Shale gas and South Africa's challenge of meeting the NDC pledge

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Abstract

South Africa is facing the triple challenge of (a) fueling economic development and meeting the growing energy demand; (b) increasing the reliability of the electricity system; and (c) ensuring that domestic greenhouse gas emissions peak no later than 2030 to meet its nationally determined contributions (NDC) under the 2015 Paris Agreement. Recently discovered domestic shale gas reserves are being considered as a potential new energy source to provide clean, reliable and cheap electricity while mitigating greenhouse gas emissions relative to the dominant coal sector. In order to determine if shale gas can play a viable role in solving South Africa's energy trilemma, we apply a country-level version of the integrated assessment model MESSAGEix to analyze and quantify the interdependencies between shale gas, the energy system and South Africa's greenhouse gas emissions trajectory. Our results indicate that shale gas extraction costs must be below than 3 USD/GJ for this energy source reach a significant share in the fuel mix; this is well below current cost estimates. If, however, low-cost shale gas is available, both coal and low-carbon sources are replaced by natural gas. Whether carbon dioxide emissions increase or decrease as a result depends on the stringency of the climate change mitigation policy in place: without carbon pricing, natural gas replaces coal and mitigates harmful emissions; under high carbon prices, power generation from coal is phased out in any case, and natural gas competes with zero-carbon renewables, leading to an increase of emissions compared to a no-shale scenario.

Keywords: MESSAGEix, carbon tax, scenario analysis, COP 21, NDC, Integrated Assessment Modeling

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1. Introduction

South Africa's (SA) economy is characterized as one of the most carbon-intensive in the world (Alton et al., 2014; Winkler, 2007). National CO_2 emissions per capita are approximately twice as high as the global average, 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 an electricity sector based on coal-fired power plants.

Table 1: Key indicators on SA's energy system in comparison to the world (all indicators refer to 2016).

	Unit	**South Africa**	**World**	**Source**
Population	millions	56	7 466	WB 2018
Total Primary Energy Supply (TPES)	EJ/a	5.1	560	BP 2017
GDP per Capita	USD_{2010}/capita	5 273	10 201	WB 2018
TPES per Capita	GJ/capita	91	75	
CO_2 per Capita	tCO_2/capita	8.7	4.7	
CO_2 per GDP	$kgCO_2/USD_{2010}$	1.7	0.5	
Anthracite Reserves	EJ	290	21 051	BP 2017
Natural Gas Reserves	EJ	0.6	7 210	
Crude Oil Reserves	EJ	0.1	10 380	
Shale Gas Resources*	EJ	392	7 994	EIA 2015

* Unproved technically recoverable wet shale gas resources.

Today, carbon-intensive consumers are still the major drivers of economic development in South Africa (Klausbruckner et al., 2016). But in spite of plentiful domestic resources, the electricity sector has been experiencing shortages and blackouts due to suboptimal management and the reliance on old and inefficient coal power plants. This energy shortage peaked in 2008 during the so-called *electricity crisis* and has since been hampering economic development; security of supply dropped while electricity tariffs were increased high above inflation.[1] This development has raised awareness about the urgent need to modernize, diversify

[1] The nominal price of electricity increased by over 330 % between the financial years 2008/09 and 2015/16 (ESKOM, 2018).

and strengthen the South African power plant portfolio (Eberhard et al., 2014; Pegels, 2010).

In addition to this need for a modernization and diversification of the electricity sector, the South African government defined ambitious targets for the decarbonisation of the entire energy system. At the 2015 Conference of the Parties in Paris, South Africa confirmed and strengthened its intention to reduce greenhouse gas (GHG) emissions (UNFCCC, 2015). According to the Nationally Determined Contributions (NDC), South Africa envisions national GHG emissions peaking no later than 2030 and decreasing thereafter (UNFCCC, 2015). As shown in Figure 1, the proposed peak-plateau-decline trajectory will demand 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 the subject of heated public debates: industrial-scale hydraulic shale gas fracturing, or *fracking*, a technique enabling natural gas production from previously uneconomic shale gas resources. Reserves in South Africa are speculated to be found in abundance (392 EJ) across the Karoo Basin in central and southern South Africa (Scholes et al., 2016; EIA, 2015). With its lower direct CO_2 emissions compared to coal, natural gas derived from shale is considered as a possible remedy for South Africa's energy challenge. It may satisfy the growing energy demand while emitting less direct GHG and other pollutants than the current coal-based power plant fleet (Burnham et al., 2012). On the one hand, promoters point out the benefits of large-scale domestic shale gas development: economic growth, reduced local air pollution (e.g. sulfur, black carbon), and decreasing dependence on imports (Department of Minerals and Resources, 2012). On the other hand, opponents of fracking voice concerns about the potential negative social and environmental impacts resulting from shale gas extraction, such as increased threats of earthquakes, water pollution, ground water table lowering, and methane leakage (Esterhuyse et al., 2016).

The benefits and shortcomings of shale gas utilization are hence to be seen as multi-dimensional problems. There is a potential trade-off between the economic and local climate benefits versus the potentially detrimental environmental side effects. Shale gas could reduce CO_2 emissions by replacing 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, offsetting any benefits for the climate (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, with the aim of balancing the

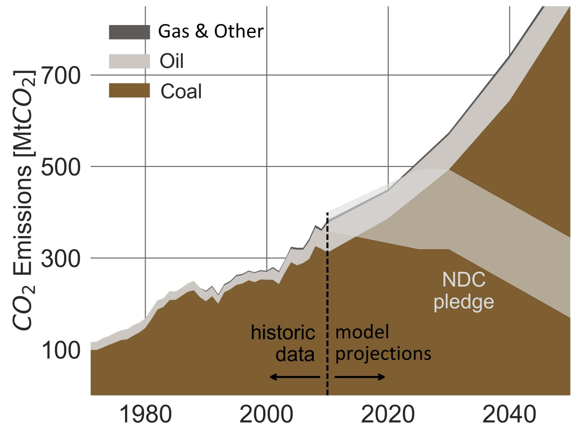

Figure 1: South Africa's energy-related CO_2 emissions as recorded in the past (1971-2010) and as calculated for a *business-as-usual* scenario per emissions source. The fair shaded area shows South Africa's NDC reduction pledge.

competing goals of cheap and reliable energy, stable economic development, and a clean and safe environment. In order to support an informed debate and facilitate the decision-making process, the South African government has commissioned scientific assessments to conduct transparent and comprehensive analyses of the effects of shale gas fracking (Scholes et al., 2016; Department of Minerals and Resources, 2012). In the meantime, it placed a moratorium on the granting of licenses for the exploration of shale gas (Department of Energy, 2016a).

