# South Africa's Shale Gas Resources – Chance or Challenge?

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**Abstract**

South Africa faces the triple challenge of (a) fueling its economic development by meeting the rapidly growing energy demand; (b) increasing the reliability of its power system; and (c) letting domestic greenhouse gas emissions peak between 2020 and 2025 in line with its pledge to the UNFCCC under the Paris agreement. Recently discovered domestic shale gas reserves are currently under evaluation as a potential new energy source, to provide clean, reliable and cheap electricity while mitigating greenhouse gas emissions. But, the impact of shale gas on greenhouse gas emissions is far from settled. In order to evaluate if shale gas can play a viable role in solving South Africa's energy dilemma, we apply a country-level version of the integrated assessment model MESSAGE to analyze and quantify the interdependence between shale gas extraction and climate change mitigation effort regarding the South African energy pathways and its domestic greenhouse gas emissions.

Our results illustrate, that low cost shale gas can lower the overall energy system costs compared to the no-shale-gas counterfactual. At the same time, a system with abundant low cost natural gas from shale sources requires a stronger carbon price signal compared to the no-shale-gas scenarios in order to achieve the same desired mitigation goals. Therefore, reaching the mitigation goals might be more economically achievable utilizing low cost shale gas in combination with a more stringent climate policy measure compared to a no-shale-gas scenario.

*Keywords:* MESSAGE, carbon tax, scenario analysis, COP 21, INDC, Integrated Assessment Modeling

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## 1. Introduction

South Africa's economy is one of the most carbon-intensive in the world (Alton et al., 2014; Winkler, 2007). Compared to the global average, South Africa's $CO_2$ emissions per capita are about twice as high and $CO_2$ emissions per unit of GDP are close to three times as high (Table 1). Abundant coal resources and a heavily subsidized mining sector used to attract and support energy-intensive industries and a power sector based on coal. Today those carbon intensive consumers are the major drivers of economic development in South Africa (Klausbruckner et al., 2016). In spite of the large domestic resources, the power sector has experienced shortages and blackouts due to suboptimal management, the reliance on old and inefficient coal power plants, and the rapid increase in power demand. This energy shortage resulted in fast-rising electricity prices which today hamper economic development (Eberhard et al., 2014).

Table 1: Key indicators on South Africa's energy and $CO_2$ emission intensity in comparison to the world in the model base year (2010) and the latest published year (2014) (WB, 2016b; BP, 2016; IEA, 2014).

| | | South Africa | | World | |
|---|---|---|---|---|---|
| | | **2010** | **2014** | **2010** | **2014** |
| Population | millions | 51 | 54 | 6 900 | 7 200 |
| Gross Domestic Product (GDP) | billion $USD_{2010}$ | 375 | 410 | 65 600 | 72 900 |
| Primary Energy Supply (PES) | EJ | 5.9 | 6.3 | 544 | 574 |
| $CO_2$ Emissions | $MtCO_2$ | 410 | 440 | 30 500 | 32 400 |
| PES per Capita | GJ/capita | 117 | 113 | 80 | 80 |
| $CO_2$ per Capita | $tCO_2$/capita | 8.0 | 8.1 | 4.4 | 4.5 |
| $CO_2$ per GDP | $kgCO_2/USD_{2010}$ | 1.1 | 1.1 | 0.5 | 0.4 |

Recently, the South African government committed to a significant reduction of greenhouse gas (GHG) emissions (UNFCCC, 2015). At the 2015 Conference of the Parties in Paris (COP21), South Africa confirmed and strengthened its intention to reduce GHG emissions. According to the Paris agreement, the Nationally Determined Contribution (NDC) of South Africa envisions GHG emissions to peak no later than 2030, and to achieve a decline of GHG emissions thereafter (UNFCCC, 2015). As shown in Figure 1, the proposed trajectory implies a significant structural transformation of the South African energy system, as it departs drastically from current emissions projections under "business-as-usual" assumptions (Klausbruckner et al., 2016; Henneman et al., 2016).

One potential structural measure for ending South Africa's energy crisis is currently under governmental review and subject of heated public debates: industrial-scale hydraulic shale gas fracturing (so called *fracking*), a technique enabling natural gas production from previously uneconomic shale gas resources (CSIR and SANBI, 2016). With its lower $CO_2$ emissions compared to coal, natural gas derived from shale is considered a possible remedy for South Africa's energy challenge. It may allow to satisfy the growing energy demand while emitting less GHG and other pollutants than the current coal-based power plant portfolio (Burnham et al., 2012). As with most technological advances, there are supporters and opponents of shale gas exploitation in South Africa. On the one hand, shale gas fracking opponents voice concerns about the potential negative social and environmental impacts caused by shale gas extraction. They cite impacts experienced in the US such as increased threat of earthquakes, water pollution, ground water table lowering, and methane leakage during the fracking process and relate them to the South African geology and geography (Esterhuyse et al., 2016). On the other hand, promoters point out the substantial benefits that large-scale domestic shale gas development could have: economic growth, reduced local air pollution (e.g. sulfur, black carbon), and decreasing import dependence.

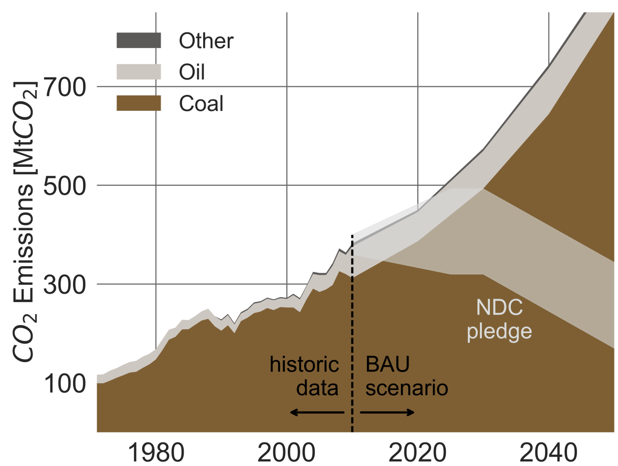



Figure 1: South Africa's energy-related $CO_2$ emissions as recorded in the past (1971-2010) and as calculated for a no-carbon-price *business-as-usual* (BAU, 2010 - 2050) scenario per emissions source. The fair shaded area shows South Africa's NDC reduction pledge.

