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Value Measurement Analysis of Energy Tradeoffs in South Africa

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Abstract. South Africa (SA) is facing multiple energy challenges. Current infrastructure is aging, population is growing, industry is expanding, and the level of development is increasing. In addition, existing energy practices depend heavily on coal, are environmentally unsustainable and conflict with international climate change mitigation polices. Therefore, in the near future SA must replace, expand and transform its energy portfolio. This study considers three main thermal electric generation technologies as the most viable options of this energy transition: improved coal power plants that implement best practices, natural gas fired power plants that utilize imported gas from Botswana and Mozambique, or natural gas power plants that utilize domestic shale gas from the Karoo region. It is unlikely that either natural gas option will fulfill all future electricity requirements. Therefore, where possible, this study seeks to evaluate the most favorable replacement of coal. Within the shale gas alternative, this study performs a comparative analysis of three water scenarios for hydraulic fracking; either water is sourced from local groundwater aquifers, from seawater about 300km from the fracking site or from coal mine waste in the Mpumalanga region, about 1000km from the fracking site.

Multiple environmental, social and economic criteria are incorporated in the analysis with respect to multiple decision makers in a stochastic value measurement approach to identify the applicability of this method in providing decision support for guiding environmental and energy policy interventions in SA. The value measurement analysis performed has a stochastic variation of the value function as well as a stochastic exploration of preferences from decision makers. Furthermore, this study models different decision makers with distinct attribute weights, reflecting the perspectives of a neutral decision maker, a water activist, a global warming activist, a bean counter and a social-focused decision maker.

A key result is that coal is the least desirable option regardless of cost because of its high environmental impact across almost all categories. In addition, the imported gas alternative is consistently preferred by decision makers because of the "advantage" that environmental impacts that occur outside SA borders are not accounted for in policy regulations. With respect to fracking alternatives, transporting mine waste for hydraulic fracturing is the least viable alternative because of the high cost and impact of transportation as well as the higher risk of contamination due to the use of lower quality water. The seawater and groundwater alternative were equally competitive because of the unresolved tradeoff of water use vs. risk of aquifer contamination.

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Introduction. South Africa (SA) must increase energy generating capacity to support an increasing population, higher standard of living, and growing industry. In addition, SA's energy infrastructure is aging and current practices are environmentally unsustainable (Wassung, 2012; Prasad et al., 2012; Beg et al., 2002). This means SA energy practices must undergo a rapid transformation and expansion. Currently, coal provides 93% of electricity capacity at a high environmental cost (Kessides et al., 2007; Nkomo 2005, Winkler, 2007). Coal electricity is one of the main contributors to climate change which affects SA in terms of food security because of the intensification of droughts and floods (Schulze, 2005; Beg et al., 2002). In addition, climate change plays an important role in South Africa's international relations as it must comply with climate change mitigation policies. Part of this is the UN carbon emission targets (Masters, 2009). Furthermore, coal burning generates critical air pollutants. In fact, SA generates the second largest amount of anthropogenic mercury emissions in the world – the majority of which come from the domestic combustion of low-grade coal (Dabrowski et al., 2008; Masekoameng et al., 2010). Mercury is detrimental to human health because it is a neurotoxin and can bioaccumulate. Other equally detrimental pollutants are particulate matter, SO_X and NO_X – all which impact human and environmental health (Miller, 2005).

Coal extraction also generates toxic waste that is difficult to manage. For instance, Acid Mine Drainage (AMD) which forms when water goes into mine voids and comes into contact with sulfur and oxygen is managed through pumping the water out of mine voids to avoid spillovers (Eberhard, 2011). However, when water levels are not properly managed, AMD can overflow and potentially contaminate waters systems even years after the mining takes place (Interministerial Committee, 2010; Bell et al., 2001).