In the present work, we evaluate shale gas exploitation as a policy option to end South Africa's energy shortage and mitigate the country's fast-rising greenhouse gas emissions. In contrast to previous studies, we carry out an large-scale scenario analysis of the GHG mitigation potential of shale gas using a country-level application of the open-source Integrated Assessment Modelling framework MESSAGEix. We find that under current cost estimates, shale gas is not economical. However, if shale gas becomes available at low cost, it can impact South Africa's energy related GHG emissions, with the direction of the impact depending on the stringency of the climate policy in place.

The paper is structured as follows: first, a literature review introduces the current status of the South African energy system with special focus on the electricity sector. The literature review further introduces the currently ongoing scientific debate on shale gas development. Next, the model MESSAGEix-South Africa is described, including the underlying data assumptions as well as the parametrization of the scenario ensemble. In chapter four, the model results are presented and compared against the scenarios without any development of shale gas.Chapter five discusses the results and concludes.

2. Literature Review

2.1. South Africa's Energy System

South Africa's energy systems is dominated by it's rich domestic coal resources, with anthracite and other bituminous coal supplying close to 70 % of the total primary energy. As a legacy of the economic sanctions and trade embargoes imposed in the mid-1980s to pressure the South African government to end apartheid, South Africa uses close to 15 % of its annual domestic coal supply in coal-to-liquid and coal gasification units. In South Africa today, more than 25 % of the domestic fuel oil supply is provided through coal-to-liquid plants that turn domestic coal into high-grade liquid fuels (IEA, 2016). To date, natural gas plays a minor role, supplying less than 3 % of the primary energy mix; one fifth of that is used for producing fuel oils using gas-to-liquid plants. This low share of natural gas, limited to the industrial sector, is due to a lack of domestic supply and low import capacities (Pollet et al., 2015).

South Africa's power system is run by the the state-controlled utility Eskom. In 2015, Eskom owned approximately 91 % of South Africa's installed power generation capacity, while municipalities owned 2 % and only 3 % were held by private companies (Eberhard et al., 2016). The installed power generation capacity is dominated by coal fired power plants (83 %), followed by oil and gas fired turbines, renewable power generation facilities and nuclear power plants, resulting in a fuel use for electricity lead by coal (93 %), followed by nuclear energy and renewable sources.

As decided by the government and the South African Department of Energy, the development of the South African energy system is guided by the Integrated Energy Plan (IEP). The IEP is a model based macro-economic policy roadmap and planning framework designed to provide a vision of future energy infrastructure investments for the Republic of South Africa. It was first issued by the Department of Energy in 2003 following a decree in the White Paper on Energy Policy of 1998 (Department of Energy, 2016a). The vision laid out in this report was strongly connected to the underlying input parameters and model assumptions, such as technological and demand development, financial conditions, commodity and emissions costs. These assumptions are subject to change; hence, the IEP requires regular updates. This necessity became painfully obvious during the electricity crisis of 2008, when insufficient power supply caused power outages and forced load shedding. As a response, the Ministry of Energy mandated that the Department of Energy reviews and publishes the IEP on an annual basis. The latest IEP was published in 2016 (Department of Energy, 2016a) (at the time of writing).

One part of the IEP is the Integrated Resource Plan (IRP), a long-term policy document for South Africa's electricity supply strategy and the official government plan for new generation capacity. It was published first in 2012 and an updated version is currently in consultation. This iteration is expected to be finalized in 2019 (Department of Energy, 2013, 2016b). The IRP's main purpose is to identify the optimal investment strategy for the South African power system, given the local, social, economical and technical-engineering constraints. The projections modeled in the IRP provide a possible composition of South Africas power generation to cover the electricity demand forecast within the next three decades.

To cover the power demand of 520 TWh forecast for 2050 in the baseline scenario, IRP recommends installing 130 GW of additional power generation capacity by 2050, of which approximately one third each should be constituted of wind turbines and gas fired power stations; the remaining third should be supplied by nuclear power stations, solar photovoltaic units (PV) and coal fired power plants (Table 2). While the majority of the required new capacity is expected to be built by Eskom, a significant share is to be installed by Independent Power Producers through the Independent Power Producer Procurement Program (IPPPP), a successful tender process for the installation of required power generation capacity introduced by the South African government in 2011.[2]

Table 2: Planned five year average new build capacities in the base case scenario of the IRP [MW/a] (Department of Energy, 2016b)

		PV	**Wind**	**Nuclear**	**Gas**	**Coal**	**Others**	**Total**
	2020	356	567	-	1 752	-	15	2 690
Five year	2025	580	1 060	-	1 846	1 750	412	5 648
annual average	2030	580	1 320	-	1 339	1 125	750	6 929
[MW]	2035	608	1 540	1 359	2 190	1 500	-	7 197
	2040	674	1 640	2 718	1 728	750	-	7 510
	2045	722	1 580	1 903	640	-	-	4 895
Total by 2050 in [GW]		17.6	37.4	20.4	35.3	15.0	2.8	**128.5**

The IRP baseline scenario is, just like all four IEP scenarios, based on the assumptions that economically

[2]The IPPPP is set up to procure renewable and non-renewable power generation capacity through bid rounds. Each bid round is designed to a determined size differentiated by technology. Between the first bid round in 2011 and the end of the fourth bid round in 2017, 6.3 GW of renewable power projects could be procured through the IPPPP of which 3.2 GW had been constructed and connected to the grid by the end of 2017 (IRENA, 2018).

recoverable volumes of shale gas are extracted and that shale gas is available on the South African market at a competitive price. In our analysis, we develop an ensemble of scenarios that highlight the impact and significance of this assumption. We outline alternative scenarios incorporating the possibility that shale gas might not be economically viable or not available for extraction for other reasons such as environmental regulation.