Hence, the benefits and shortfalls of shale gas utilization are to be seen as a multi-dimensional problem with some researchers valuing the economic and climate benefits higher than the detrimental environmental side effects and the other way around. Some researchers find that shale gas could reduce $CO_2$ emissions by substituting coal as a more efficient and cleaner fuel (Hultman et al., 2011; Cathles et al., 2012; Burnham et al., 2012; O'Sullivan and Paltsev, 2012). Other studies observe that non-$CO_2$ emissions associated with the production of shale gas, most importantly fugitive methane, might increase life-cycle GHG emissions of this fuel to levels above those of coal combustion (Howarth et al., 2011; McJeon et al., 2014; Miller et al., 2013; Howarth, 2015). These contradicting views pose a challenge to the South African government when designing and implementing an effective carbon mitigation strategy, while at the same time carefully balancing the competing goals of cheap and reliable energy, stable economic development, and a clean and safe environment. In order to inform the debate and facilitate the decision process, the South African government has commissioned the Strategic Environmental Assessment for Shale Gas Development in South Africa to conduct a transparent and comprehensive analysis on the effects shale gas fracking (CSIR and SANBI, 2016).

In the present work, we add to this assessment by evaluating shale gas exploitation as a measure designed to end South Africa's energy shortage and mitigate the countries' fast-rising greenhouse gas emissions. We conduct an extensive scenario analysis of the GHG mitigation potential of shale gas conducted with a country-level version of the Integrated Assessment Model MESSAGE.

## 2. Methodology

To identify the economic boundaries of shale gas development and the associated change in $CO_2$ emissions, we employ a multi-scenario analysis. We utilize a long-term horizon, linear, least-cost integrated assessment model of the South African energy system (MESSAGEix South Africa). Its main objective is to explore the uncertainty and evaluate important factors that impact the potential role of gas. Therefore a lean model was built that enables large scale sensitivity analysis. MESSAGEix South Africa is well-suited to evaluating the GHG emission impact of shale gas fracking as it describes the entire energy supply system. The linear model setup is computationally lean, which is a prerequisite for solving a large number of long-term scenarios to fully explore the ranges of different pathways in terms of emissions and the role of shale gas in the future South African energy system. This is important for capturing the full picture of system dynamics behind shale gas, the energy system, the economy and its impact on climate forcing and the entire set of possible outcomes inevitable in the face of the uncertainty connected to it.

### 2.1. The MESSAGEix South Africa model

MESSAGEix South Africa is a country-level application of the Integrated Assessment Model MESSAGEix (Model for Energy Supply Strategy Alternatives and their General Environmental Impact), developed at the International Institute of Applied Systems Analysis (IIASA) over the past decades (Riahi et al., 2012).

For this analysis, we use the new MESSAGEix platform (Huppmann et al., in preparation): this framework consists of a GAMS implementation of the energy-engineering-economic-environment (E4) optimization model; a dedicated database infrastructure for version-controlled management of input assumptions and model results; interfaces to scientific programming languages Python and R for efficient data processing; and a web user interface for visualization and analysis. The modeling platform is geared towards efficient scientific workflows as well as the highest level of transparency of both input data and modeling results.

For developing the MESSAGE South Africa model, we implemented a workflow to collect data from multiple sources, thereby automating much of the parametrization and calibration of a national energy system model. These data sources include the most recent global version of the MESSAGE model (Krey et al., 2016), statistics provided by the International Energy Agency (IEA, 2016), historical power plant installation data from CARMA (Ummel, 2012; Wheeler and Ummel, 2008), and various national reports and statistics (see section 2.2).

Building a ”stand-alone” national model requires assumptions on commodity trade and the global price levels of fossil fuels to ”close” the model, in particular because of South Africa’s dependence on oil imports and its substantial coal exports. For our analysis, global commodity prices and upper bounds on imports and exports are based on the recently published Shared Socioeconomic Pathways (SSP), a scientific narrative framework of socioeconomic development projections for climate change research (Riahi et al., 2017; O’Neill et al., 2017; van Vuuren et al., 2017). We chose the SSP narrative as they allow us to understand the results of our analysis in the global development context. Out of the five available SSP scenarios, we based our assumptions on the moderate development ”middle of the road” pathway SSP2 (Fricko et al., 2017; KC and Lutz, 2017; Dellink et al., 2017).

The analysis focuses on the medium-term outlook until 2050. This is the time frame of relevance for the development of a shale gas industry and the horizon that will decide if South Africa can reach the emission trajectory proposed in the NDC. The underlying model extends to 2100 to avoid ’end-of-timehorizon’ effects, which might oteherwise bias the numerical results.

### 2.2. *Data & Scenario Assumptions*

In order to maintain consistency with the global version of the MESSAGE model, technology specifications, development costs and boundaries are based on the region ”Sub-Saharan Africa” of the global data set (Krey et al., 2016; GEA, 2012). However, we adjust certain parameters, most notably the technology costs, where better data from national sources was available (Bedilion et al., 2012; Department of Energy, 2013).

*Energy Demand:*. In our model the energy demand is represented as ”useful energy” demand, i.e. the demand for energy services such as heating or electric appliances, such that the model endogenously determines the optimal mix of technologies and final energy consumption under the given constraints on the energy system and policy measures in place. In MESSAGEix South Africa the demand is split into three energy-consuming sectors: residential & commercial (RC), industry and transport (Table 3). The energy demand of the RC and industrial sectors is split into a specific electric and a thermal demand as well as a consumption of non-energy feed-stock in the petrochemical industry. This detailed representation of future energy consumption is extrapolated for South Africa based on the historical development and the SSP2 scenario parameters.

