Capital Adjustment Costs and Nationally Determined Contributions - How to Avoid Double Transitions of Energy Capital?

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Research Question

1. What constitutes optimal investment paths for the clean energy transition, given different initial conditions of advanced vs. emerging market economies?
2. How does the optimal investment path change with different policy options to achieve nationally determined contributions (NDCs)?

Motivation

How to set up the capital stock to transition from a fossil fuel to a renewable based energy system accounting for disparities in existing capital stocks between advanced and emerging markets?

- Energy demand of advanced economies is served by existing energy infrastructure, whereas emerging market economies have growing energy supply needs.
- Today fossil-based technology $\sim$ 40 % more productive; 2030: 10% details
- Dirty and clean energy technologies are highly substitutable in the long run but require costly infrastructure adjustment but high capital adjustment costs

$\rightarrow$ The danger of a potential double transition of the energy capital stocks in the next decades is due to high ongoing dirty energy investment rates in some countries and weak (or weakening) nationally determined contributions during the mid-transition

Results in a Nutshell:

- **Advanced economy** like EU is cleaner but with legacy dirty capital: form of adjustment costs matters for phaseout and stranded assets
- **An emerging economy** like India or Peru is faster growing with larger overall investment needs.
  - Due to the expected clean energy productivity convergence, clean energy investment expands immediately to smooth adjustment costs and meet growth needs.
  - Modest additional climate policy is sufficient to reduce initial buildup in dirty energy capital stocks.
- Under the central calibration, compared to carbon budgets consistent with current NDCs, climate policies in line with reaching 1.5 C globally entail modest welfare costs for both types.

Carbon budget vs. net zero target

- Compared to a simple net zero target, more stringent carbon budgets achieve the phaseout with lower emissions and fewer stranded assets but slightly higher overall adjustment costs.

Literature Overview

- **Importance of adjustment costs for capital investment:** Lucas (1967), Gould (1968), Mussa (1977), David & Venkateswaran (2019), Hall (2004), Cooper and Haltiwanger (2006)
- **Optimal investment:** Burda et al. (2024), Arkolakis and Walsh (2023), Campiglio et al. (2022), Vogt-Schilb et al. (2018), Baldwin et al. (2020), Coulomb et al. (2019)
- **Initial conditions:** Fischer et al. (2004)

Contribution

- We show how country-specific characteristics—like levels of economic development, composition of starting capital stocks, and climate ambition—influence transition paths (incl. near-term investments in dirty energy, cumulative adjustment costs & stranded assets).
- Quantification of the productivity advantage of dirty energy technology and the initial clean and dirty energy capital stocks.
- Analysis of the effectiveness of net zero commitments compared to carbon budgets for investment strategies.

Capital Adjustment Costs

- Convex adjustment costs make fast changes in capital stocks very costly.
- Convex capital adjustment costs capture the increasing opportunity costs to use scarce resources, such as skilled workers, appropriate capital, or production lines, to perform the capital stock transition.
    - **Example:** Retrofitting all buildings in a country in three months much more expensive than doing it over three decades (Vogt-Schilb et al. 2018).
- Adjustment costs in capital stock transformation can operationalize the endogenous change in substitutability between clean and dirty energy sources.

Clean Technology Catching Up back

	2021	2030	2021	2030	
	EU		**India**		
Sector	$\frac{M_D}{M_C}$		$\frac{M_D}{M_C}$		Unit of Measurement
Electricity	0.57	0.52	0.89	0.98	VALCOE
Heating	1.19	0.78	1.19	0.78	LCOH
Transportation	1.56	1.56	1.56	1.56	LCOD
Industry (Steel)	2.3	1.5	1.4	1.1	Prod. cost
Average	1.4	1.09	1.26	1.11	

Table: Productivity advantage of dirty energy technology (M_D) over clean energy technology (M_C) in several sectors over time.