2.2. Shale Gas

A multitude of studies have been conducted on environmental impacts of shale gas and fracking, such as its climate forcing potential (Howarth, 2015), local air pollution (Field et al., 2014; Altieri and Stone, 2016), and effects on the water supply (Vengosh et al., 2014). Most scientific studies base their assessments on data acquired in the US, the only country to produce shale gas at industrial scale today. However, the number of publications focusing on countries such as Australia, Canada, China and the UK is quickly rising, as those countries are eager to increase their production. In the following section, those studies and the three existing reports on the impact of shale gas in South Africa (Scholes et al., 2016; Altieri and Stone, 2016) are reviewed with a focus on live cycle assessments of the environmental factors such as GHG emissions impact, air quality, water use and pollution.

Electricity generated from natural gas has significantly lower direct CO_2 emissions from power generation compared to coal or oil combustion, although they are still higher than electricity generated from low to no-carbon sources such as renewables and nuclear fuels (IPCC, 2006). Nevertheless, uncertainty exists about the life-cycle emissions of shale gas, especially if non-CO_2 emissions such as fugitive methane emissions are considered. Several studies suggest that life-cycle GHG emissions of electricity from shale gas might be as high as those of electricity generated from conventional natural gas, which is approximately half the GHG emissions per unit compared to electricity produced from coal (Burnham et al., 2012; Dale et al., 2013; Hultman et al., 2011; Jiang et al., 2011; Laurenzi and Jersey, 2013; Stephenson et al., 2011; Weber and Clavin, 2012; Heath et al., 2014). However, some more recent studies find that life-cycle emissions might have been underestimated in previous studies and that fugitive methane emissions might be considerably higher than previously assumed (Brandt et al., 2014; Karion et al., 2013; Miller et al., 2013; Pétron et al., 2012; Schneising et al., 2014). Considering these new estimates, several researcher conclude that electricity from shale gas might have higher live cycle GHG emissions than electricity from coal (Howarth et al., 2011; McJeon et al., 2014; Miller et al., 2013; Howarth, 2015). In their risk assessment on South Africa, Winkler et al. (2016) see shale gas as a climate opportunity if used as a replacement for coal. They, however, evaluate the achievable climate benefit through shale gas fracking as susceptible to the risk of being eroded by fugitive methane emissions. Altieri and Stone (2016) add to this assessment by analyzing the air pollution of shale gas fracking through NO_x, particulate matter, and non-methane volatile organic compounds and find that these emissions will worsen local air quality and potentially have negative impacts on human health.

While the direct emissions impact of shale gas fracking is dependent on the scale of methane leakage, concerns about indirect GHG emissions, such as additional emissions from increased energy use or from replacing low-carbon renewable energy sources with shale gas, have been raised (Alvarez et al., 2012; Brandt et al., 2014). Research indicates that those emissions might be decisive for establishing the overall direction of the GHG emissions impact of shale gas (Kersting et al., 2015). Multiple studies that evaluate the combined effect of direct and indirect GHG emissions of shale gas on a global scale find that increases in global supplies of unconventional natural gas will either not significantly reduce the trajectory or might even increase greenhouse gas emissions (e.g.: McJeon et al. 2014; Kersting et al. 2015). The same has been found to be true on the national level in analyses of the United States (Newell and Raimi, 2014; Shearer et al., 2014). Our study contributes to literature by analyzing the combined impact of direct and indirect GHG emissions effect of shale gas utilization for South Africa.

Apart from its GHG emissions impact, shale gas fracturing has been related to other serious environmental concerns such as water table lowering, contamination, and the increased risk of earthquakes (Cooper et al., 2016; Scanlon et al., 2014). While the risk of increased occurrences of earthquakes as a result of shale gas fracking is assumed to be low in South Africa, the high water demand and the risk of water resource contamination is especially concerning for a water-scarce country such as South Africa (Durrheim et al., 2016). Approximately 75 % of South Africa's shale resources are located in arid areas or regions with high water stress, where already today water resources are barely sufficient to meet demand as potable surface- and groundwater resources are seriously constrained. Therefore, it is questionable if capacity to supply the large amounts of water required for industrial scale shale gas fracking exists (Calderón et al., 2018; Reig et al., 2014; Hobbs et al., 2016). However, further geoscientific analyses and data are required in order to assess to what extent this water scarcity might limit or even prevent economic shale gas production (Hobbs et al., 2016).

3. Methodology

To identify the economic prospects of shale gas development and the associated change in CO_2 emissions under climate change mitigation policies, we employ a multi-scenario analysis. We utilize a novel long-term horizon, linear, least-cost integrated assessment model of the South African energy system, MESSAGEix-South Africa. The main objective is to explore the uncertainties connected to shale gas utilization and to identify and evaluate the most relevant factors that impact the potential role of shale gas. Therefore, we developed this model specifically geared towards large scale sensitivity analysis. MESSAGEix-South Africa is well-suited to evaluate the GHG emissions impact of shale gas fracking as it provides a description of the entire energy supply chain. 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 detailed scenario analysis is necessary to capture 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 potential outcomes in the face of the uncertainty connected to it.

3.1. Model Description - MESSAGEix-South Africa

MESSAGEix-South Africa is a country-level application of the Integrated Assessment Model MESSAGEix, developed at the International Institute of Applied Systems Analysis (IIASA) over the past four decades. MESSAGEix is a dynamic bottom-up technology based optimization model designed for medium to long-term energy planning and policy analysis that provides a framework to represent energy systems with all their interdependencies and correlations. MESSAGEix can describe the entire energy system including resource extraction, trade, conversion, transmission and distribution, and the provision of energy end-use services such as light, space conditioning, industrial process heating, and transportation (Figure 2). The model solves the least-cost solution of satisfying energy demand under various technical-engineering and other constraints, incorporating the macro-economic feedback from price changes on demand; the results indicate required capacity investment, energy system configuration, and emissions, amongst other variables.

For this analysis, we developed a country-level ”stand alone” model of the South African energy system using the open-source MESSAGEix platform (Huppmann et al., 2018): this framework consists of a GAMS implementation of the energy-engineering-economic-environment optimization model; a dedicated database infrastructure for version-controlled management of input assumptions and model results; interfaces with 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.