*Energy Resources & Potentials:*. Data on fossil energy commodities considered in the model are based on national and international resource assessments (Table 2). The renewable energy potential was estimated based on spatially disaggregated data set available online (Tables 4, 5 & 6) (Eurek et al., 2016; Pietzcker et al., 2014). Considering the vast wind energy potential of South Africa, only the on-shore wind energy potential of production sites close (0-50 miles) to consumption sites was considered for this analysis. However, not even this small share of South Africa's wind power potential was fully exploited in any of the scenarios. Utilization of renewable power potentials in MESSAGEix South Africa is based on a linear representation distinguishing across multiple availability classes (Sullivan et al., 2013). The formulation also considers system-wide impacts regarding the reliability of variable renewable energy sources and ensures sufficient installation of firm, dispatchable capacity.

*Greenhouse Gas Emissions:*. MESSAGEix South Africa calculates GHG emissions 'production-based', i.e. only fuels combusted and fugitive emissions occurring within country-boundaries are contribute to the country's GHG emissions. In the current version, the most important GHGs from the energy system, $CO_2$ and $CH_4$, in 2010 representing about 85 % of total GHG emissions, or 99 % of GHG emissions from the energy system, are accounted for in the model (WB, 2016b; Witi et al., 2014).[1] The emission factors are based on literature. The $CO_2$ emission factors are based on emission factors based on IPCC national inventory guidelines (IPCC, 1996), the $CH_4$ emission factors are based on recent research by Höglund-Isaksson (2017). In order to compare the modeled emission trajectories to the national GHG reduction path proposed in the NDC, we adjust the trajectories by the proportional share of non-$CO_2$/$CH_4$ and non-energy-related emissions.

*Carbon Price:.* A suite of policies will be enacted to meet South Africa's emission mitigation goals; these will include fiscal incentives, regulatory policies and public financing. However, for the purpose of this study we decide to use carbon pricing as a proxy mechanism to represent the effect induced through a balanced policy portfolio. The marginal carbon tax rate proposed in the current draft of South Africa's carbon tax bill is 9 USD/t$CO_2$ (120 ZAR/ t$CO_2$) (Ministry of Finance, 2015). Taking into account the multiple tax exemptions in the bill, the effective rate is estimated to vary between 0.4 to 3.5 USD/t$CO_2$ (6 to 48 ZAR/ t$CO_2$) (WB, 2016a). The South African government proposes an escalation rate for the carbon tax of 10 % for the first two years (2017 – 2019) (Ministry of Finance, 2015). However, the carbon tax bill has not yet been implemented and no decisions have been made on how the tax will develop after the first introduction phase. Thus we assume that there will be no carbon price before 2020. We test various levels of the introductory carbon price and project an escalation of 5 % per year across all sectors and industries.

*Shale Gas:.* The shale gas volumes considered in the model are based on the shale gas availability assessment by the eia (2015). Their assessment concludes that 370 tcf (400 EJ), i.e. around 60 times South Africa's current primary energy use or close to global primary energy use in 2015 (500 EJ), of shale gas are technically recoverable in South Africa. This might be an overestimation of the realistically extractable resource volume (Geel et al., 2013), but, as the resource volume is found not to be the limiting factor to the shale gas extraction across scenarios, the impact of the overestimation is not significant. The growth limitations for the shale gas industry are based on the growth rates experienced in the U.S. (e.g. Fayetteville, Marcellus, Woodford, Bakken, Haynesville and Barnett plays) (eia, 2016a; Richter, 2015). In our model we limit the South African shale gas production during the first decade of production to 50 % of the respective U.S. production growth rates because South African does not yet have the necessary gas infrastructure, including

[1]The global warming potential metric used by the model is based on the cumulative forcing potential over 100 years as listed in the IPCCs Fifth Assessment Report (Myhre et al., 2014).

long-distance pipelines and local distribution networks. This calculation results in a annual production limit during the fist decade of 1 EJ/a and thereafter in an annual growth rate of ±10 %, which confirms literature estimates on on South Africa's shale gas industry potential (Altieri and Stone, 2016).

Given the numerous uncertainties connected to shale gas exploitation in South Africa, we base our study on a analysis of more than 10,000 scenario. Within those scenarios we vary the most influential input parameters across a wide range of values: (a) the average shale gas extraction cost, (b) the average effective carbon price, (c) the price development of imported fossil fuels and (d) the assumed growth parameters of the import and export markets.

*Carbon Capture and Storage:.* We consider carbon capture and storage (CCS) technologies in the transformation as well as in the power sector.[2] As carbon capture and storage technologies are not yet available on commercial scale to the South African market, the first year of operation is defined to be 2030 earliest.

### *2.3. Scenario Description*

*No-Shale-Gas Scenarios:.* We first construct a set of scenarios which exclude shale gas exploitation in order to provide a reasonable counterfactual with which to assess the implications of shale gas utilization. This no-shale-gas scenario set considers 61 introductory carbon price levels ranging from 0 to 60 USD/t$CO_2$and escalating at 5 % per year. This extensive range reflects (a) the high carbon prices required for limiting global warming to 1.5°C (Aldy et al., 2008), (b) the low effective carbon tax level scheduled for introduction in South Africa (3.5 USD/t$CO_2$) and (c) the current situation of no effective carbon price (Ministry of Finance, 2015).

*Shale Gas Scenarios:.* The scenarios introduced now consider shale gas utilization under thirty different extraction cost levels ranging from 1 to 10 USD/GJ and the same carbon prices as in the first set of scenarios. For the first part of the analysis, we reduce the number of scenarios to the seven representative carbon tax levels already evaluated in the no-shale-gas scenario section to focus on the salient aspects. The subsequent analysis uses the entire set of 1800 scenarios.

