting: Standard integrated assessment models (IAMs) treat a dollar of damage in Bangladesh equivalently to a dollar in Norway, ignoring vastly different capacities for adaptation.

The economic case for carbon pricing rests on the First Welfare Theorem: that competitive markets achieve *Pareto*-efficient allocations only when externalities are absent. Carbon emissions represent a classic negative externality that, left unpriced, leads to overproduction relative to the social optimum. The efficiency gain from *Pigouvian* correction is illustrated by the deadweight loss triangle eliminated when the tax aligns private and social marginal costs:

$$\text{Welfare gain} = \frac{1}{2}(P^* - P_0)(Q_0 - Q^*)$$

where  $P^*$  is the socially optimal price,  $P_0$  the pre-tax price,  $Q_0$  the unregulated quantity, and  $Q^*$  the socially optimal quantity.

Furthermore, carbon pricing offers \*cost-effectiveness\*: by allowing emissions reductions wherever they are cheapest across the economy, the aggregate abatement cost is minimized relative to prescriptive technology mandates.

Carbon pricing is widely criticized as regressive — meaning it imposes a proportionally larger burden on lower-income households, who spend a higher share of their income on energy and carbon-intensive goods. Define the regressivity coefficient  $\Phi$  as:

$$\Phi = \frac{\Delta e_{\text{low}}/y_{\text{low}}}{\Delta e_{\text{high}}/y_{\text{high}}}$$

where  $\Delta e$  is the increase in energy expenditure and  $y$  is income. Empirical studies consistently find  $\Phi > 1$ , confirming regressivity (Goulder *et al.*, 2019; Ohlendorf *et al.*, 2021).

Mitigation strategies include revenue recycling: returning carbon tax revenues as flat dividends (equal per-capita transfers), which can render the policy progressive in net terms (Boyce & Riddle, 2007). The British Columbia carbon tax, combined with income tax cuts and low-income credits, has been held up as a model, though critics note its revenue neutrality may have diluted environmental ambition.

Distributional justice across nations is a further concern. Developing nations emit less historically yet face greater climate vulnerability. A uniform global carbon price does not, by itself, compensate for this asymmetry. The Common but Differentiated Responsibilities (CBDR) principle enshrined in the UNFCCC framework suggests graduated obligations, but carbon markets have struggled to operationalize this fairly.

#### *Empirical Evidence*

- European Union ETS (est. 2005): The largest carbon market in the world. Early phases (2005–2012) suffered from permit over-allocation, yielding prices near zero and negligible abatement. Reforms from 2018 onward (Market Stability Reserve) have driven prices to €60–100/tCO<sub>2</sub>, with credible studies estimating 3–5% emissions reductions beyond business-as-usual (Bayer & Aklın, 2020).
- British Columbia Carbon Tax (est. 2008): Murray & Rivers (2015) estimate a reduction of 5–15% in per-capita fuel consumption relative to counterfactual provinces, with no detectable adverse effect on GDP.

- Limitations: Carbon leakage — the relocation of emissions-intensive production to jurisdictions without carbon pricing — remains a persistent empirical and theoretical concern. The EU's Carbon Border Adjustment Mechanism (CBAM), introduced in 2023, represents a structural response.

## Renewable Energy Transition

The renewable energy transition envisions replacing combustion of fossil fuels (coal, oil, natural gas) — which currently supply approximately 80% of global primary energy — with zero-carbon sources, principally solar photovoltaics (PV), wind turbines, hydroelectric power, and, in some scenarios, nuclear fission. The electrification of end-uses (transport, heating, industry) is a necessary complement.

### *Fundamental Assumptions*

A foundational assumption is that renewable technologies follow Wright's Law (also called the experience curve): unit costs decline by a fixed percentage with each doubling of cumulative installed capacity:

$$c(n) = c_1 \cdot n^{-b}$$

where  $c(n)$  is the cost of the  $n$ -th unit,  $c_1$  is the cost of the first unit, and  $b$  is the learning parameter (related to the learning rate  $LR = 1 - 2^{-b}$ ).