To develop the MESSAGEix-South Africa model, we implemented a workflow to collect data from

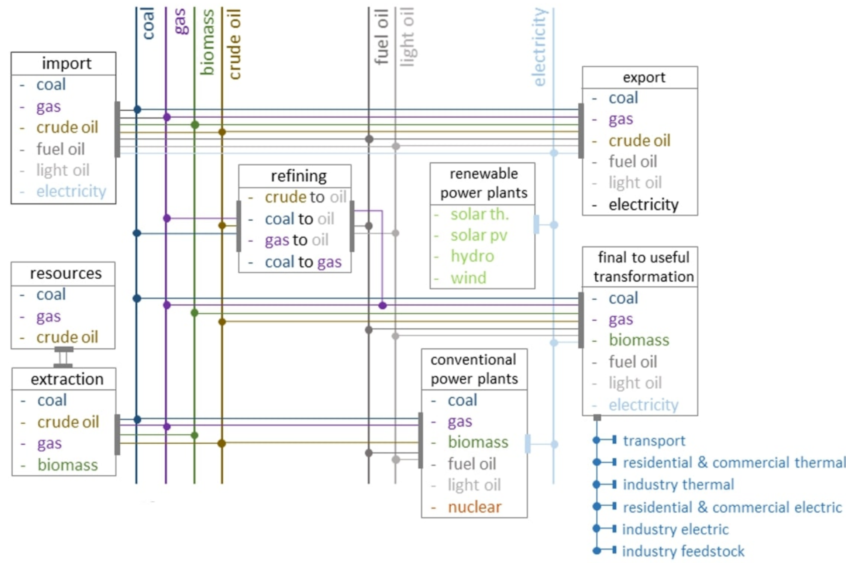

Figure 2: Stylized model work flow chart showing the commodities and technology groups described by the model MESSAGEix-South Africa.

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), energy use 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, as described in detail in subsection 3.2.

In order to adequately describe the utilization of South Africa's vast renewable energy potential and its feedback on the electric sector variability and reliability, the linearized renewable energy utilization representation suggested by Sullivan et al. (2013) is implemented in the MESSAGEix framework. The implemented methodology incorporates metrics for describing required reliability and variability-balancing in the the electricity sector using capacity reserves and flexibility factors. The formulation thus respects system-wide stability effects and ensures the installation of sufficient dispatchable capacity at all times considering the impacts of volatile power generation from wind and solar.

This analysis focuses on the medium-term outlook until 2050, the time frame of relevance for the development of a shale gas industry and the horizon determining if South Africa can reach the emissions trajectory proposed in the NDC. The underlying model extends to 2100 to avoid end-of-time-horizon effects, which

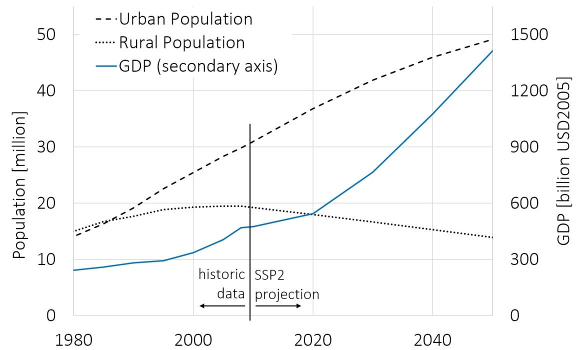

Figure 3: Historic development (1980-2010) of the urban and rural population as well as of the GDP, and the SSP2 projections (2020-2050) of the same (IIASA Energy Program, 2018).

might otherwise bias the numerical results.

3.2. Data & Scenario Assumptions

In order to maintain consistency with the data set and most recent analyses of the global MESSAGE model, technology specifications, development costs, and constraints were based on the region "Sub-Saharan Africa" of the global data set (Krey et al., 2016; GEA, 2012). For the same reason, all socio-economic data, such as the development of the population and the GDP (Figure 3), 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 narratives as they allow us to explain the results of our analysis in the global development context. Of the five available SSP scenarios, we based our assumptions on the "middle of the road" pathway SSP2 which represents a moderate future development (Fricko et al., 2017; KC and Lutz, 2017; Dellink et al., 2017). However, we adjusted parameters, most notably the technology costs, fossil and renewable resource potentials and historically installed capacities, where better data from national sources was available (Bedilion et al., 2012; Department of Energy, 2013).

3.2.1. Energy Resources & Potentials

Data on fossil energy commodities considered in the model are based on national and international resource assessments (Table 1). The renewable energy potential of photovoltaic and solar thermal power generation, is based on spatially disaggregated data sets prepared by the Potsdam Institute for Climate Impact Research and the German Aerospace Center (Pietzcker et al., 2014). The renewable energy potential of economic wind power generation, is based on a spatially disaggregated data set prepared by the National Renewable Energy Laboratory (Eurek et al., 2017). Considering the vast wind energy potential of South Africa, only the most profitable sites (on-shore sites located closer than 100 miles to consumption) are considered for this analysis. Given that the available wind power potential was never a limiting bound on the wind power generation, this assumption does not impact the model results.

3.2.2. Shale Gas

The shale gas volumes considered for this analysis are based on the shale gas availability assessment by the EIA (2015), which claims that 392 EJ of shale gas, i.e. approximately sixty times South Africa's current primary energy use or close to 70 % of global annual primary energy use in 2016, are technically recoverable in South Africa. This estimate includes unproven technically recoverable resources and might therefore be an overestimation of the realistically extractable resource volume (Geel et al., 2013). However, the impact of this overestimation is not significant as the resource volume is, in none of the tested scenarios, the limiting factor for shale gas extraction. The growth limitations for the shale gas industry are based on the growth rates of approximately 2 EJ/a experienced during the development of the major U.S. shale plays, i.e the Fayetteville, Marcellus, Woodford, Bakken, Haynesville and Barnett plays (EIA, 2016a; Richter, 2015). In our model we limit the South African shale gas extraction during the first decade of production to 50 % of the U.S. production growth rates because South Africa does not yet have the necessary gas infrastructure, including long-distance pipelines and local distribution networks. This calculation results in an annual production limit during the first decade of 1 EJ/a and thereafter in an annual growth rate of ±10 %, which confirms literature estimates on South Africa's shale gas industry potential (Altieri and Stone, 2016).

3.2.3. 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 sectors: residential & commercial (RC), industrial, and transportation (Table 3). The energy demand of the RC and industrial sectors is subdivided into specific electric and thermal demand as well as consumption of non-energy feedstock (Figure 2). This representation of future energy consumption is extrapolated for South Africa, based on the historical development and the GDP and population forecast for South Africa developed in the SSP2 framework (Figure 3).