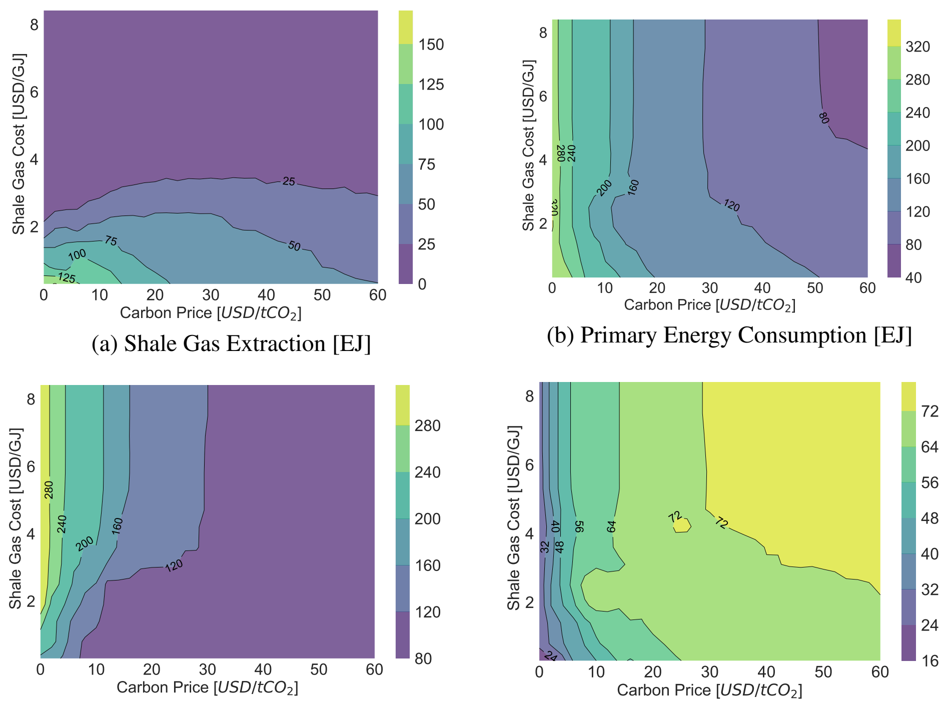
[2]CCS-capable fuel transformation technologies available to the model are: coal to methanol, synthetic liquids (coal to light and fuel oil) and gas to methanol. CCS-capable power plants technologies available to the model are: coal, integrated coal gasification and gas combined cycle power plants.

## 3. Results

We now consider the differences in results between the scenarios with and without a carbon price without shale gas available and the same scenarios with shale gas available at various cost levels in terms of energy demand, efficiency of the energy system, GHG emissions and the GDP development.

### *3.1. Temporally Aggregated Scenario Results*

Figures 2 and 3 show the temporally aggregated results of 1,800 shale-gas-scenario runs. All plots show the cumulative values of one specific variable over the time horizon (2020-2050) for each of the scenarios.




(a) Shale Gas Extraction [EJ]

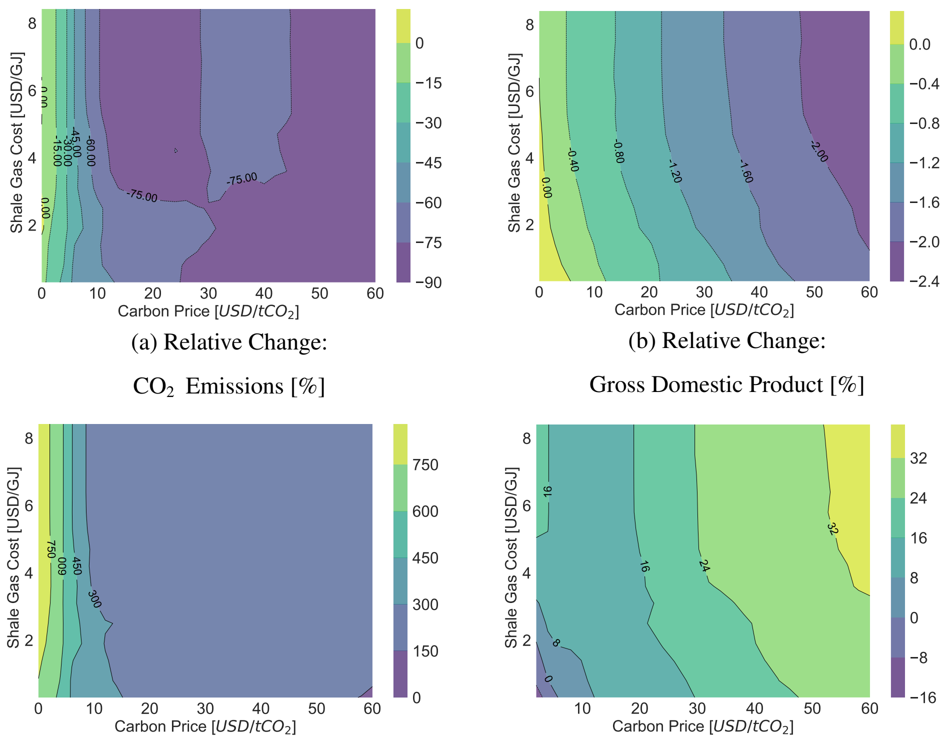
(b) Primary Energy Consumption [EJ]

(c) Coal Extraction [EJ]

(d) Energy Use from Renewable Sources [EJ]

Figure 2: Cumulative model results (2020-2050) on the usage of renewable energy carriers and fuels.

*Shale Gas Utilization and Energy Use:*. Shale gas is used if variable extraction costs lie below about 3 USD/GJ. Beneath this cost level, the economics of shale gas extraction depend on the carbon price in place: the higher the extraction costs, the higher the carbon price needs to be to make shale gas economically favorable over other fuels (Figure 2a). If shale gas use is economically viable, it reduces coal use by up to one third (Figure 2c). However, low cost shale gas also reduces renewable energy use by up to 30 %




(a) Relative Change: $CO_2$ Emissions [%]

(b) Relative Change: Gross Domestic Product [%]

(c) $CO_2$ Emitted per GDP [$gCO_2$/USD]

(d) Mitigation Costs [ USD/$tCO_2$]

Figure 3: Cumulative model results (2020-2050) on $CO_2$ emissions and the GDP. (a) and (b) show the relative change of the scenario results compared to the no-shale-gas and no-carbon-price baseline scenario. The mitigation costs shown in (d) are here defined as the ratio between the GDP reduction per ton of $CO_2$ mitigated.

(Figure 2d). While coal use is reduced more significantly at higher carbon prices, renewable energy use is reduced stronger at low carbon prices.