Energy capital stocks in the EU *(preliminary - work in progress for India as well)* details

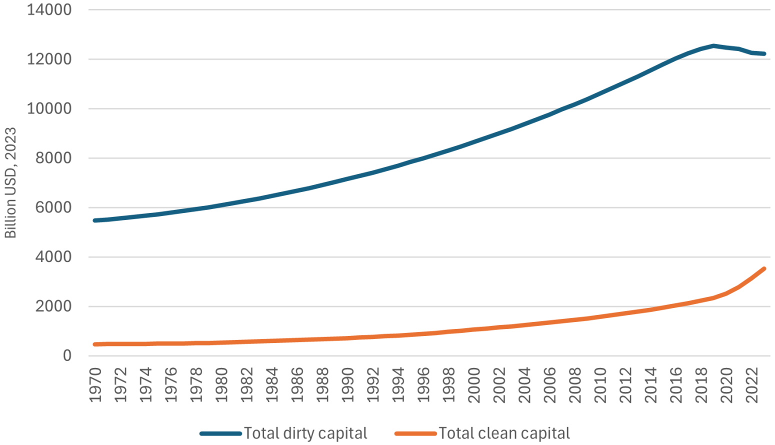
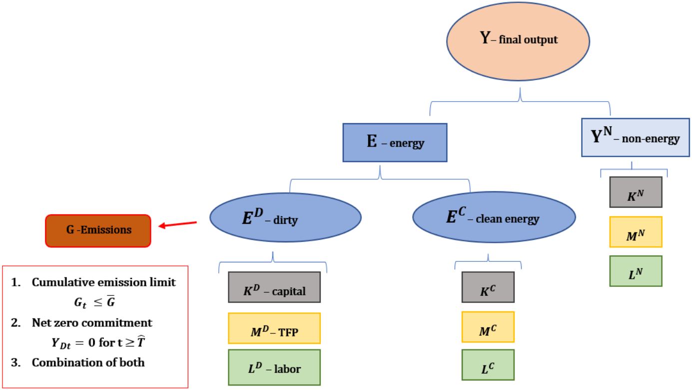


Figure: Clean and dirty energy capital stocks in the EU

Production Structure of our Four Sector Growth Model

We study optimal and constrained transition paths chosen by a social planner in a four-sector growth model based on Burda, Goeth and Zessner-Spitzenberg.



Energy catch up

Social Planner Problem details

Maximize PDV of utility from consumption

$$\max_{\left\{ K_t^C,\, K_t^D,\, L_t^C,\, L_t^D,\, G_t \right\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t u(C_t) \quad \text{with} \frac{C_t^{1-\theta}}{1-\theta}$$

subject to the final production constraint

$$Y_t = \left(\gamma Y_{Nt}^{\frac{\epsilon-1}{\epsilon}} + (1-\gamma) Y_{Et}^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{\epsilon-1}}.$$

Energy is produced using clean and dirty energy:

$$Y_{Et} = Y_{Dt} + Y_{Ct}.$$

All inputs (clean & dirty energy, non-energy) are produced with respective Cobb-Douglas technologies

$$Y_{it} = M_{it} K_{it-1}^{1-\alpha_i} L_{it}^{\alpha_i}, \qquad i \in \{N, D, C\} \quad \text{with} \quad \alpha_C = \alpha_D < \alpha_N.$$

Social Planner Problem continued

Resource constraint: $Y_t = C_t + \sum_{i \in \{N,D,C\}} I_{it} + \sum_{i \in \{N,D,C\}} \Omega^i(K_{it}, K_{it-1}).$

Capital adjustment costs: symmetric & sector-specific (Aguiar & Gopinath, 2007) details

$$\Omega^i(K_{it}, K_{it-1}) = \frac{c_i}{2}\left(\frac{I_{it}}{K_{it-1}} - \delta_i - z_i\right)^2 K_{it-1} \quad \forall\, i = C, D, N$$

- Central scenario assumption: Excess investment below and beyond depreciation & growth incurs adjustment costs $\rightarrow$ costs on net investment but replacement investment is free.
  - Sensitivity: costs based on gross investment
- **Assumption:** z_i (with $z_D = 0$) as the limit of the growth rate of capital stock K_i as $t \rightarrow \infty$. $\Rightarrow$ no adjustment costs in long run.

Solution method: Extended path method (Maliar et al. 2020)

What is the optimal investment path for the clean energy transition given different initial conditions?