Table 3: 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
	Total	**1 622**	**2 300**	**2 863**	**3 540**	**4 198**

3.2.4. Commodity Trade

MESSAGEix-South Africa is a national application; therefore, it requires assumptions on commodity trade and the global price levels of fossil fuels to close the model. As South Africa is highly dependent on oil imports and is exporting substantial quantities of coal, those assumptions are particularly relevant. For our analysis, global commodity prices and upper bounds on imports and exports are based on the SSP2 scenario. The resulting commodity prices are displayed in table 4.

Table 4: Commodity market prices for under SSP2 scenario assumptions [USD2005/GJ] (Fricko et al., 2017).

	2010	2020	2030	2040	2050
Gas	4.8	4.1	4.6	5.3	6.2
Coal	2.1	2.4	2.3	2.7	2.8
Oil	2.9	4.0	4.8	5.4	6.3
Electricity	5.7	9.5	10.0	10.7	12.0

3.2.5. *Greenhouse Gas Emissions*

MESSAGEix-South Africa considers CO_2 and CH_4 emissions as 'production-based', i.e. only CO_2 and CH_4 from fuels combusted and fugitive CH_4 emissions occurring within country-boundaries contribute to the country's GHG emissions budget. For South Africa this method accounts for 99 % of all energy related GHG emissions, and for 85 % of total national GHG emissions (WB, 2018; Witi et al., 2014). In order to compare the modeled emissions trajectories (considering energy related CO_2 and CH_4 only) to the national GHG reduction path proposed in the NDC, we adjusted the proposed trajectories to the proportional share of non-CO_2/CH_4 and non-energy-related emissions.

The CO_2 and CH_4 emission factors for stationary combustion, considered in the model, are based on the IPCC (2006) national inventory guidelines; the fugitive CH_4 emission factors are based on recent research by Höglund-Isaksson (2017). 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).

3.2.6. *Carbon Price*

A suite of policies will be enacted to meet South Africa's emissions mitigation goals; these will include fiscal incentives, regulatory policies and public financing. However, for the purpose of this study we 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 latest draft of South Africa's carbon tax bill is 9 USD/tCO_2 (Ministry of Finance, 2017). Taking into account the multiple tax exemptions in the bill, the effective rate is estimated to vary between 0.4 to 3.5 USD/tCO_2 (WB, 2016). The South African government proposes to raise the carbon tax by 2 % above annual inflation during the years between introduction (scheduled for January 2019) and 2022 and a reduced annual increase matching the inflation rate in the years thereafter (Ministry of Finance, 2017). The final decision on the date of introduction will be, however, taking into account the state of the economy and thus be delayed. Therefore, we assume that there will be no carbon price before the model year 2020. In the scenario analysis we test various carbon price levels and project an rise of 5 % per year across all sectors and industries.

3.2.7. *Carbon Capture and Storage*

We consider carbon capture and storage (CCS) technologies in the transformation as well as in the power sector.[3] Because carbon capture and storage technologies are not yet available at commercial scale, we estimate the first year of operation to be 2030 at the earliest, which is in line with current governmental expectations (Department of Energy, 2016a).

3.3. *Scenario Description*

Given the numerous uncertainties connected to shale gas exploitation in South Africa, we base our study on an analysis of 3 660 scenarios. Within this scenario ensemble, we vary the two most influential input parameters: the average shale gas extraction cost and the average effective carbon price across a wide range of values.

3.3.1. *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 incorporates 122 introductory carbon price levels ranging from 0 to 60 USD/tCO_2 each, increasing 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., 2010), (b) the low effective carbon tax level scheduled for introduction in South Africa (3.5 USD/tCO_2) and (c) the current situation of no effective carbon price (Ministry of Finance, 2017).

3.3.2. *Shale Gas Scenarios:*

The shale gas scenarios incorporate shale gas utilization under thirty different extraction cost levels ranging from 1 to 10 USD/GJ and the 122 carbon prices levels introduced in the no-shale-gas scenarios. For the first part of the analysis, we display the results of the entire set of 3 660 scenarios in a temporally aggregated manner in order to create a comprehensive understanding of the impact of shale gas upon the energy system, the GHG emissions and the economy. Then, we reduce the number of scenarios to seven representative carbon tax levels for which we show the impact of shale gas costs on the GHG emissions development over the model horizon. Finally, we present the combined impact of the availability of cheap

[3] 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 natural gas combined-cycle power plants.

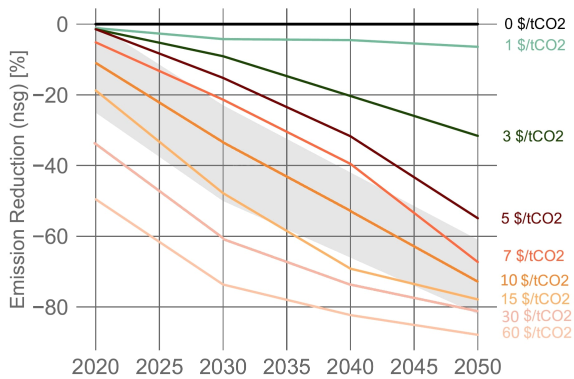

Figure 4: No-shale-gas scenarios relative reduction of energy related CO_2 & CH_4 emissions relative to BAU [%] under nine selected carbon prices relative to the zero carbon price scenario. The NDC pledge is shown as the gray shaded area.

abundant shale gas with and without carbon prices on the power system using six representative scenarios (shale gas extraction cost: 1 & 3 USD/GJ, carbon price: 0, 10 and 30 USD/tCO_2).

4. Results

4.1. Reaching the NDC Pledge without domestic shale gas

Figure 4 shows the relative GHG emissions reduction in the no-shale-gas scenarios for nine representative carbon prices relative to the no-shale-gas/no-carbon-price scenario. The figure shows that in all no-shale-gas scenarios the variations in carbon price cause a strong variation in the emissions trajectories. 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 10 USD/tCO_2 (introduction 2020, growing at 5% p.a. thereafter), or above is required in order to transform the emissions trajectory to resemble the trajectory proposed in the NDC.

Focusing on the power sector, the introduction of a carbon price leads to a diversification of the fuel mix. In the absence of climate policy, coal will remain the dominant fuel source for power generation, with coal power plant capacities increasing to 100 GW total installed capacity. By 2050, the total annual power output from coal plants increases to 700 TWh by 2050. With increasing carbon prices and correspondingly higher electricity tariffs, electricity demand decreases relative to the baseline and generation from renewable energy sources provides a growing share of installed capacity. Already a moderate introductory carbon price of 10 USD/tCO_2could reduce power demand by 10 % and motivate the installation of over 100 GW of renewable power generation capacity, thereby halving the power generation from coal by 2050. This power plant portfolio would require a coal power plant fleet for base load of approximately 50 GW (Figure 5). If the carbon tax is introduced at 30 USD/tCO_2 the coal power plant fleet will contribute no more than 5 % of installed capacity by 2050. Instead, renewables will dominate the power plant fleet with approximately 150 GW of combined installed capacity supported by 20 GW of nuclear and 50 GW of gas-fired power stations for base- and peak load purposes, respectively.