Energy demand is elastic to energy costs: with increasing carbon prices energy demand decreases but the availability of low cost shale gas can delay this feedback. The availability of low cost shale gas can therefore increase the useful energy demand across all scenarios compared to the respective no-shale-gas scenarios. This is also true for primary energy consumption at most shale gas cost and carbon price levels. But, at shale gas extraction costs above 2 USD/GJ and carbon prices between 7 to 20 USD/$tCO_2$ the opposite effect appears: primary energy consumption is decreased by shale gas utilization (Figure 2b). As a result, the ratio between the useful energy consumption and the fossil primary energy consumption is decreased by shale gas use in most scenarios, apart from those low primary energy use scenarios at shale gas extraction costs above 2 USD/GJ and carbon prices between 7 to 20 USD/$tCO_2$ .

*Emissions and Socio Economic Implications:.* The cumulative $CO_2$ emissions over the 2020 to 2050 time horizon are strongly reduced with increasing carbon price. The emissions are however also influenced by shale gas use. At carbon prices above 5 USD/t$CO_2$ shale gas use increases $CO_2$ emissions (Figure 3a). This effect fades at carbon prices above 30 USD/t$CO_2$.

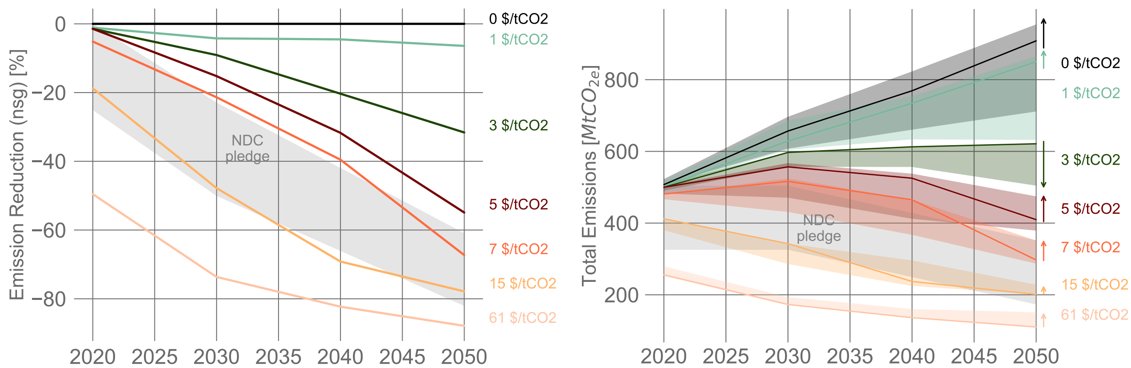
The gross domestic product (GDP) as a measure for energy system supply cost and elastic demand is affected by carbon prices and shale gas costs: The higher the carbon prices are, the more expensive the energy system gets. The cumulative GDP decreases by up to 2 % with increasing carbon prices (Figure 3b). However this effect can be subdued by the availability of potentially low cost shale gas. The average macro-economic costs for mitigating one ton of $CO_2$ is for example significantly reduced from 12 to 4 USD/t$CO_2$ at a 5 USD/t$CO_2$ carbon price (Figure 3d). However, the amount of $CO_2$ emitted per USD of GDP generated is nevertheless increased by shale gas use at carbon prices above 5 USD/t$CO_2$ compared to the same scenario without economically available shale gas (Figure 3c). It should be noted that the GDP effects described here do not include benefits from reduced climate change impacts or co-benefits or adverse side-effects of mitigation action (e.g., reduced air pollution and associated health and environmental impacts).

### *3.2. Emission Trajectories and the NDC Pledge*

*No-Shale-Gas Scenarios:.* Figure 4a shows the relative greenhouse gas ($CO_2$ & $CH_4$) emission reduction in the no-shale-gas scenarios under different carbon prices relative to the BAU (no-shale-gas and no-carbon-price) scenario. The figure shows that in all no-shale-gas scenarios the carbon price is the determining factor for the development of the energy systems emission trajectory. The variations in carbon price induce a strong variation of emission trajectories and the energy sector's diversity. We find that even though any positive carbon price will lead to a reduction in emissions compared to the no-carbon-price scenario, an introductory carbon price of 7 USD/t$CO_2$ (in 2020, growing at 5% p.a.), or above is required in order to transform the emission trajectory to resemble the desired peak-plateau-decline development (Figure 4b). If the carbon price is increased beyond this value the overall level of emissions decreases further and the emission peak moves towards earlier points in time.

In our model the emission trajectory pledged in South Africa's NDC can be met without the utilization of shale gas under the assumptions stated above if a carbon price of 7 USD/t$CO_2$ or above is introduced by 2020, growing to 22 USD/t$CO_2$ by 2050.

*Shale Gas Scenarios:.* Figure 4b summarizes the energy-related GHG emissions under seven illustrative carbon price trajectories under various gas extraction costs. It visualizes the impact imposed by carbon




(a) Relative GHG emission reduction [%]

(b) Absolute GHG emissions [ $MtCO_2$]

Figure 4: Energy-related $CO_2$ & $CH_4$ emissions at selected carbon prices under various gas extraction costs. The gray shaded area shows South Africa's NDC reduction pledge (UNFCCC, 2015) (a) shows the relative reduction in the no-shale-gas scenarios under selected carbon prices relative to the zero carbon price (BAU) scenario. (b) shows the impact of shale gas utilization upon the GHG emission trajectory. The lines indicate the no-shale-gas scenarios, the shaded areas indicate the emission range if shale gas is available at various extraction costs. The figure shows that shale gas utilization decreases emissions at low carbon prices (green), but increases them at moderate to high carbon price levels (red).

price and shale gas extraction costs upon the emission trajectory. While Figure 4a is about the relative emission reduction, Figure 4b displays the development of the absolute GHG emissions of the scenario sets. The figure displays the temporal disaggregation of what has been found before: shale gas utilization can impact South Africa's energy-related GHG emissions in either direction depending on the carbon price and the shale gas extraction costs. While at low carbon prices, the availability of shale gas can lower South Africa's GHG emissions, the emissions can increase compared to the no-shale-gas-baselines if carbon prices of 5 USD/$tCO_2$ an above are in place.