Different Cumulative Carbon Budget Scenarios

1. **CBSTEPS:** carbon budget that corresponds to the stated policies scenario including carbon pricing (Baseline)
2. **CB+1.5C:** corresponds to a carbon budget including carbon pricing associated with meeting 1.5C globally details

EU

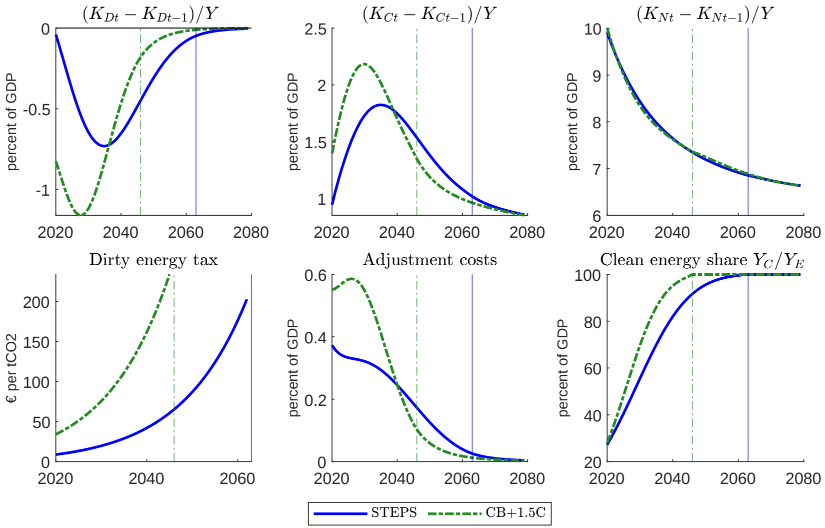


Figure: Transition paths EU

India

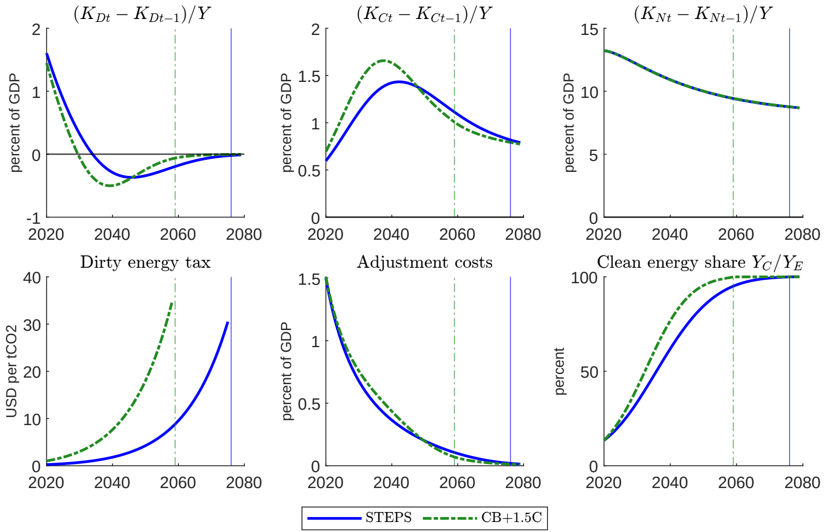


Figure: Transition paths India

Key Takeaways

- Due to the expected productivity convergence, it is optimal for India to immediately increase investment into the clean energy technology – even without further climate policy.
- The carbon tax necessary for 1.5C is much higher for the EU than for India.
- In India, even a low carbon tax lowers an initial buildup in dirty capital.
- In both nations, the pursuit of the 1.5°C climate target significantly curtails emissions yet implies higher costs for the initially elevated clean energy investment.
- For CB 1.5C the overall clean energy capital stock needs to be bigger to substitute the initially more productive dirty energy capital stock.

How do different NDC policies affect the optimal transition path?

Different NDC Policies

1. *CBSTEPS:* carbon budget that corresponds to the stated policies scenario including carbon pricing (Baseline)
2. *CB+1.5C:* corresponds to a carbon budget including carbon pricing associated with meeting 1.5C globally details
3. **CB+1.5C+NZ2040:** same carbon budget as for 1.5C (carbon pricing) with additional net zero target by 2040.
4. **NZ2050:** requires all energy demands to be met with carbon-free sources by 2050, after which CO2 intensive technologies can no longer be used (no carbon pricing)

