Appendix A. Sensitivity Analysis

In order to estimate the impact of key input assumptions on our model results, we conducted a sensitivity analysis along two critical dimensions. We varied the applied discount rate as well as the trade bounds. The results of the sensitivity analysis are displayed in figure A.1; below, we discuss the results in detail along these two aspects of the model.

Trade Bounds

A fundamental drawback of stand-alone national models is that international trade has to be calibrated as a model-exogenous parameter. In order to estimate the impact caused by the chosen trade calibration, we reran our scenarios in one high-trade and one low-trade setup. In the high-trade setup we raised the constraints and bounds on all trade technologies by 100 %, thus giving the model twice the flexibility on trade volumes. In the low-trade case, we decreased the bounds by 50 %, thus halving the leeway on imports and exports. The results show, that even though the trade bounds do influence the model results significantly, the dynamics of shale gas, coal and emission mitigation remain alike.

High Trade: In the high trade scenarios, coal extraction for export increases as long as this is economically feasible under the applied carbon price. If the price increases over the threshold of about 15 USD/tCO_2, coal extraction is reduced to levels below the scenarios with the standard trade assumptions and coal is substituted by natural gas from domestic shale gas sources where economically viable, or through imported high-quality fuels otherwise. The same holds true for the shale gas extraction, i.e., more shale gas is extracted below its economic threshold (around 30 USD/CO_2) and slightly less in the scenarios thereafter. The high trade scenario has no significant influence upon the renewable energy use.

As a result, fossil primary energy consumption increases to levels above the model scenario at low carbon prices, but decreases below the model scenario values at carbon prices of 25 USD/tCO_2 and above. These dynamics induce an increase in CO_2 emissions at no- to low carbon prices but significantly reduces emissions at carbon prices of 15 USD/tCO_2 and above.

Low Trade: Vice versa in the low trade scenario, the marginal cost of coal decreases as the export market is not available and thus more coal is used domestically. The lacking export demand leads to a lowered coal extraction at no- to low carbon prices below the economic coal export threshold ($\leq$ 15 USD/tCO_2) and thus to a decrease in primary fossil energy supply at those carbon price levels. At higher carbon prices the dynamics reverse. This is on the one hand due to the fact that the coal resources are still available in those scenarios but there is no other use for the coal than to use it domestically, thus, the marginal costs decreases significantly. On the other hand, South Africa heavily depends on imports for their gasoline and natural gas supply. If those supplies are limited, more coal is needed for the production of synthetic fuels.

In the low trade scenarios shale gas extraction at low carbon prices is curtailed by the limited trade opportunities. However, the limited access to high quality fuels (such as methane gas and fuel oil) from the import market increase the marginal utility of shale gas and thus increases domestic shale gas use at higher carbon prices. Due to the decreased marginal costs of both, coal and shale gas, in the low trade scenarios renewable energy use is reduced compared to the model scenarios.