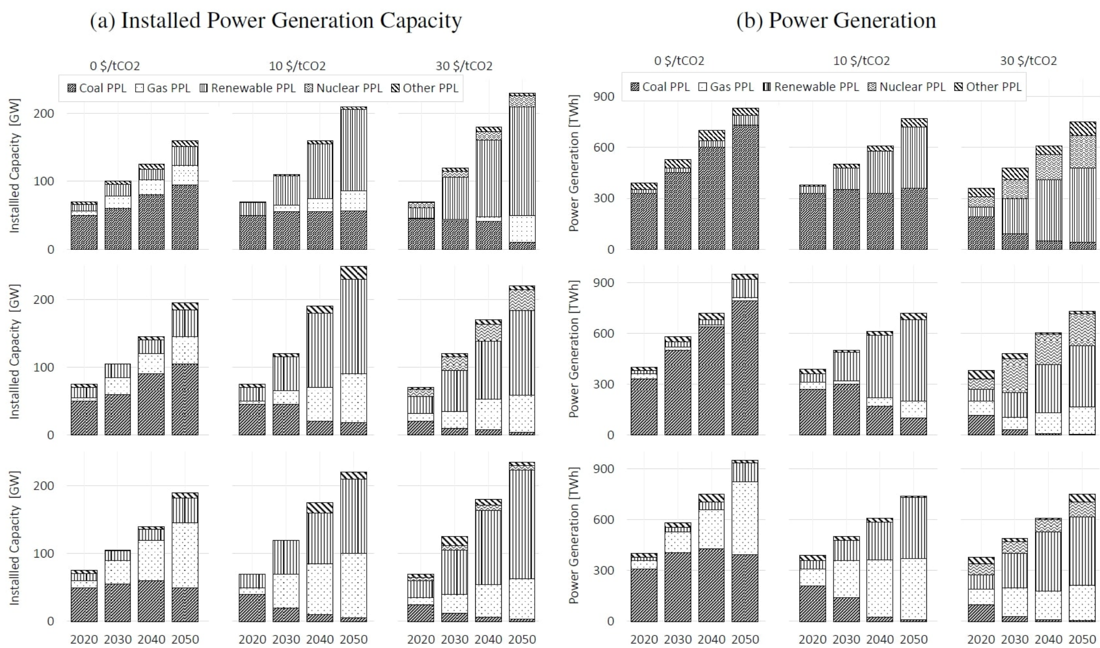

Figure 5: Installed Capacity and power generation at nine selected scenarios featuring three different carbon prices (from left to right: 0, 10, and 30 USD/tCO_2), a scenario set without shale gas (top) and two sets at variable shale gas extraction costs (center: 3 USD/GJ, bottom: 1 USD/GJ).

These no-shale-gas scenarios illustrate that the emissions trajectory pledged in South Africa's NDC can be met without the utilization of shale gas. We find that an effective carbon price of 10 USD/tCO_2 installed by 2020 increasing by 5 % p.a. to 43 USD/tCO_2 by 2050 is sufficient for reducing South Africa's energy-related GHG emissions to the level required for meeting the trajectory proposed in the NDC.

4.2. The Impact of Shale Gas on Emissions and Economic Development

To explain and quantify the combined effect of shale gas under various extraction cost assumptions and a carbon tax on the energy system, we show the results of all 3 660 scenarios in terms of their primary fossil fuel and renewable energy consumption, the costs of the energy system, and the GHG emissions and GDP development,induced by the scenario parameters. In order to compare the scenarios comprehensively, all results are aggregated over the model horizon of interest, i.e. the numbers shown in figure 8 are to be understood as the sum over the period 2020-2050.

Our results show that shale gas is economically competitive if variable extraction costs lie below 3 USD/GJ (Figure 8a). If shale gas extraction is more expensive, no shale gas is used under any carbon price assumption. If, however, shale gas can be produced for less than 3 USD/GJ, the economics of shale gas extraction depend on the carbon price: higher extraction costs require higher carbon prices to make shale gas economically favorable compared to other fuels (Figure 8a). But if shale gas use is economically viable, it can impact the energy system by increasing as well as decreasing fossil fuels and renewable energy use depending on the stringency of climate change mitigation policy.

If extraction of shale gas is very cheap and available in abundance (variable extraction costs below 2 USD/GJ), fuel-switching from coal to shale gas is triggered, thereby reducing coal use by up to 30 % (Figure 8c). Simultaneously, cheap shale gas economically outperforms renewable energy sources (Figure 8d), thereby reducing renewable low- and no-carbon technology deployment by up to one third and increasing overall primary fossil energy consumption (Figure 8b). Additionally, the energy demand is elastic and therefore responds with an increase to the availability of low cost shale gas. These three overlaying effects slightly decrease GHG emissions compared to the no-shale-gas scenarios if carbon taxes are below 5 USD/tCO_2, as in such scenarios shale gas primarily replaces coal rather than renewable energy sources. If, in contrast, carbon taxes are above 5 USD/t$CO_2$the effect is inverted and overall energy-related GHG emissions are increased (Figure 8e) relative to a scenario with equivalent carbon prices and no shale gas availability. These effects hold true for most scenarios; however, when shale gas extraction costs are between 2 and 3 USD/GJ and carbon prices are between 10 to 20 USD/tCO_2 primary energy consumption of fossil fuels is decreased by shale gas utilization as the combination of carbon tax and shale gas extraction costs induce an increase of renewable energy utilization that surpasses the demand increase (Figures 8b & 8d).