NDC Policy Comparison - EU

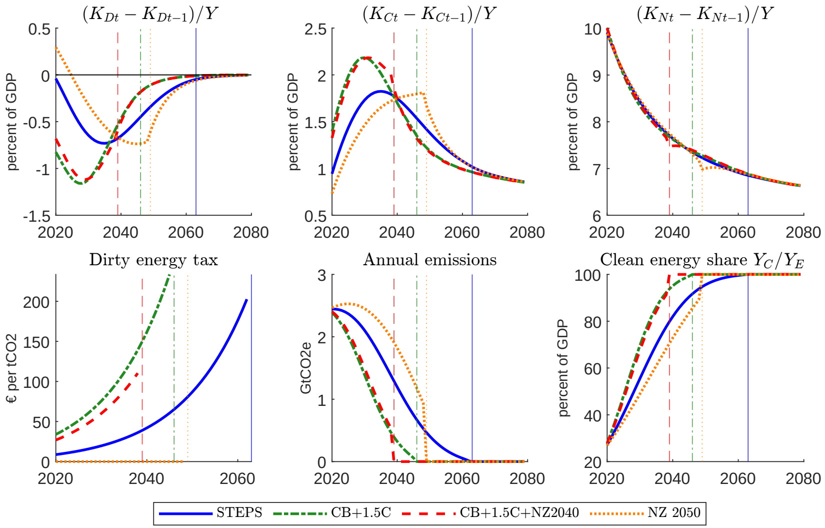


Figure: EU transition paths for different NDC policies

NDC Policy Comparison - India

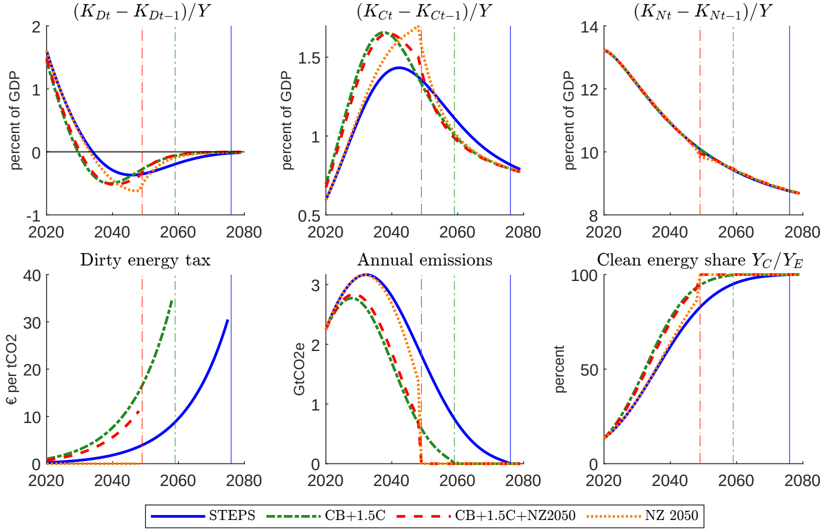


Figure: India transition paths for different NDC policies

Welfare comparison between transition scenarios in the EU and India

EU Scenario	**Phase -out year**	**Carbon budget $GtCO_2e$**	**CO_2 Price (€/ton)**	**Δ Welfare during transition % ch. to STEPS Reference**	**Stranded assets $\frac{K_D(\bar{T})}{Y(\bar{T})}$**	**Avg. adj. costs $\frac{\Omega}{Y}$ to 2060**
CBSTEPS	2064	51	9		0.4	0.2
CB+1.5C	2047	29	34	-0.2	1.4	0.3
CB+1.5C+NZ2040	2040	29	27	-0.2	4.5	0.3
NZ2050	2050	59	0	0	4.6	0.2

India Scenario	**Phase -out year**	**Carbon budget $GtCO_2e$**	**CO_2 Price (USD/ton)**	**Δ Welfare during transition % ch. to STEPS Reference**	**Stranded assets $\frac{K_D(\bar{T})}{Y(\bar{T})}$**	**Avg. adj. costs $\frac{\Omega}{Y}$ to 2060**
CBSTEPS	2077	98	0.2		0.2	0.4
CBSTEPS+NZ2070	2070	98	0.2	0	0.5	0.4
CB+1.5C	2060	63	1	-0.03	0.5	0.4
CB+1.5C+NZ2050	2050	63	0.7	-0.1	2.4	0.4
NZ2050	2050	77	0.0	-0.1	3.9	0.4

Key Takeaways

- Compared to a simple net zero target, a cumulative carbon budget with optimal emission pricing that achieves the same dirty energy phase out date (e.g.$\sim$ 2050) results in significantly fewer emissions and fewer stranded assets, although total adjustment costs may be somewhat higher.
- The simple net zero target without any emission pricing leads to a front loading of emissions, exploiting the remaining initial advantage of dirty energy technology and requiring a catch-up of clean investment later.
- Overlapping a cumulative carbon budget for 1.5 C with a binding net zero target (e.g. 2040) lowers the carbon price needed to meet the carbon budget but significantly increases stranded assets.
- Climate policy aiming at phasing out dirty energy by 2050 (1.5C) carries only modest welfare costs for India and the EU.