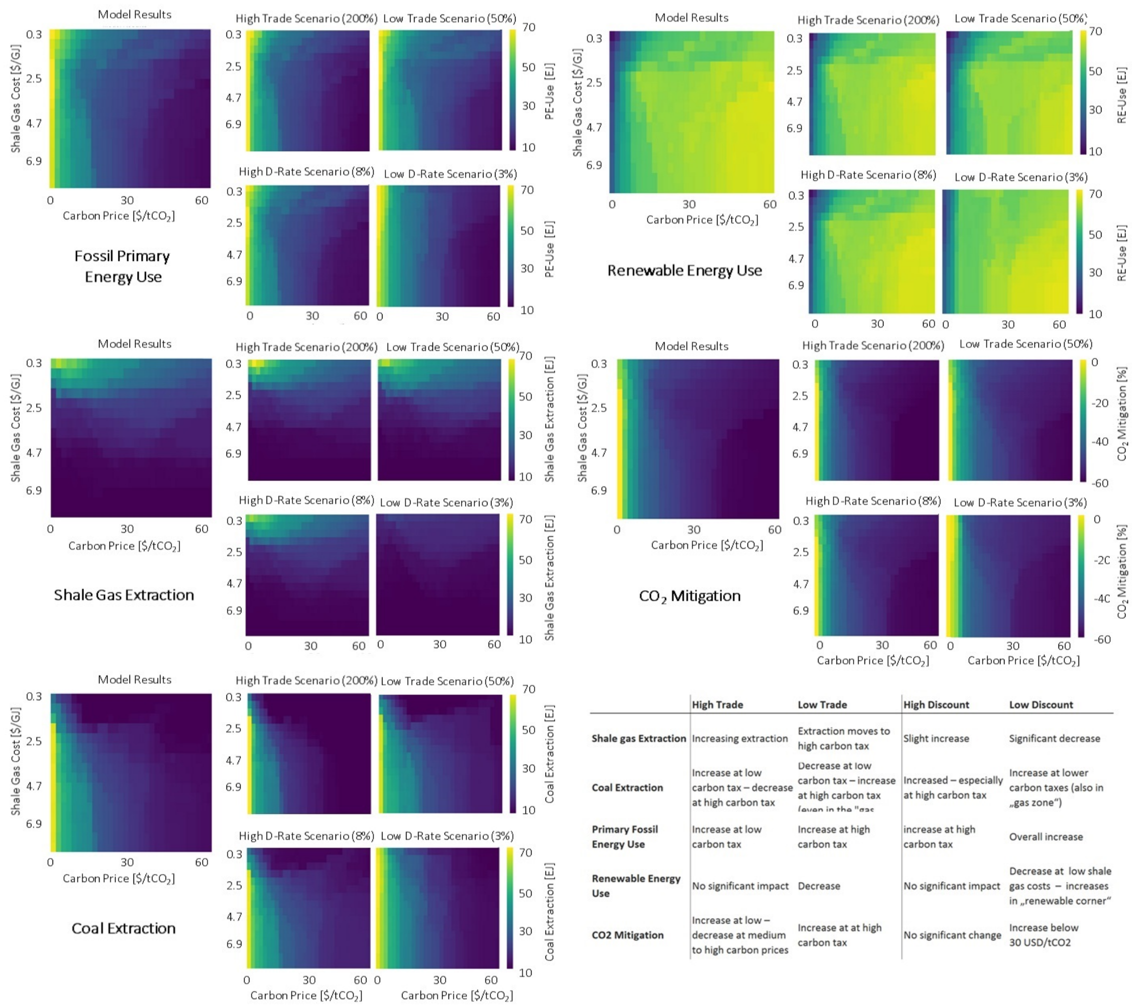
In summary, this leads to a significant increase in primary energy supply at moderate to high carbon prices and thus to significantly higher CO_2 Emissions.

Discount Rates

The discount rate applicable to energy models such as MESSAGEix-South Africa is a heavily debated topic. To verify whether the effects observed in this paper hold true also under a different discount rates, we repeated the analysis in a high-discount-rate (8 %) and a low-discount-rate scenario (3 %) setup, compared to a discount rate of 5 % for all results presented in the main text of this work. The remaining parameters where left unchanged in order for the results to distinctly single out the impact of the variation in the discount rate. The results show that, just as for the trade bound analysis, the discount rate does influence the model results but does not alter the fundamental model dynamics. The key findings of our work are robust against alternative discount rate assumptions.

High Discount Rate: A high discount rate favours technologies with relatively lower investment and higher operating costs, in particular gas-fired power plants. Only minor changes are observed across the scenarios when assuming a high discount rate. Shale gas extraction is overall slightly increased compared to the moderate scenario; coal extraction is slightly increased especially at higher carbon prices. Those dynamics lead to overall increased primary fossil energy demand and hence higher CO_2 emissions compared to the scenario results using the standard discount rate.

Low Discount Rate: At a low discount rate of 3 %, shale gas use becomes economically less competitive and only small quantities of shale gas are used in most scenarios. In the low-to-moderate carbon price scenarios, energy is instead provided by increased coal extraction; in the moderate-to-high carbon price scenarios, demand is met by imported high-quality fuels and nuclear power; and at very high carbon prices, higher utilization of renewable power. However, as the lower discount rate discourages gas use, renewable power use is impeded due to the reliability and flexibility constraints to ensure. Overall, this leads to an increase in primary energy supply. However, this effects fades at very high carbon prices in which gas-independent investment-heavy flexible renewable power stations, such as solar thermal power stations with storage facilities, become economically viable. The same dynamics affect the CO2 emissions accordingly and can be observed in the CO_2 mitigation plot.



	High Trade	Low Trade	High Discount	Low Discount
Shale gas Extraction	Increasing extraction	Extraction moves to high carbon tax	Slight increase	Significant decrease
Coal Extraction	Increase at low carbon tax – decrease at high carbon tax	Decrease at low carbon tax – increase at high carbon tax (even in the "gas	Increased – especially at high carbon tax	Increase at lower carbon taxes (also in „gas zone“)
Primary Fossil Energy Use	Increase at low carbon tax	Increase at high carbon tax	increase at high carbon tax	Overall increase
Renewable Energy Use	No significant impact	Decrease	No significant impact	Decrease at low shale gas costs – increases in „renewable corner“
CO2 Mitigation	Increase at low – decrease at medium to high carbon prices	Increase at at high carbon tax	No significant change	Increase below 30 USD/tCO2

Figure A.1: Comparative results of the model runs and the sensitivity variation.