The gross domestic product (GDP) as a measure of energy system supply costs and elastic demand is affected by carbon prices and shale gas costs: with higher carbon prices, the energy system becomes more expensive. The cumulative GDP decreases by up to 2 % with increasing carbon prices (Figure 8f). But low cost shale gas can attenuate this effect: the average macro-economic costs for mitigating one ton of CO_2 is significantly reduced if cheap shale gas is available to the market (Figure 8h). Nevertheless, the amount of CO_2 emitted per USD of GDP generated is increased by shale gas use at carbon prices above 5 USD/tCO_2

(Figure 8g). [4]

The results of this scenario analysis show that shale gas would only be introduced to the South African energy system if extraction costs are below 3 USD/GJ. Furthermore we show that the cumulative GHG emissions over the next decades are strongly reduced with increasing carbon prices but that they are also influenced by shale gas use: at carbon prices above 5 USD/tCO_2 shale gas use increases CO_2 emissions (Figure 8e), though this effect fades at carbon prices above 30 USD/tCO_2.

4.3. Deployment of Shale Gas Over Time

Figure 6 summarizes the energy-related GHG emissions under seven carbon price trajectories with various gas extraction costs. It visualizes the impact imposed by carbon price and shale gas extraction costs upon the emissions trajectory. While Figure 4 shows the relative emission reduction, Figure 6 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 could increase compared to the no-shale-gas-baselines if carbon prices of 5 USD/tCO_2 and above are in place.

Shale gas extraction

Figure 7 shows the development of the shale gas extraction for various carbon prices and extraction costs. It indicates the high price sensitivity of shale gas fuel use. Only if shale gas extraction is very cheap (around 1 USD/GJ) and a carbon price is introduced, shale gas extraction is economically competitive to coal from 2020 on. Thus, only in those scenarios the assumed technological extraction constraint[5] becomes binding. In the following decades the carbon price remains a decisive impact factor to shale gas use: without a carbon price, shale gas extraction increases gradually over time, such that more natural gas is used in later decades compared to scenarios with a carbon price; but the introduction and deployment of shale gas is more rapid during the first decades if a carbon price is introduced.

[4] It should be noted that the GDP effects described here do not include benefits from reduced climate change impacts or advantages and disadvantages connected to mitigation action (e.g., reduced air pollution and associated health and environmental impacts).

[5] 1 EJ in the first year increasing by 10 % annually.

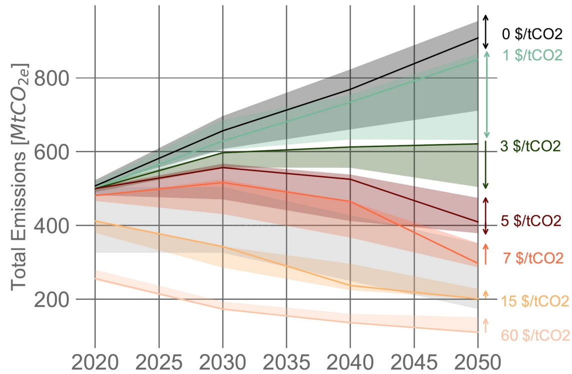

Figure 6: Energy-related GHG emissions at seven selected carbon prices under various gas extraction costs. The lines indicate the no-shale-gas scenarios, the shaded areas indicate the emissions range if shale gas is available at various extraction costs. The figure shows that shale gas utilization decreases emissions at low carbon prices (green), but increases them at moderate to high carbon price levels (red). The gray shaded area shows South Africa's NDC reduction pledge (UNFCCC, 2015).

The power sector

In the following the development of the power sector is analyzed for six scenarios (carbon tax: 0, 10 and 60 USD/tCO_2; shale gas extraction costs: low (1 USD/GJ) and moderate (3 USD/GJ)) in detail. Figure 5a shows the total installed capacity and figure 5b the total production over the planning horizon for the selected scenarios featuring variable shale gas extraction costs of 3 and 1 USD/GJ and carbon prices of 0, 10 and 30 USD/tCO_2.

In a no-carbon-price scenario, moderately priced shale gas (3 USD/GJ) has a small impact on the system: despite the lower energy costs compared to the no-shale-gas scenarios energy demand increases by 9 % and the majority of the electricity remains to be produced by coal fired power plants (86 %) over the entire time horizon. However, compared to the no-shale-gas scenarios, more electricity is generated from variable renewables (5 %) as they are complemented well by flexible gas-fired power plants.

At a carbon price of 10 USD/tCO_2 renewable power generation facilities raise electricity generation to approximately 40 % of the total power demand of 2050. Supported by gas power plants, renewable power reduces coal power generation to below 50 % of total installed capacity. If carbon prices increase further to 30 USD/tCO_2, coal power generation could diminish by 2040 as renewable and gas power stations are complemented by nuclear power facilities to meet electricity demand.

If low-cost shale gas (1 USD/GJ) is available in abundance, gas-fired power plants will dominate South Africa's future power generation fleet whether or not a carbon price is in place. In all scenarios, the low

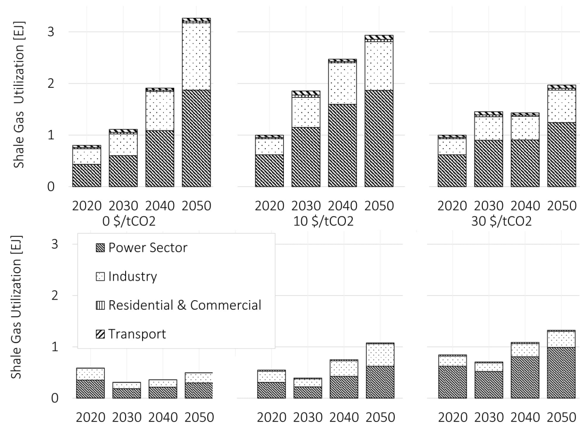

Figure 7: Shale gas extraction and utilization (indicated by the sectoral shares) at nine selected scenarios featuring three different carbon prices (from left to right: 0, 10, and 30 USD/tCO_2), and three variable shale gas extraction costs (from top to bottom: 5, 31 USD/GJ).

cost shale gas replaces the otherwise dominating power source. Without a carbon price in place, low-cost shale gas will supersede the otherwise predominant power generation from coal. At a carbon price of 10 USD/tCO_2 the gas-fired power stations will not only economically out-compete coal power plants but also crowd out renewables, therefore displacing both technologies by approximately the same amount. At a carbon price of 30 USD/tCO_2 a small share of nuclear power will supplement low cost shale gas fired power stations, inducing a power generation portfolio similar to the portfolio exhibited at moderate shale gas costs (Figure 5b).