In addition, coal based electricity is water intensive at the early stages of raw material extraction, as well as the production phase during thermal generation. This is problematic, because SA is one of the most water scarce nations in the world (Mueller et al., 2009). Yet, it has a mining industry which requires large amounts of water. In fact, the relationship between energy technologies and water, known as the energy-water nexus, is increasingly being recognized as a key element of sustainable systems (von Uexkûll 2004; Prasad et al., 2012). Given the scarcity of water resources and its importance in human and industrial development, it is imperative that energy generation in SA applies appropriate water management strategies (Wassung, 2012b). In particular, thermal energy generation technologies have a strong energy-water nexus because the generation stage requires water (Prasad et al., 2012; Sovacol and Sovacol, 2009).

Because of these concerns, it is generally recognized that SA must reduce coal consumption. This study identifies three main fuel options for nearby thermal electricity generation alternatives; best practice coal, imported natural gas, and domestic shale gas. Natural gas power plants are more efficient and burn much cleaner than coal (JISEA, 2012). SA can increase natural gas imports from Botswana and Mozambique, or begin extracting unconventional shale gas reserves from the Karoo. According to the Energy Information Administration (EIA), the Karoo region in SA has the fifth largest reservoirs of shale gas in the world (Kuuskra et al., 2011). Shale gas is categorized as "unconventional gas" similarly to coal bed methane and tight gas. Both sources of natural gas have relatively the same environmental impact at the generation plant, which compared to coal-fired electricity is about half the life cycle greenhouse gas emissions (JISEA, 2012). Moreover, reduced carbon and air pollutant emissions from gas fired power plants help utility companies meet ozone, carbon, and nitrogen and sulfur oxide emission standards (Clark et al 2012). Therefore, natural gas resources provide an opportunity for economic growth, reduction of greenhouse gas emissions, compliance of international climate change mitigation policies, diversification of the energy portfolio, and, in the case of shale gas, maintain energy independence.

Conventional natural gas imported from outside SA's borders has majority of its impact outside SA. Therefore, water use, impacts during processing transportation and extraction is not accounted for in this analysis because existing policies only account for environmental impacts within a nation's borders. Alternatively, shale gas extraction, processing and of course combustion occurs in SA. Therefore, domestic production of shale gas appears to have a higher overall environmental footprint than conventional imported natural gas.

Unconventional gas extraction practices, particularly hydraulic fracking raises serious upstream environmental concerns and uncertainties (Vermuelen 2012, Greef, 2012, Clark et al 2012, Ehrenberg 2012, Mooney 2011). Fracking provides the additional stimulation necessary for unconventional gas reservoirs because unlike conventional gas resources, low permeability in unconventional resources does not allow gas to move freely to the surface. Therefore, fracking makes unconventional resources economically viable because it reaches greater volumes of rock from a single vertical well, and stimulates the gas flow through induced fractures (Lee et al 2011). Hydraulic fracking is the process of injecting fracking fluid at high pressures down the well to form fractures in the rock formation. Fractures allow for gas pockets to connect and initiate the free flow of gas. Fracking fluid consists mainly of water and sand (to maintain open fractures) and chemical additives. Water use for fracking has raised concerns because each fracking job takes between 2 and 5 million gallons of liquids, 2% of which are additives such as acids, biocides, corrosion and scale inhibitors, gels, and friction reducers (Clark et al 2011). Despite the chemicals being such a small portion of the fracking fluid, the quantities are so large that it can mean there are over 900 gallons of hydrochloric acid in each fracking job (Cooley and Donnelly 2012).

In addition to water use, there are water *quality* concerns due to the risk that fracking fluids, along with additional components that leach from the shale formations (such as natural occurring radiation, hydrocarbons, salt, minerals and brine) can contaminate groundwater aquifers through fractures or casing failures (Clark et al 2012). Where hydraulic fracking takes place, there have been short term groundwater quality implications due to the vibrations created during the drilling process (Groat and Grimshaw 2012) and studies have shown large methane concentrations in water resources near drilling sites (Osborn et al 2011). Methane intrusions have also resulted in explosions due to gas build up in wells and houses in areas of intense shale gas drilling (Drajem 2012).

Water-based fracking also generates flowback water, a combination of fracking fluid, brine and other components in the shale formation that return to the surface once the pressure is released. This water cannot be released to water bodies and it cannot be treated in municipal water treatment plants. Flowback water is typically disposed of through ground injection or reused. The quality of flowback water is variable, which makes reuse difficult where treatment is required to remove dissolved solids and salts that can interfere with additives.