### *3.3. Impacts on the Power Sector Development*

Figure 5 shows the total installed capacity and Figure 6 the total production over the planning horizon for twelve selected scenarios featuring variable shale gas extraction costs of 10, 3 and 1 USD/GJ and carbon prices of 0, 10 and 30 USD/$tCO_2$.

*High Cost (10 USD/GJ) Shale Gas Scenarios:.* The total power generation capacity of the no-carbon-price and high cost shale gas scenario reaches 155 GW in 2050 whereof the majority is coal fired power plants (65 %). The power generation over the entire time horizon is also dominated by coal power plants (more than 87 %), while renewable power stations supply no more than 9 % to the power generation. The coal dominated power plant portfolio is complemented with 30 GW of each gas fired (open and combined cycle gas turbines) and renewable power plants (photovoltaik, solar thermal, concentrated solar and wind power plants). The remainder is made up of nuclear power stations and electricity imports.

With increasing carbon prices the power demand decreases and the renewable power stations gain share. At 10 USD/t$CO_2$ the summed power demand over the time horizon reduces by 10 %. 38 % of the power supply is produced from renewable sources. If the carbon price is increased to 30 USD/t$CO_2$ the renewable power generation is further expanded to half of the total power demand and coal power generation is reduced to 18 %. As coal use is further reduced in this scenario, the remaining power generation is prevailed by nuclear power stations (20 %). In both scenarios gas power plants persist on low full load hours only supporting the power system during peak load. The increase in renewable power generation, in the carbon price scenarios, is accompanied by an increase in total installed power generation capacity: at a carbon price of 10 USD/t$CO_2$ a total of 210 GW of power generation capacity is installed, at 30 USD/t$CO_2$ this value further increases to 240 GW (Figures 5 - 6).

*Moderate Cost (3 USD/GJ) Shale Gas Scenarios:.* In a no-carbon-price scenario, moderately priced shale gas has a small impact on the system. The lower energy costs compared to the no-shale-gas scenarios increase energy demand by 9 % even though the majority of electricity is still produced by coal fired power plants (86 %). However, more electricity is generated in fluctuating renewable power stations (5 %) as they are complemented by flexible gas fired power plants (5 %).

At a carbon price of 10 USD/t$CO_2$ renewable power generation facilities increase their share enough to supply close to 40 % of the total power demand. Supported by gas power plants, renewable power reduces coal power generation to below 50 %. If carbon prices increase further to 30 USD/t$CO_2$ coal power generation is diminished by 2040 as renewable and gas power stations are complemented with nuclear power facilities.

*Low Cost (1 USD/GJ) Shale Gas Scenarios:.* If low cost shale gas is available in abundance, gas fired power plants dominate South Africa's power generation fleet with as well as without a carbon price in place. In all scenarios, the low cost shale gas replaces the otherwise dominating power source.

Without a carbon price in place, low cost shale gas supersedes the otherwise predominant coal power generation. At a carbon price of 10 USD/t$CO_2$ the gas fired power stations do not only economically outcompete coal power plants but also renewable power generation, therefore displacing both technologies by about the same amount. At a carbon price of 30 USD/t$CO_2$ low cost shale gas supplements a small share of nuclear power, inducing a power generation portfolio similar to the portfolio exhibited at moderate shale gas costs.

## 4. Discussion & Conclusion

South Africa is considering to utilize its shale gas reserves to reduce its high greenhouse gas emissions and initiate a downward shift in line with its GHG mitigation pledge at the Paris climate conference. In this paper, we evaluate the consequences of introducing shale gas upon South Africa's energy-related GHG emissions and the related implications for South Africa's ambitions on fulfilling the NDC pledges: reducing greenhouse gas emissions emissions to 398 - 614 Mt$CO_2$-e, including land use, land use change and forestry, over the period 2025-2030 (UNFCCC, 2015). Our impact assessment extends previous research for South Africa by constructing a technology-specific assessment model of the South African energy system that incorporates global development trends through projections from the SSP2 pathway. Unlike previous studies, this study evaluates several thousand scenarios to properly capture the full range of shale gas cost and carbon price assumptions.

The no-shale-gas scenarios confirm and extend the findings of previous research: a carbon price can effectively reduce South Africa's energy-related GHG emissions (Merven et al., 2014; Henneman et al., 2016). As already described in literature, we too find, that already a moderate carbon price of 7 USD/t$CO_2$ (in 2020, growing at 5% p.a.), could reduce the South African GHG emissions by 60 % compared to the BAU (no-shale-gas and no-carbon-price) scenario, leading to a fulfillment of the NDC pledge (Pegels, 2010). Additionally our systematic sensitivity analysis add to literature by allowing for a detailed impact assessment on effects, that carbon prices have upon the countries power system and the energy supply chain.

The shale gas scenarios indicate that: if shale gas is abundant at low cost it can impact South Africa's energy future significantly, thereby confirming for South Africa what has previously been found for other countries (Baranes et al., 2017). Further, the extensive scenario analysis gives insights on how and under which conditions this impact might occur. We find that for shale gas to have a significant impact, variable extraction costs have to lie well below 3 USD/GJ. While shale gas extraction costs experienced in the United States range between 2 to 6 USD/GJ (eia, 2016b), current estimates on shale gas extraction costs considering the South African geology and infrastructure range between 4 to 10 USD/GJ (CSIR and SANBI, 2016) which indicates that lowering extraction costs below current estimates would be necessary for shale gas to play a substantial role. The analysis, however, further reveals, that if shale gas extraction is economically viable, it can impact South Africa's GHG emissions either way, in particular depending on the level of climate policy ambition in place. We find that under an modestly ambitious climate policy (carbon prices below 5 USD/t$CO_2$ in 2020) shale gas can help lowering South Africas GHG emissions, primarily by substituting coal as the primary fuel source.[3] But, under a more ambitious climate policy, shale gas is competing with low-carbon fuels such as renewable energy sources, thereby leading to higher GHG emissions. To achieve the same emissions reduction as without shale gas, it would therefore be necessary to tighten climate policy and the implied carbon prices. However, with that adjustment of climate policy in place, abundant shale gas can lower GHG mitigation costs compared to a situation without cheap shale gas resources as well as provide some economic benefits.

