Supplementary Information: Averting the steel carbon lock-in through strategic green investments

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Supplementary Note S1: Effect of different climate ambition levels on the steel transition

In this work, we focus on a 1.5°C-compatible trajectory, with an overshoot of approximately 1.75°C. Below, we show how our base scenarios vary when changing climate ambition, for two cases: higher climate ambition (Supplementary Fig. S1, 1.5°C compatible trajectory with a lower peak temperature below 1.7°C, peak budget of 650 Gt CO_2 from 2020), and lower climate ambition (Supplementary Fig. S2, 2°C compatible trajectory, with 67% likelihood, peak budget of 1000 Gt CO_2 from 2020).

The main components of the steel transition are overall similar to the main scenarios shown in Figure 3, but the speed differs. In 2050, *Fast Transition (1.5°C, low overshoot)* has under 100 Mt of steel produced through the BF-BOF pathway, compared to 250 Mt in the standard *Fast Transition* and 440 Mt in *Fast Transition (2°C)*. Limiting coal-based steel is therefore a key component of achieving a 1.5°-compatible transformation.

In the *Transition with Lock-in (1.5°C, low overshoot)* scenario, BF-BOF-CCS also appears as a key mitigation option to reduce the impact of running otherwise unabated coal-based plants. We find that 239 Mt of steel are produced through this pathway in 2050, compared to 542 Mt of steel through BF-BOFs. We explore further conditions for BF-BOF-CCS to be a viable decarbonization option in Supplementary note S2.

Importantly, the difference between the *Transition with lock-in* and *Fast Transition* scenarios shrinks with declining climate ambition, but remains significant in a 2°C-compatible trajectory. This indicates that addressing the steel lock-in (and minimizing new investments in coal-based steel) is crucial for returning to 1.5°C, as shown in the main text, but Figure S2 hints that this is also cost-effective when considering 2 °C-aligned pathways.