Furthermore, shale gas extraction in the US has shown to generate local air quality problems such as crystalline silica dust (from sand in hydraulic fracking), fugitive volatile organic carbons, benzene and nitrogen oxides emission from the use of equipment during the extraction process (Clark et al 2012, Wells 2012, Esswein et al 2012). It is estimated that unconventional gas practices utilize about twice the number of trucks than conventional gas. This additional traffic places a burden in transportation infrastructure, creates nuisance for the local community, and increases the risk of accidents and spills (Cooley and Donnelly 2012, Carr et al 2012). For this reason, South African hydro geologists call for a careful examination prior to beginning extraction (Vermuelen 2012).

Due to water use concerns surrounding hydraulic fracking, some have proposed using alternative sources of water such as seawater and mine waste. This study performs a second analysis that compares three hydraulic fracking practices namely, fracking with groundwater, seawater and mine waste. The mine waste comes from coal mines in the Mpumalanga region, and the sea water comes from the nearest coast. The use of alternative water reduces water burden as none of those sources is suitable for human consumption. However, the use of lower quality water increases the risk of aquifer contamination because in the event that the fracking fluid does reach the aquifer, the consequences would be more severe.

In addition to environmental aspects, energy technologies influence the nation's social and economic aspects. For instance energy projects in SA have resulted in population displacement communities (Terminski 2012) and a sustainable energy plan should avoid such social impacts. Alternatively, energy infrastructure brings social benefits with respect to job creation. For instance, in 2005 the energy industry in SA contributed to 15% of its GDP and created 250,000 jobs (Nkomo, 2005). Furthermore, energy decisions have multiple decision makers and stakeholders which introduce additional layers of complexity to the problem. Therefore, energy systems have environmental, economic and social constraints that cannot be evaluated by single indicators or discrete values. Therefore, policy regulations can benefit from the inclusion of integrative frameworks capable of evaluating multiple dimensions, decision makers and stakeholders under high uncertainty and variability when designing policy interventions. The framework does not act as a one-directional solver, but rather as a discussion platform that aids decision makers in reaching a balanced compromise.

Goals. This study evaluates the implementation of shale gas electricity via hydraulic fracking, as compared to best-practice coal and imported natural gas via decision analysis. In addition, this study performs a comparative analysis of various hydraulic fracking practices. To analyze the multiple environmental, social and economic dimensions and simulate a diverse range of perspective from decision makers, this study applies a stochastic approach to value measurement (Keeney and Raiffa, 1976; Belton and Stewart, 2002; Loken, 2007), a Multi-criteria Decision Analysis (MCDA) method that can analyze multiple criteria with different units (both quantitative and qualitative), simulate a diversity of perspectives from decision makers and maintain incommensurability among different criteria.

Investigative Method. This study consists of two different case studies using MCDA through stochastic value measurement. The first case study analyzes three fuel options for the nearby future energy demands of SA, and the second evaluates various hydraulic fracking alternatives.

Both case studies began by searching the literature to identify and select of criteria to evaluate the options in both cases. The main concerns were global warming potential, water use, and groundwater contamination which are all controversial issues in the shale gas debate in SA (de Wit, 2011). Furthermore, there are additional air quality concerns with regards to coal based electricity as well as economic benefits from the coal mining industry (such as job creation). Some aspects of these technologies are easier to quantify as in the case of air pollutants. However, other impacts such as tourism, and local community impacts are more challenging to quantify. Nevertheless, with further examination additional criteria can be added to this analysis.