For solar PV, the learning rate has empirically been approximately 20–23% per doubling of capacity — among the highest of any industrial technology (Way *et al.*, 2022, Joule). Solar LCOE (Levelized Cost of Energy) has fallen from roughly \$380/MWh in 2010 to below \$30/MWh in 2023, a decline of over 90%.

Wind and solar are variable renewable energy (VRE) sources — their output depends on meteorological conditions. This creates integration challenges as VRE penetration increases. The net-load curve (total demand minus VRE output) exhibits the so-called duck curve: a midday trough when solar is abundant and a steep evening ramp when it sets. Managing this requires:

$$E_{\text{storage}} \geq \int_{t_1}^{t_2} \max(0, P_{\text{VRE}}(t) - P_{\text{demand}}(t)) dt$$

— that is, sufficient storage capacity to absorb surplus generation.

The assumption that storage (primarily lithium-ion batteries, and potentially green hydrogen) can scale to meet this need at acceptable cost is increasingly supported but not yet demonstrated at full-grid scale in major economies.

### *Economic Justification*

The economic case has shifted dramatically since 2010. Whereas early advocacy rested on externality correction (the carbon price needed to make renewables competitive), current economics increasingly favors renewables on pure private cost grounds. BloombergNEF (2023) reports that new-build solar and wind are now the cheapest source of new electricity generation in most of the world, with no carbon price required.

The macroeconomic case is buttressed by:

- Energy security: Reduced dependence on imported fossil fuels decreases geopolitical vulnerability and terms-of-trade shocks.
- Employment co-benefits: The IEA (2021) estimates that clean energy transitions could generate 14 million new jobs by 2030, though with significant geographic mismatch versus fossil fuel job losses.
- Air quality co-benefits: Combustion of fossil fuels produces particulate matter (PM<sub>2.5</sub>), NO<sub>x</sub>, and SO<sub>2</sub>. The WHO estimates 7 million premature deaths annually attributable to air pollution. Electrification and renewable energy simultaneously address climate and air quality objectives.

The systems integration cost — the additional expense of managing a grid with high VRE penetration — is a genuine economic challenge. *Hirth et al. (2015)* estimate that at 30–40% wind penetration, the value of additional wind capacity declines significantly, reflecting grid saturation effects.

### *Societal Fairness Critique*

Intra-generational equity: The energy transition imposes transition costs disproportionately on workers and communities economically dependent on fossil fuel production (coal miners in Appalachia, oil workers in Alberta, coal communities in Poland). Just transition frameworks — public investment in retraining, economic diversification, and income support — are widely advocated but inconsistently implemented.

Access and energy poverty: In the Global South, approximately 775 million people lacked access to electricity as of 2022 (IEA). A renewable-centric model raises questions: is it equitable to deny developing nations the fossil fuel development pathway used by wealthy nations? The counter-argument is that distributed solar provides a leapfrog opportunity, bypassing costly grid infrastructure — but this requires concessional financing that the international community has been slow to provide.

Mineral supply chains: The transition requires massive scaling of lithium, cobalt, nickel, and rare earth elements. Mining operations raise concerns about environmental justice in producer nations (DRC, Chile, Indonesia), including community displacement and labour standards.

### *Empirical Evidence*

- Denmark: Wind power supplies over 50% of annual electricity consumption; system balancing achieved through interconnection with Norwegian hydro and flexible demand.
- Germany (Energiewende): Renewables reached 62% of electricity generation in 2023. However, the phase-out of nuclear power simultaneously with the coal phase-out has increased system costs and, temporarily, gas dependence.
- IEA Net Zero Emissions (NZE) Scenario (2021): Projects that solar becomes the single largest source of electricity globally by 2050, requiring annual solar capacity additions of 630 GW/year by 2030, compared to ~240 GW installed in 2022.
- Costs: Utility-scale solar LCOE in 2023 ranged from \$24–96/MWh depending on region, compared to new coal at \$65–150/MWh (*Lazard, 2023*).