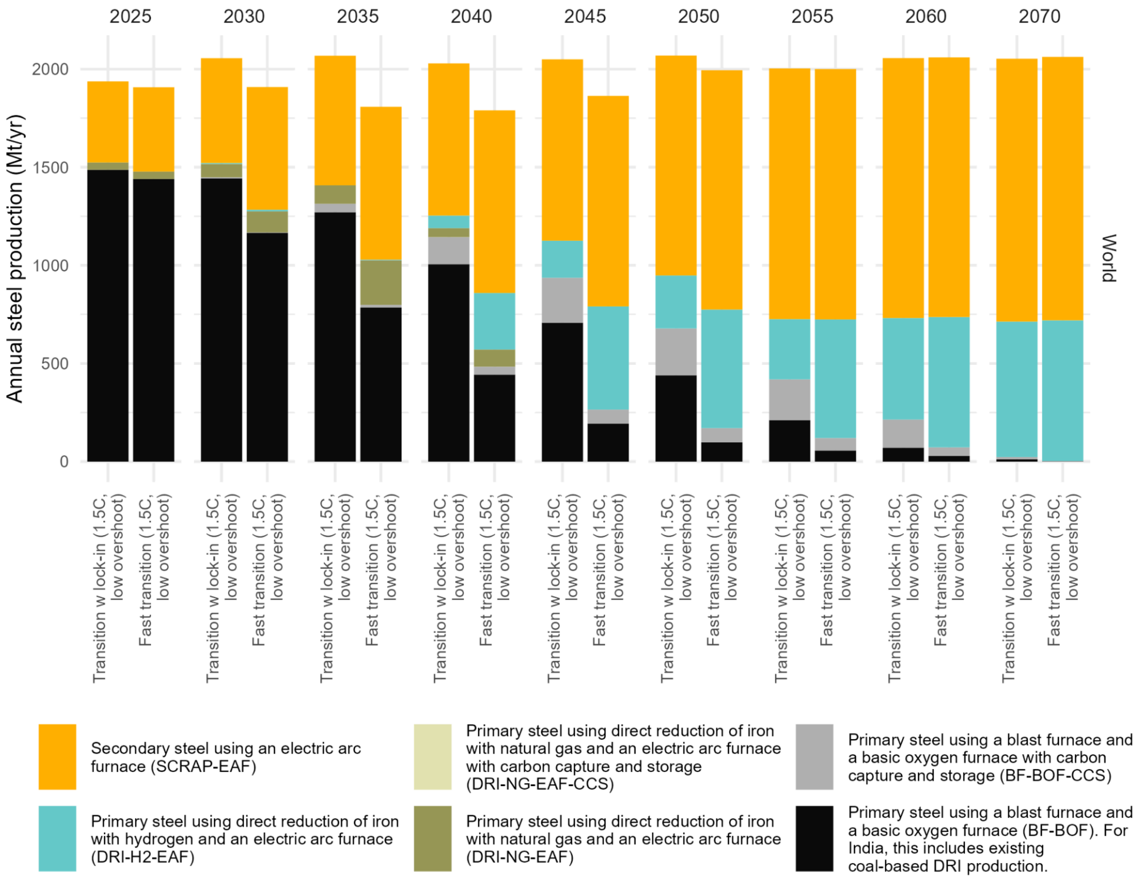

Fig S1: Global steel production under the *Transition with lock-in* and *Fast Transition* scenarios, for more ambitious climate mitigation (1.5°C compatible pathway with 1.7°C overshoot).