Case 1: Fuel Options

The first case study accounts for 13 criteria, three of which are measured qualitatively. The remaining quantitative criteria are measured in different units (Table 1). The options (or alternatives) considered in Case 1 include:

1. Best-practice coal (BPC): This alternative is representative of the new generation of coal fired plants in SA such as Medupi and Kusile which are expected to perform to the same standards as Western coal fired plants.
2. Fracking using groundwater (FGW): This alternative utilizes existing groundwater in the Karoo basin in the fracking process. Groundwater requires no additional processing prior to the fracking process, and it requires minimal transportation.
3. Imported natural gas (ING): This option uses imported conventional natural gas from Botswana and Mozambique in gas fired power plants. Environmental indicators only include impacts that occur within SA' borders. Therefore, this alternative has an environmental advantage particularly with water issues because it does not utilize SA's water resources nor it contaminates SA's groundwater resources.

Case 2: Fracking Options

The second case study accounts for 8 criteria, one of which is measured qualitatively. This case study shares six of the same criteria as in Case 1. The remaining two criteria account for the additional job creation using the transportation of fracking fluid as well as criteria which accounts for the cost of fuel spent during transportation of fracking fluid (Table 1).

The options (or alternatives) considered in Case 2 include:

1. Fracking using groundwater (FGW): This alternative utilizes existing groundwater in the Karoo basin in the fracking process. Groundwater requires no additional processing prior to the fracking process, and it requires minimal transportation.
2. Fracking using seawater (FSW): This alternative requires additional water treatment prior to the fracking process and it requires longer distance transport by truck for the coastal areas to the Karoo region. This study estimates a distance of 300 km.
3. Fracking using mine waste (FMW): This alternative also requires additional water treatment prior to the fracking process and it requires transportation from nearby mines. The water comes from acid mine drainage of tailings.

Table 1. Criteria definition for Case 1 and Case 2

Aspect	Criteria	Definition	Unit per MWh	Application of criteria in Case studies
Environmental	Global Warming Potential	This criterion represents the Global Warming Potential (GWP) measured in kg of CO_2 equivalents at a 100 year time frame, and it includes greenhouse gases emitted during raw material extraction, processing, transportation and combustion (gas or coal) during electricity generation. Note that distribution to consumers is not included, as distribution infrastructure is currently not in place and location varies.	kg of CO_2 eq	Case 1 and 2
	Water Use	This criterion represents the total volume of water, in m^3, consumed during all stages of electricity that would otherwise be available for human consumption. In the case of coal-based electricity, this indicator covers the water involved in cleaning and coal processing, and in the case of shale gas, it includes groundwater use for hydraulic fracking.	m^3	Case 1 and 2
	Land use	Land required by each alternative for the extraction and processing of electricity. This criterion accounts for surface land use. In the case, of coal-based electricity this indicator includes the area utilized for coal mining.	m^2	Case 1
	Waste	Waste that is generated during the production of electricity that is subsequently contained. This criterion represents mine residues in the case of coal, and used fracking fluid in the case of shale gas.	ton	Case 1
	PM_{10}	Corresponds to particulate matter that is under 10 micrometers in diameter. Concentration of PM_{10} in the atmosphere is detrimental to humans in terms of respiratory and cardiovascular effects.	kg of PM_{10}	Case 1 and 2
	NO_x	This is an air pollutant that contributes to smog formation and acidification	kg of NO_x	Case 1 and 2
	SO_x	Sulfur oxides are released during the burning of fossil fuels and contribute to smog formation and acidification	kg of NO_x	Case 1 and 2

	Mercury	This criterion measures the amount of mercury released into the air as part of coal combustion. Mercury is a neurotoxin that can bio accumulate in the body. The combustion of coal for electricity production is one of the main causes of anthropogenic mercury emissions in South Africa, which is estimated to be second in the world.	kg of Hg	Case 1
	Aquifer and surface water contamination risk	This criterion evaluates the risk for a catastrophic event that results in the contamination of ground and surface water sources.	Low to High	Case 1 and 2
Economic	Job creation	Number of direct jobs created by each alternative.	Number	Case 1 and 2
	Cost of Production	This is the expected cost to consumers	ZAR	Case 1
	Cost of Transport	Additional cost of fuel for water transport	ZAR	Case 2
Social	Risk of displacement	This criterion evaluates the impact to surrounding populations in terms of possible displacement.	Low to High	Case 1