Summary and Conclusion

- Due to the expected productivity convergence, India always expands clean energy investment immediately.
- In India a modest climate policy is sufficient to avoid an initial buildup in dirty energy capital stocks.
- **Policy Implication:** Delaying climate action creates a risk of a double transition of the energy capital stocks, which entails higher costs in the long run, given costly capital adjustment

Excursion: The Total Carbon Price - Why net fiscal incentives for fuels matter. . .

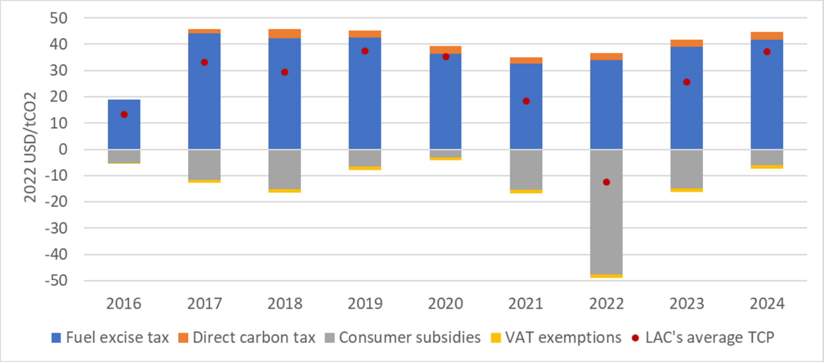
World Bank (2024): Taxing and subsidizing energy in Latin America and the Caribbean: Insights from a Total Carbon Price Approach

Total Carbon Price (TCP)

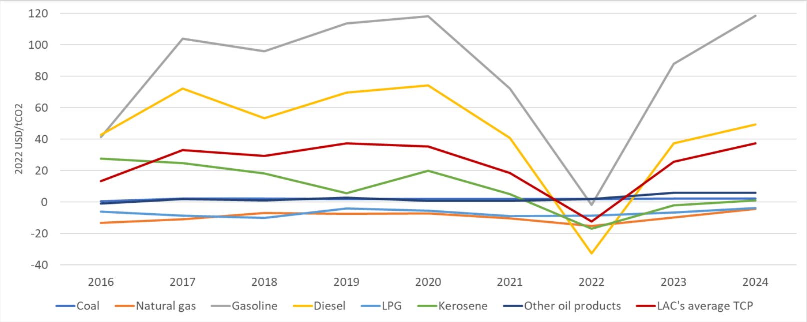
Direct and indirect priced-based fiscal instruments considered in the TCP metric

	Price-based instruments	+ or – in energy price
Direct	Carbon tax	+
	Emissions Trading Systems average marginal price	+
	Tradable performance standard	+
Indirect	Fuel excise tax	+
	Producer-side subsidies[1]	-
	Consumer-side subsidies	-
	VAT deviation from standard rate (exemption or reduced rate)	-

Contribution of Each Tax Component to Latin America's Average Total Carbon Price



Average Total Carbon Price of Each Fuel in Latin America



Conclusion

- In LAC, there is a wide dispersion between TCPs for different fuel.
- The main overall tax burden is due to fuel excise taxes.
- Large FF subsidies in LAC are mostly for natural gas and LPG
- Different fuels are used differently in different sectors (e.g., diesel and gasoline concentrated in transportation, natural gas in power generation and industry).
- Since fiscal incentives are differentiated by fuels and not by emission content, investment signals for decarbonizing each sector differ substantially.
- **Policy implication:** emission based (direct) carbon price more favorable to guide investment to low carbon alternatives in all sectors

"Due to expected productivity convergence, it is optimal for emerging market economies to immediately increase investment in clean energy technology, even without further climate policy. Delaying climate action in emerging markets risks a double transition of energy capital stocks, leading to higher long-term costs due to costly capital adjustments."