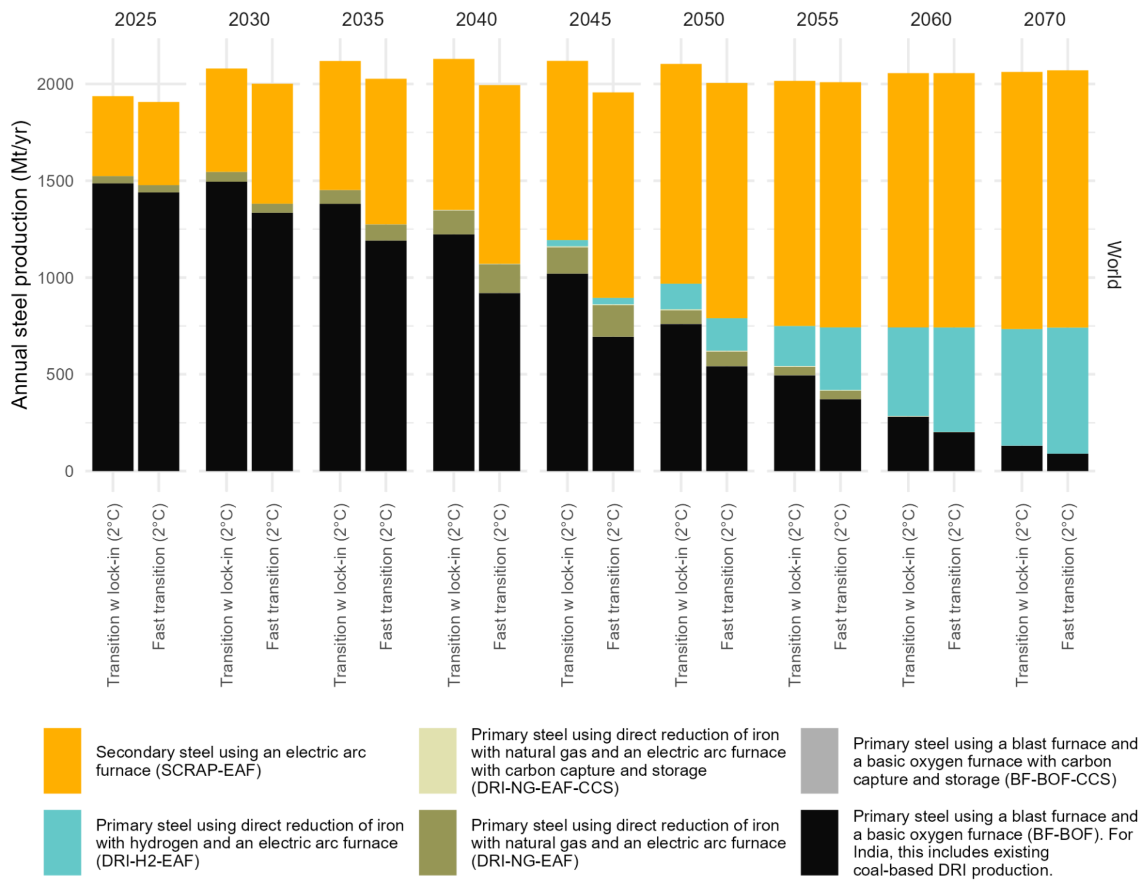

Fig S2: Global steel production under the *Transition with lock-in* and *Fast Transition* scenarios, for less ambitious climate mitigation (2°C compatible pathway with 67% likelihood).

Supplementary Note S2: The conditions for BF-BOF-CCS to emerge as a bridging option

In our main scenarios (Figure 3), BF-BOF-CCS is not present as a bridging option, despite a substantial BF-BOF lock-in. We identified two connected drivers for this:

1) Model preference for allocating carbon storage capacity to bioenergy with CCS (BECCS) for achieving substantial emission reductions, and

2) Moderate climate ambition in the medium term: our base scenarios have a higher overshoot of approximately 1.75°C, which allows part of the mitigation efforts to be postponed to later decades (scenarios with lower overshoots, requiring early action, have much more BF-BOF-CCS: see Supplementary Figure S1).

We investigated the impact of limiting BECCS in our scenarios by creating three sensitivity scenarios of *Transition with Lock-in* (TwLI):

- *TwLI (moreCCS)*: the total global CCS injection rate is increased from 19.7 Gt CO_2 $year^{-1}$ to 29.5 Gt CO_2 $year^{-1}$.

- *TwLI (LowBio)*: We introduce an upper limit of 100 EJ $year^{-1}$ of biomass production (excluding traditionally used biomass). In standard scenarios, biomass production reaches approximately 180 EJ $year^{-1}$ by 2070.

- *TwLI (moreCCS & lowBio)*: increase CCS injection rate to 29.5 Gt CO_2 $year^{-1}$ and limit biomass production to 100 EJ $year^{-1}$.

Results show a progressive increase in BF-BOF-CCS uptake in the sensitivity scenarios, with *TwLI (moreCCS & LowBio)* having the largest share: close to half the BF-BOFs in 2050 have a carbon capture retrofit (Supplementary Figure S3). We can also isolate which parameter change had the biggest effect: *TwLI (LowBio)* has a much larger BF-BOF-CCS share than *TwLI (moreCCS)*. Limiting biomass availability (which constrains the availability of BECCS) is therefore the primary condition under which BF-BOF-CCS retrofits become attractive.

BF-BOF-CCS therefore emerges as an important technology pathway in two situations:

1) Limited BECCS availability: when BECCS is constrained, the energy system cannot rely on large volumes of negative emissions in later decades to offset steel sector emissions. This increases the need for earlier mitigation within the steel sector, leading to greater reliance on BF-BOF-CCS.
2) Higher climate ambition: In scenarios with a lower temperature overshoot (for example, Supplementary Figure S1), stronger mitigation efforts are required before mid-century, leading to substantial deployment of BF-BOF-CCS (Supplementary Figure S1).

In both cases, the underlying driver is the same: the energy system requires deeper early decarbonization. When negative-emission options such as BECCS cannot fully compensate for the additional emissions in the steel sector, or when more stringent climate targets require more near-term efforts in mitigation, BF-BOF-CCS becomes a necessary bridging technology for the steel sector.