Value Measurement and Stochastic Weighting

Value measurement is an MCDA approach that utilizes a relative scale to score an option from 0 to 100 depending on the best or worst performing alternative. Figure 1 shows the value function which converts the different physical units into a unitless value from 0 to 100. In the stochastic version of MCDA, the value function changes according to the midpoint value of the attribute scale. The stochastic model performs 5000 Monte Carlo simulations that re-position the midpoint. Therefore, each run attributes a different value to each alternative on each criterion. Then the 5000 values form a probability distribution as in Stochastic Multi-attribute Analysis (SMAA) (Lahdelma et al, 1988, Lahdelam and Salminen, 2001, Tylock et al., 2012). A non-linear aggregation function (as shown in Figure 1) avoids results that lead to extreme solutions because it limits *full compensation* between criteria.

In decision analysis, the extent to which criteria are allowed to compensate each other is known as *compensation*, and it is essential that analytic frameworks recognize the nature of compensability in a problem because the aggregation function can have the greatest influence in the analysis, even beyond weights (Stewart, 2008). Full compensation means that poor performance in one criteria can compensate for good performance in other criteria. Fully compensatory methods are appropriate for monetary problems because economic profits and losses can make up for one another. However, according to strong sustainability theory, different forms of capital (social, environmental or economic) do not compensate each other (Ayers et al 1998). That is, an improvement in production costs does not necessarily justify greater air pollution. Hence, the application of fully compensatory methods for problems incorporating various forms of capital is mathematically incompatible.

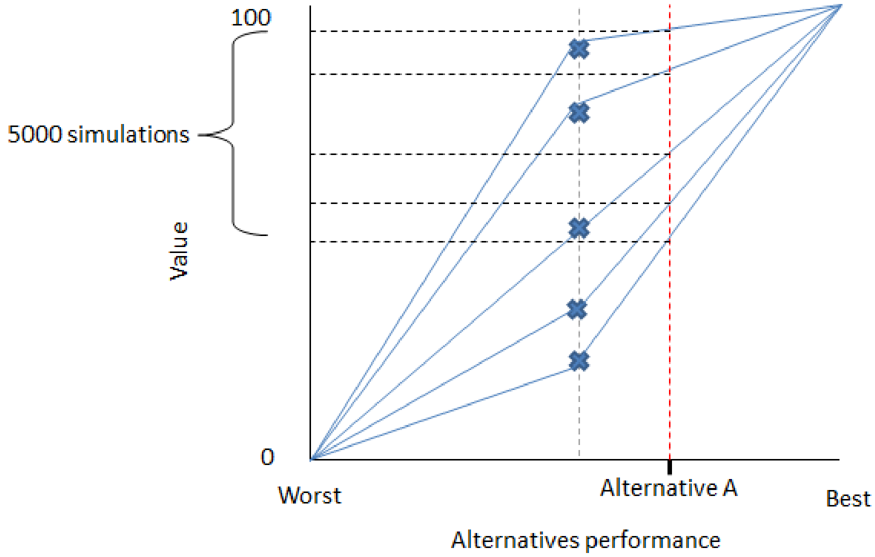

Figure 1. Stochastic Value Measurement with random midpoint modeling

After calculating the value of each alternative on each criterion, we perform stochastic weighting. Contrary to sampling discrete weight values, stochastic weighting allows for the exploration of the entire weight space. Figure 2a depicts five criteria weighted with the same level of priority. The x-axis represents the weight value, and the y-axis is the probability that a particular weight has a certain value. The beta distribution shows that it is most likely for alternatives to have weight values in the lower ranges because at all points weights must add up to 100. This approach allows decision makers to identify the most relevant tradeoffs and to analyze the problem from multiple perspectives simultaneously. Figure 2b shows the same five criteria, but this time one criterion has a higher priority. The shape of the distribution is the same, but it is shifted to the right to have higher weight values. Finally, the value distributions along with the weights for each criterion are multiplied and added to provide a score which translates to a rank. Finally, the results of this analysis are in terms of the probability of an alternative of occupying a certain rank.