We find, that motivating significant GHG mitigation requires a stronger carbon price signal if abundant shale gas is available, as overall energy system costs decrease. We conclude, that low-cost abundant shale gas in synergy with a sufficiently stringent climate policy can potentially pose a least cost solution to reaching South Africa's NDC pledge.

While our results provide insights into the South African energy system, an agenda for further research remains. First, we show that the development of the international energy market has a substantial impact on the South African energy system and its import and export structure. Therefore nesting the South African "stand-alone" model into the global MESSAGE model could help create a consistent picture South Africa in the setting of the global energy market in the SSP2 scenario. This coupled model could then also further be used to investigate alternative futures from the ensemble of the Shared Socio-economic Pathways (SSP). Second, our model setup implies that similar results on the interdependencies between shale gas utilization and GHG emissions are likely to be found for other countries facing similar energy related supply challenges such as growing demand, cheap domestic coal, potential for shale gas, and growing climate policy ambition. An extended analysis on such countries including China, Vietnam, India and Indonesia could confirm this.

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[3]Considering $CO_2$ and $CH_4$ emissions from combustion as well as fugitive $CH_4$ emissions.

**Supplementary Information - Model Input Data**

Table 2: Model assumptions on South Africa's fossil resource potential (BP, 2016; eia, 2015).

| | Anthracite Coal | Shale Gas | Crude Oil | Conventional Gas |
|---|---|---|---|---|
| Unit | EJ | EJ | PJ | PJ |
| Resource volume | 1 419 | 378 | 95 | 9 |

Table 3: Calculated useful energy demand forecast for South Africa under SSP2 scenario assumptions [PJ](Fricko et al., 2017).

| Sector | Demand | 2010 | 2020 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|
| Industry | Electric & Other Non-Thermal | 309 | 423 | 560 | 674 | 752 |
| | Thermal | 275 | 358 | 433 | 495 | 532 |
| | Feedstock | 167 | 179 | 214 | 237 | 257 |
| Residential & Commercial | Electric & Other Non-Thermal | 120 | 228 | 392 | 601 | 839 |
| | Thermal | 93 | 144 | 122 | 89 | 72 |
| | Non Commercial | 44 | 49 | 55 | 61 | 63 |
| Transport | Public & Private | 614 | 819 | 1 087 | 1 383 | 1 683 |

Table 4: Model assumptions on South Africa's onshore wind power resource potential by wind grade and distance to load [GW] (Eurek et al., 2016).

| **Capacity Factor** | **≥ 0.34** | **0.34-0.3** | **0.3 - 0.26** | **0.26 - 0.22** | **0.22 - 0.18** | **≤ 0.18** |
|---|---|---|---|---|---|---|
| near (0-50 miles) | 2 | 64 | 146 | 168 | 317 | 937 |
| transitional (50-100 miles) | 1 | 30 | 185 | 253 | 228 | 249 |
| far (100 - 500 miles) | 0 | 0 | 156 | 517 | 992 | 45 |

Table 5: Model assumptions on South Africa's photovoltaic resource potential by full load hours (Flh) and distance to load [GW] (Pietzcker et al., 2014).

| **Full Load Hours [h]** | **1300** | **1250** | **1200** | **1150** | **1100** | **1050** | **1000** | **950** | **900** | **≤ 850** |
|---|---|---|---|---|---|---|---|---|---|---|
| near (0-50 km) | 16 | 293 | 1 022 | 1 548 | 1 655 | 715 | 142 | 205 | 190 | 55 |
| transitional (50-100 km) | 27 | 202 | 768 | 1 706 | 1 799 | 1 068 | 464 | 550 | 371 | 74 |

Table 6: Model assumptions on South Africa's concentrated solar power resource potential by full load hours (Flh) and distance to load [GW] (Pietzcker et al., 2014).

| **Full Load Hours [h]** | **5800** | **5600** | **5400** | **5200** | **5000** | **4800** | **4600** | **4400** | **4200** | **≤ 4000** |
|---|---|---|---|---|---|---|---|---|---|---|
| near (0-50 km) | 9 | 62 | 54 | 221 | 291 | 389 | 161 | 62 | 28 | 47 |
| transitional (50-100 km) | 12 | 145 | 273 | 571 | 311 | 140 | 84 | 30 | 7 | 21 |