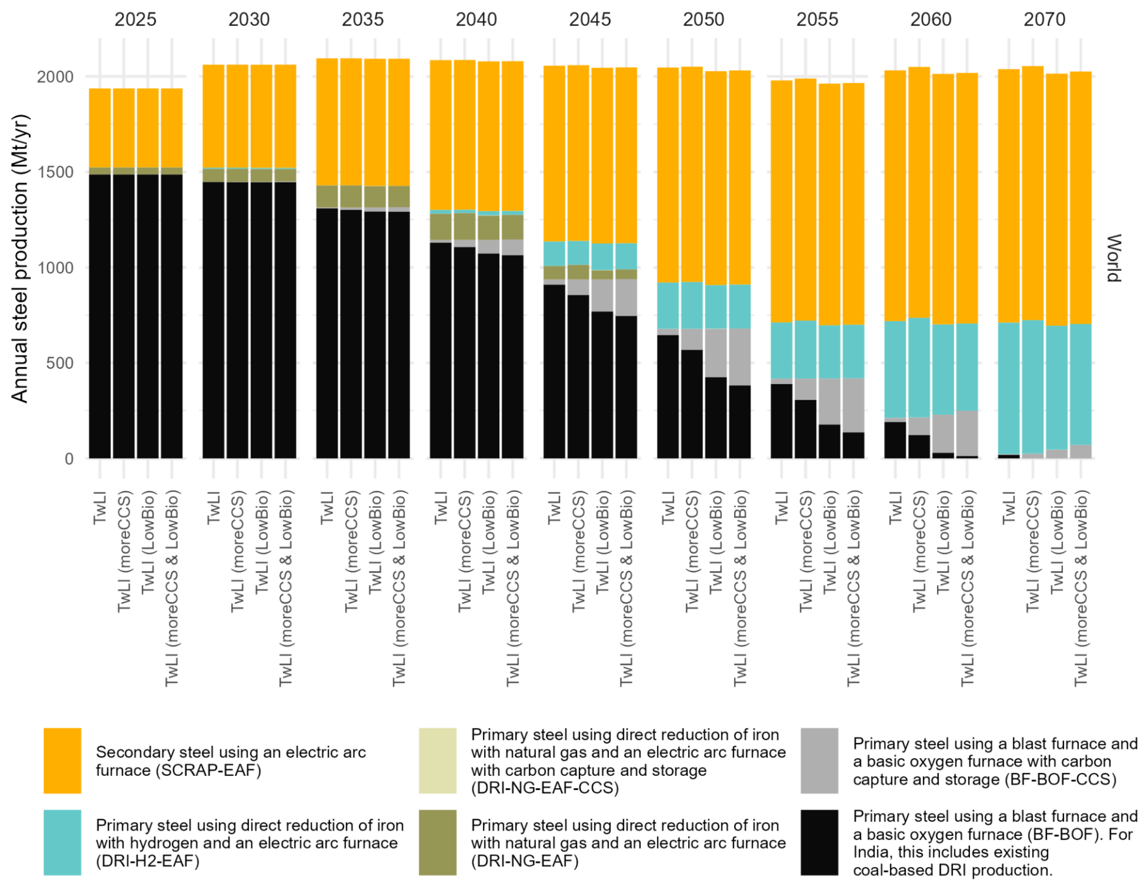

Fig S3: Effect of higher carbon storage capacity and lower biomass availability on the uptake of BF-BOF-CCS in the steel transition. TwLI: Transition with lock-in

Supplementary Note S3: REMIND variables: carbon pricing and other energy prices

The carbon price calculated endogenously by the REMIND model is shown in Figure S4. Solid fuel, gaseous fuel, hydrogen, and electricity prices are shown in Figures S5–8.