5. Conclusions and Outlook

South Africa is considering utilizing its shale gas reserves to reduce its high greenhouse gas emissions and initiate a downward shift in emissions in line with its GHG mitigation pledge submitted to the United Nations Framework Convention on Climate Change. 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 to fulfill the NDC pledges: reduce greenhouse gas emissions to 398 - 614 MtCO_2-e, including land use, land use change and forestry, over the period 2025-2030 (UNFCCC, 2015). In our impact assessment we extend previous research on 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 capture the dynamics behind shale gas costs, carbon prices and the energy system.

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 confirm that already a moderate carbon price of 10 USD/tCO_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, fulfilling the NDC pledge (Pegels, 2010). Additionally, our systematic sensitivity analysis adds to the literature by allowing for a detailed impact assessment on effects that carbon prices have upon the country's power system and the energy supply chain.

The shale gas scenarios indicate that if shale gas is abundant at low cost it can play a significant role in South Africa's energy future, thereby confirming for South Africa what has previously been found for other countries (Jacoby et al., 2012; Baranes et al., 2017). However, we find that for shale gas to have a large 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 (Scholes et al., 2016). This highlights that lowering extraction costs below current estimates is critical for shale gas to play a substantial role. However, if shale gas become available at such low prices, the effect on the greenhouse gas emissions depends on the climate policy in place. We find that under a modestly ambitious climate policy (carbon prices below 5 USD/tCO_2 in 2020) shale gas could help lower South Africas GHG emissions by replacing coal as the primary fuel source.[6] Nevertheless, this reduction will not be sufficient to meet the envisioned trajectory. But under a more ambitious climate policy, which is necessary for fulfilling the NDC pledge, shale gas is competing with low-carbon fuels such as renewable energy sources, thereby leading to comparatively higher GHG emissions and a delay in renewable energy deployment. Therefore, it would be necessary to tighten climate policy and the suggested carbon price in order to achieve the same GHG emissions reduction if low cost shale gas is available. However, with that adjustment of climate policy in place, abundant shale gas could provide some economic benefits as it decreases the GHG mitigation costs compared to a situation without cheap shale gas resources available.

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[6]Considering CO_2 and CH_4 emissions from combustion as well as fugitive CH_4 emissions from the extraction process.

Organization and the Peccei Award.

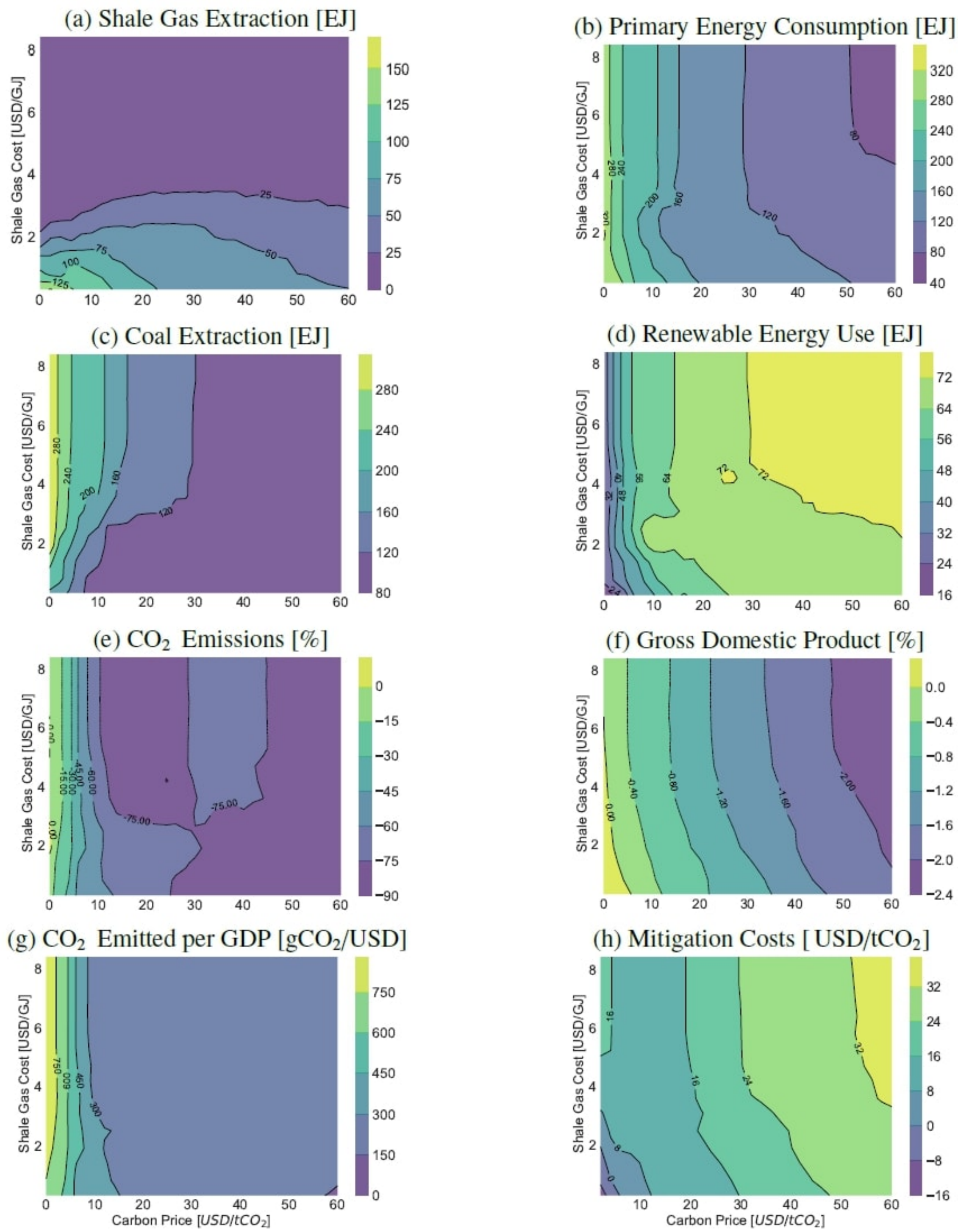

Figure 8: Cumulative model results (2020-2050) on the fossil fuel and renewable energy consumption (a)-(d), and the CO_2 emissions and the GDP. (e) and (f) show the relative change of the scenario results compared to the no-shale-gas and no-carbon-price baseline scenario. The mitigation costs shown in (h) are defined as the ratio between the GDP reduction per ton of CO_2 mitigated.

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