## Supplementary Information - Model Results on Power Sector Development

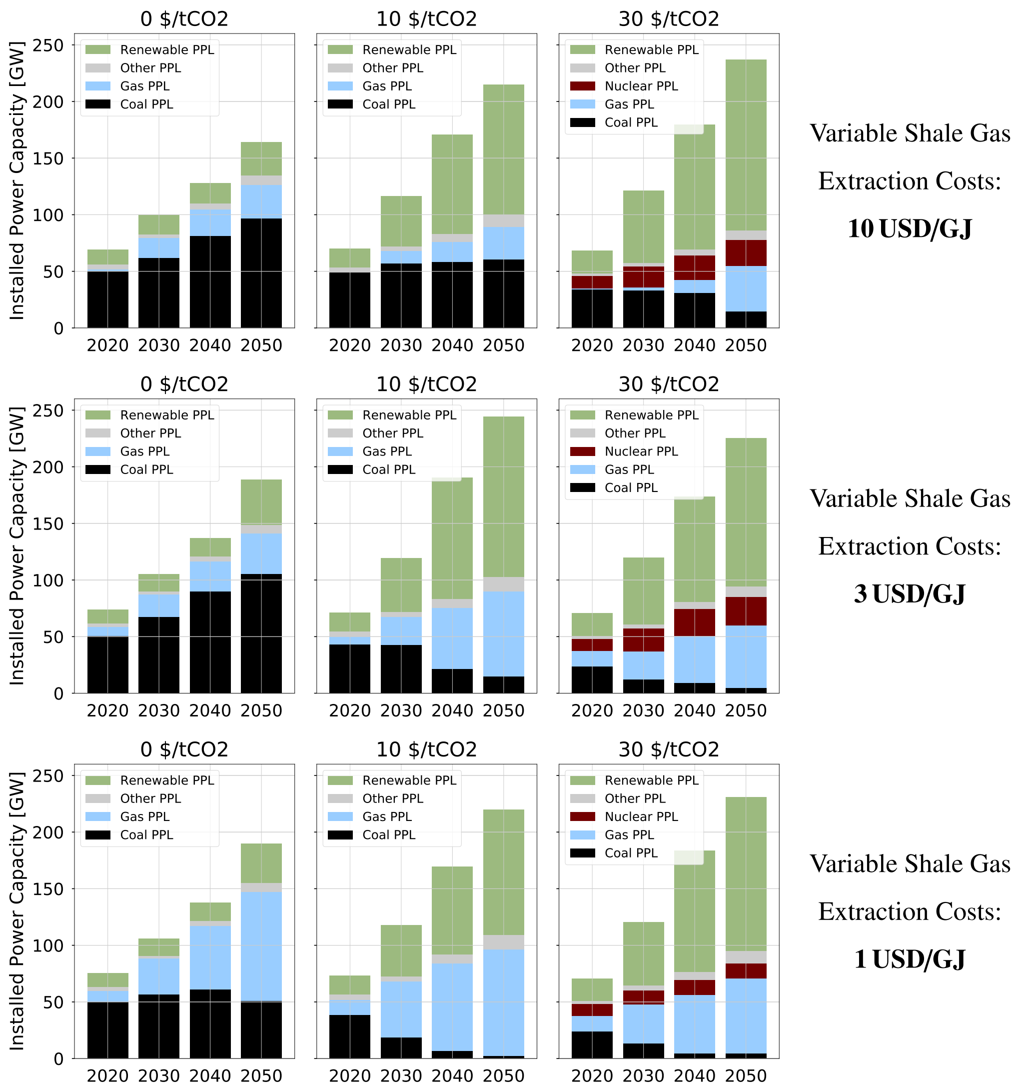


Figure 5: Installed power generation capacity at twelve selected scenarios featuring four different carbon prices (from left to right: 0, 10, 20, and 30 USD/t$CO_2$) and three different shale gas extraction cost levels (from top to bottom: 10, 3, and 1 USD/GJ).

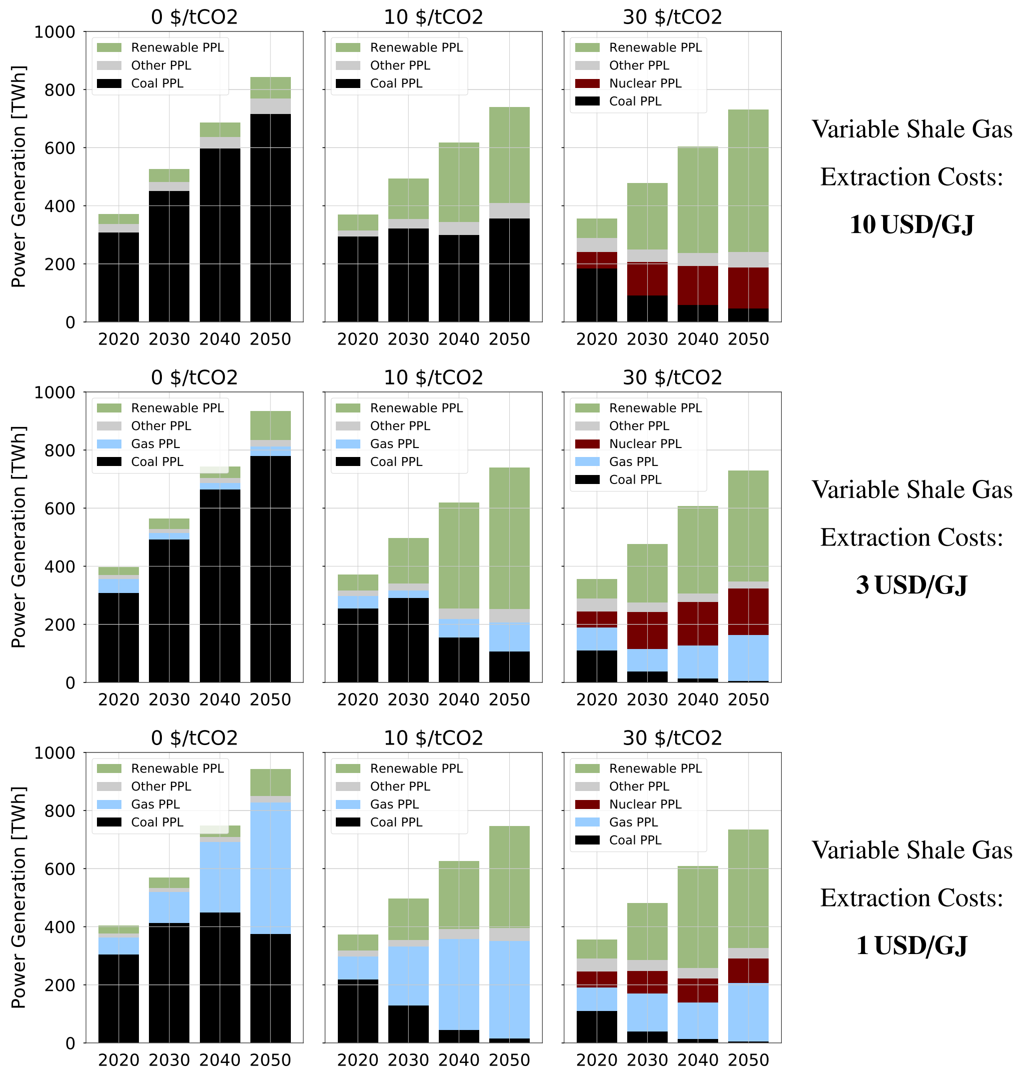


Figure 6: Power generation at twelve selected scenarios featuring four different carbon prices (from left to right: 0, 10, 20, and 30 USD/t$CO_2$) and three different shale gas extraction cost levels (from top to bottom: 10, 3, and 1 USD/GJ).

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