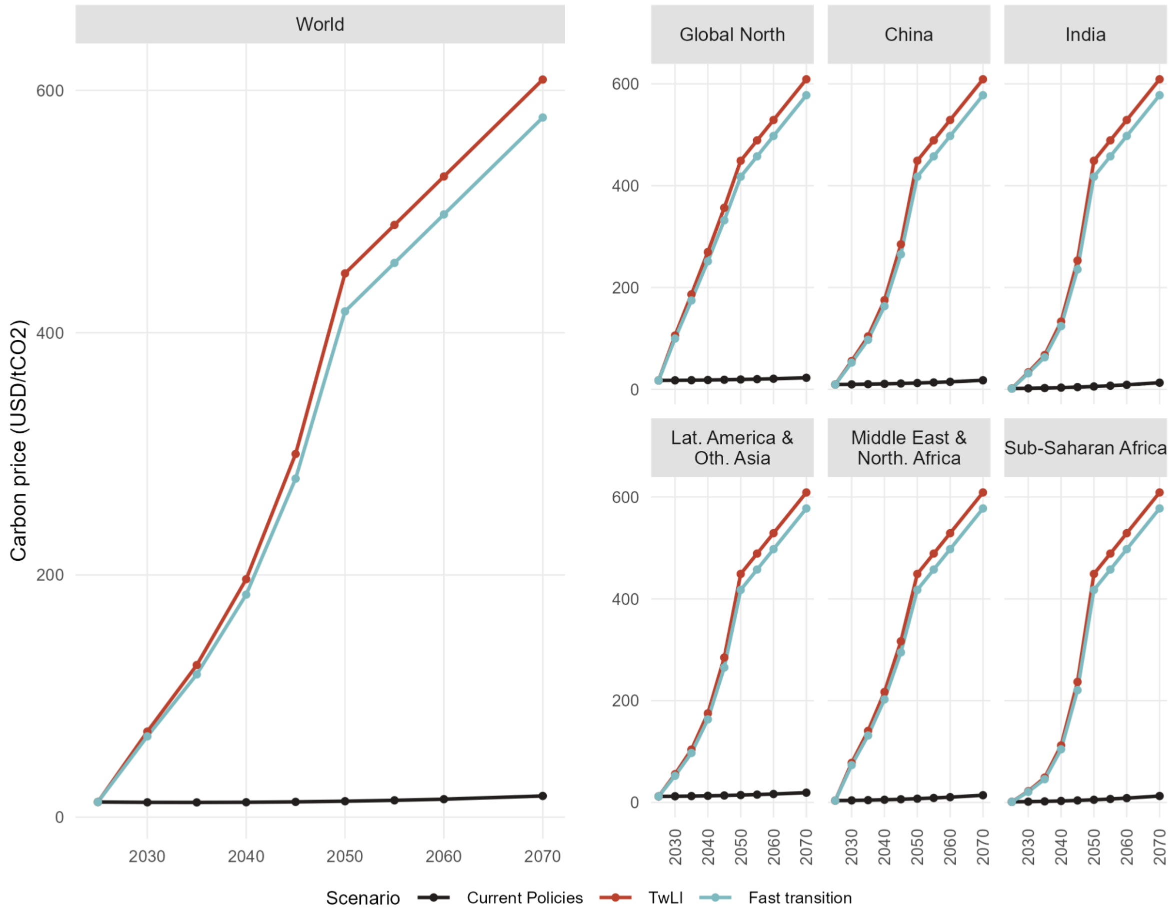

Fig S4: Global carbon price (panel a) and regional carbon prices (panel b), as endogeneously derived in the REMIND model for each scenario

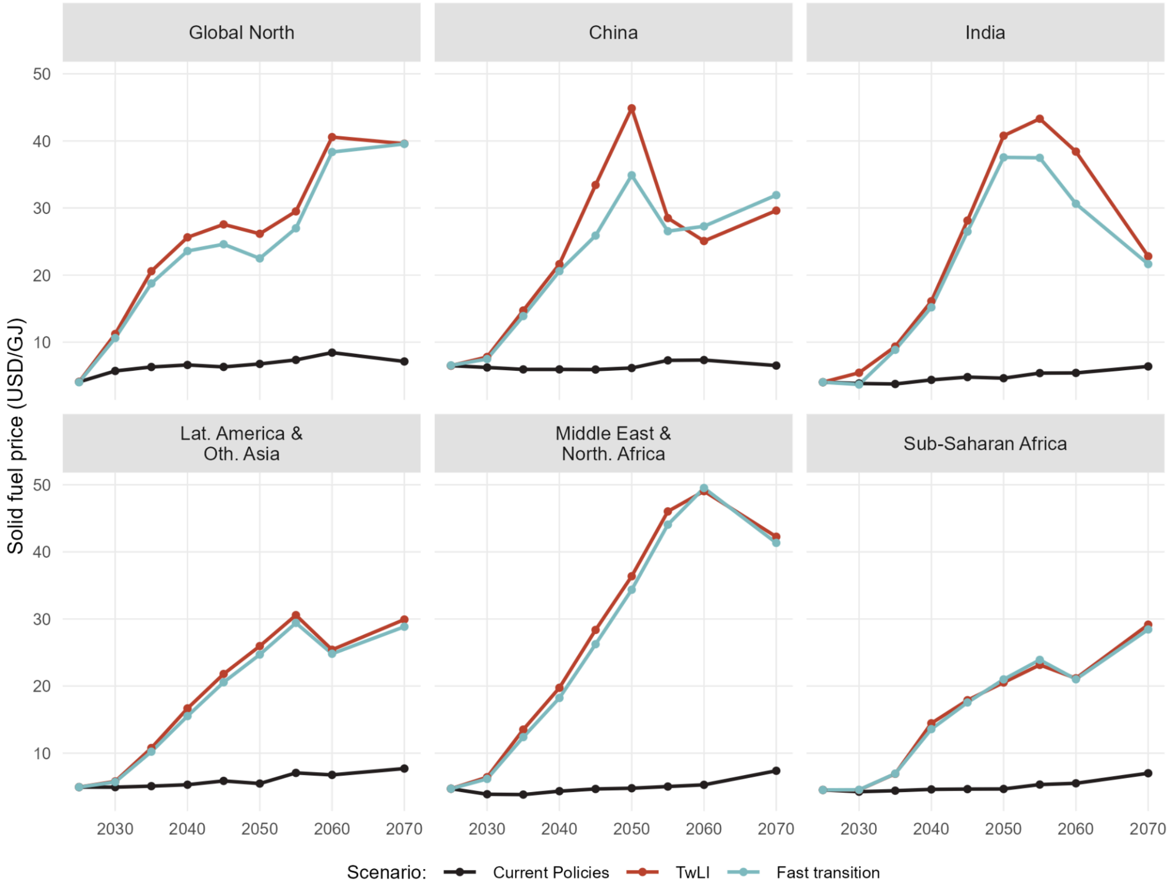

Figure S5: Solid fuel prices (coal and biomass replacing coal) for the industry sectors.

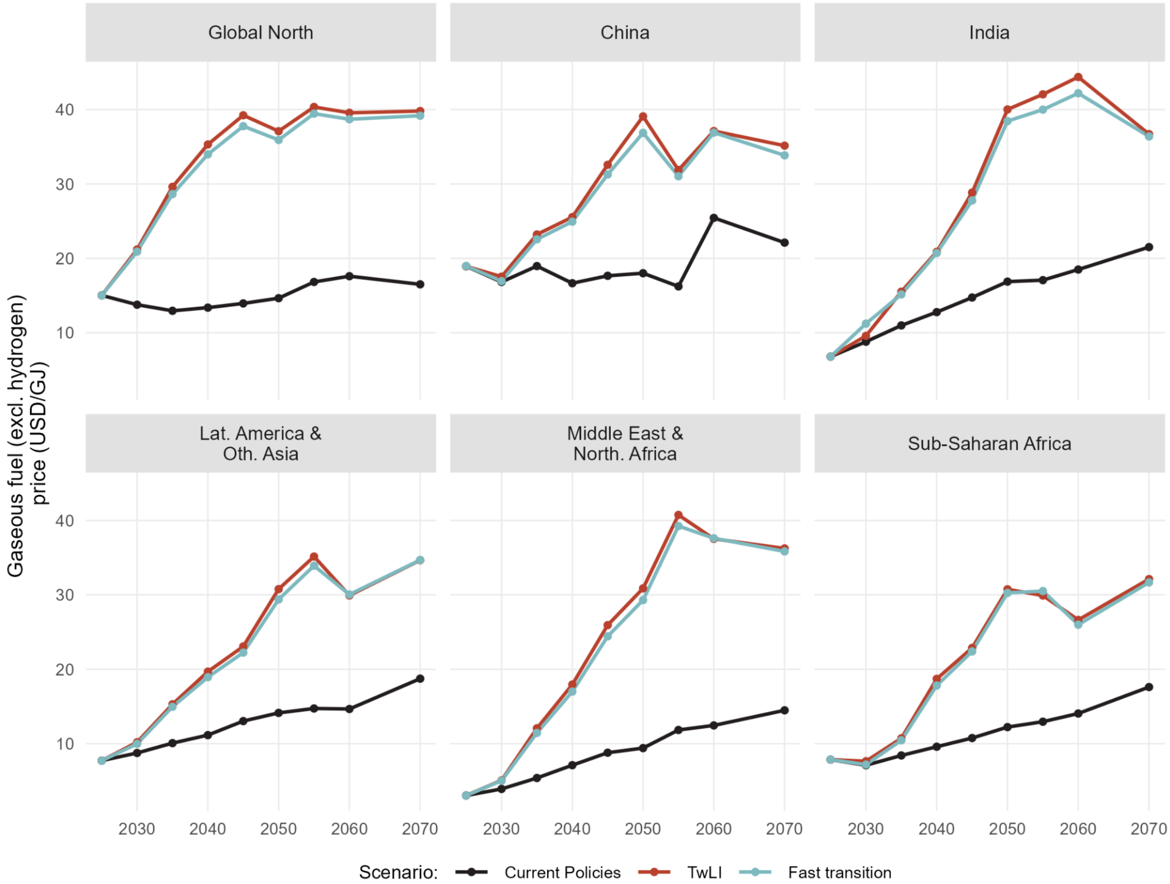

Figure S6: Gaseous fuel prices (fossil gas and biogas, excluding hydrogen) for the industry sectors.

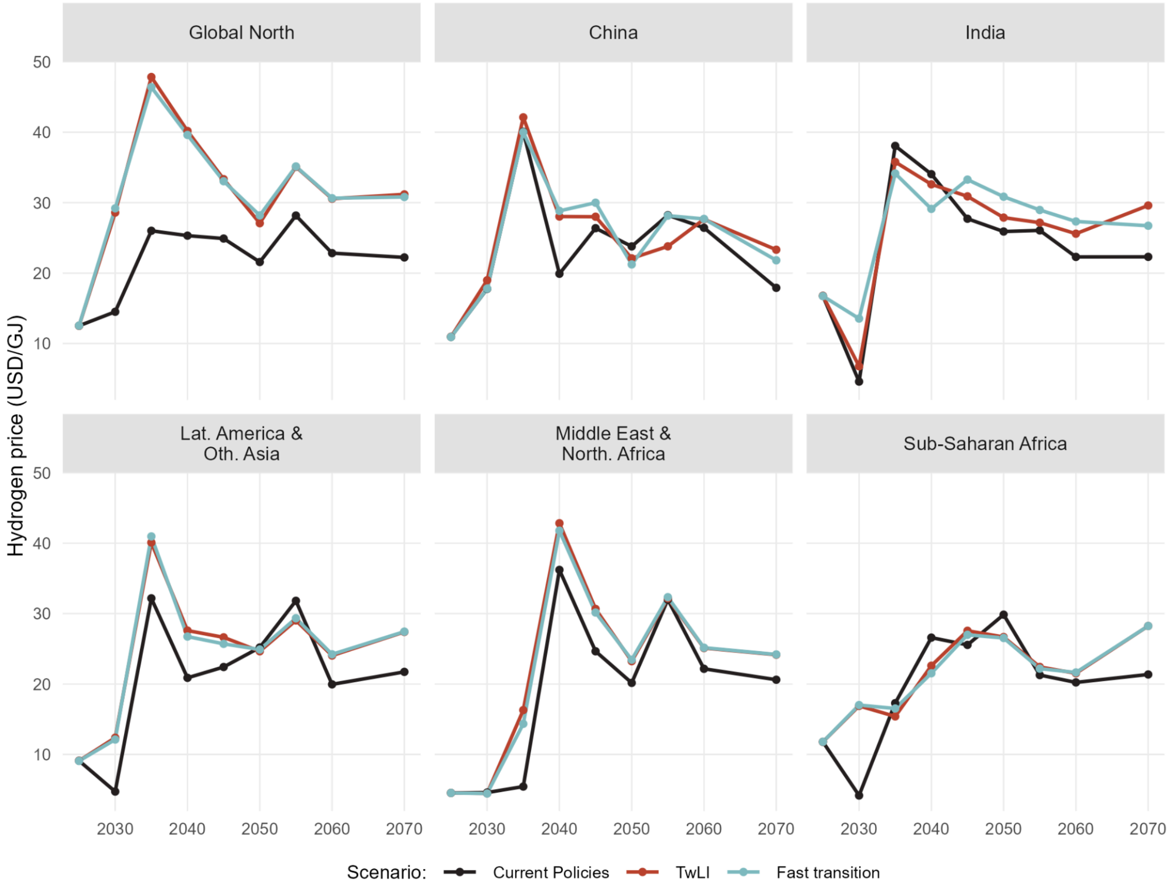

Figure S7: Hydrogen prices for the industry sectors.

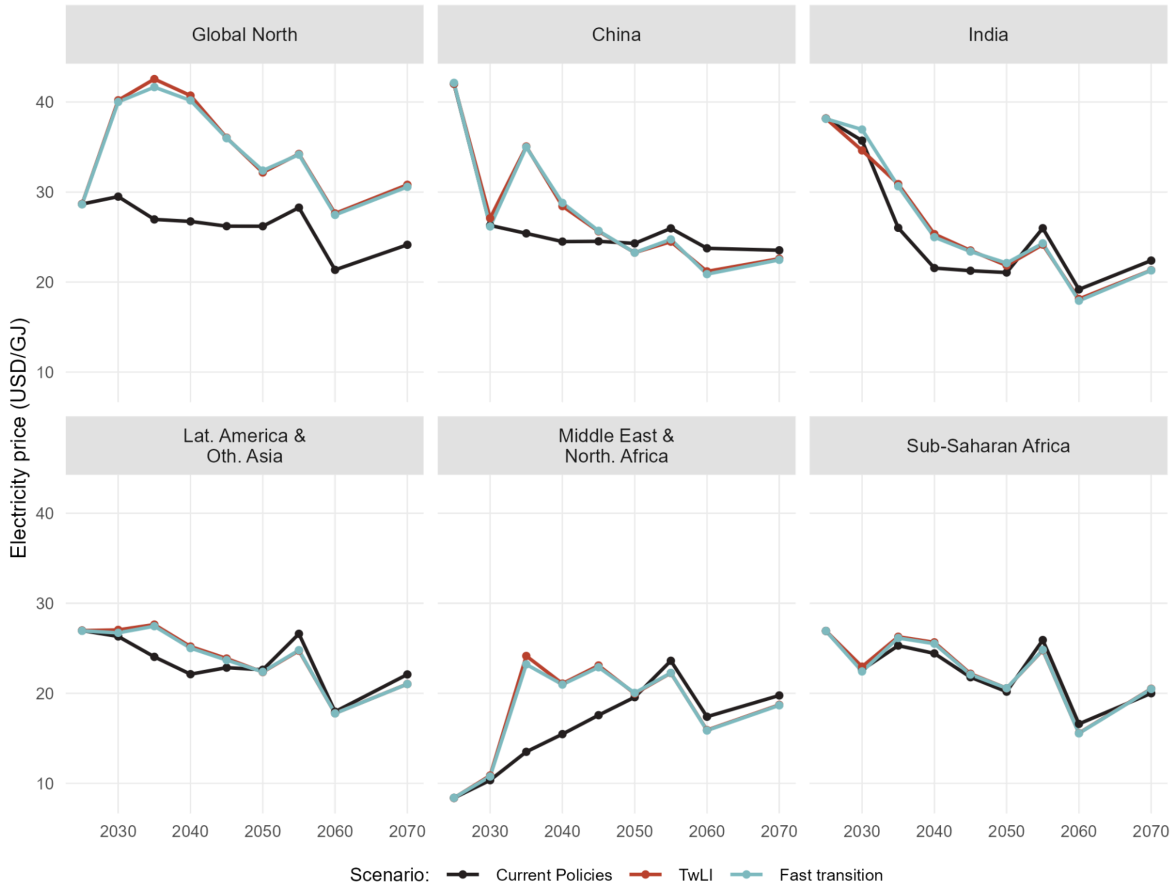

Figure S8: Electricity prices for the industry sectors.