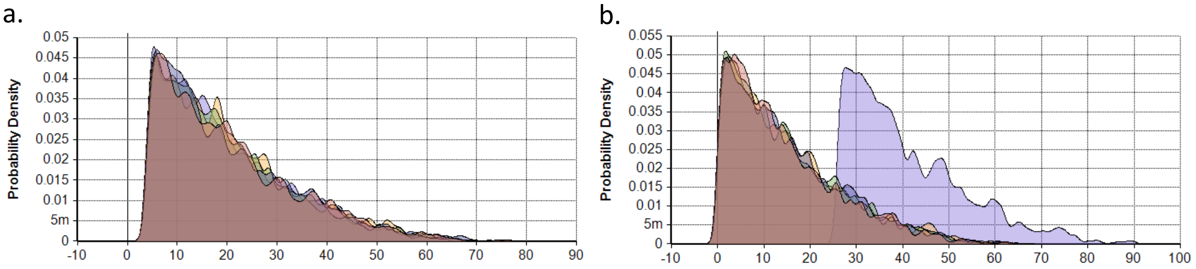

Figure 2. (a) shows a stochastic exploration of weights (b) stochastic exploration of weights with a preference

Decision Makers

This study evaluates both case studies under 5 main perspectives from hypothetical decision makers:

1. Neutral: This decision maker samples the entire weight space with no built-in priority similarly to Figure 2a.
2. Bean Counter: The bean counter has cost as a single priority, meaning that the stochastic weight function for the cost criteria is shifted to the right as shown in Figure 2b.
3. Water Activist: This decision makers places a high priority in the water use and aquifer contamination criteria.
4. Global Warming Activist: This decision makers places high priority in the global warming criteria.
5. Social Impact Focused: This decision makers places a higher priority in the job creation, risk of displacement and energy independence criteria.

Data Collection Case Study 1: Fuel Options

Data for this study comes from previously published works. Environmental data pertaining fracking takes place in the US as a proxy, because shale gas extraction does not currently take place in SA. Environmental data for BPC also takes place in the US (with some minor modifications to reflect South African coal mining practices) because the newer generation of coal fired plants are expected to have efficiencies similar to Western power plants. The imported natural gas alternative has most of its impacts outside SA therefore, only impacts associated with combustion are accounted for and are also representative of new gas fired power plants. Table 2 shows the data used for the analysis of case study 1.

Table 2. Case 1 performance data

Criteria	Unit	BPC	FGW	ING
Global Warming Potential	Kg of CO_2 eq /MWh	980	440	416
Water use	m^3/MWh	0.12	0.027	0
Land use	m^2/MWh	0.3	0.141	0
Waste	kg/MWh	152.55	16.48	0
PM 10	kg/MWh	0.33	0.0008	0.0008
NOx	kg/MWh	4.18	0.0629	0.0629
SOx	kg/MWh	7.75	0.002	0.002
Mercury	g Hg/MWh	0.17	0	0
Aquifer contamination	Qualitative Scale	Low	High	None
Job Creation	#jobs/MWh	0.00034	4.96E-06	0
Cost of production	$/MWh	-	-	-
Risk of displacement	Qualitative Scale	High	Low	None
Energy Independence	Qualitative Scale	Yes	Yes	No

Cost of production data for the three fuel options was highly variable and highly uncertain given that at present SA does not operate BPC power plants, it does not burn imported natural gas for electricity production, nor does it extract shale gas. In fact, data on cost of production for shale gas is scarce. Therefore, the Cost of Production criteria was left as a space to perform sensitivity analysis. For each decision maker this study performed three cost scenarios (1) the first scenario places coal and imported gas as the cheapest and most expensive alternatives respectively, with shale gas in the middle. The relative costs of coal and natural gas in this scenario derive from reported prices from ESKOM, 2012. (2) The second scenario places BPC and ING as having relatively the same costs as derived from the Department of Minerals and Energy, 2003 and places FGW as the most expensive alternative, having twice the cost (3) The third scenario place domestic production costs of FGW and BPC to be relatively the same with ING to be twice as costly.

Since all three alternatives have a thermo electric generation plant, it is assumed that job creation, water use, and land use is the same in BPC, ING and FGW plants. Therefore these criteria account for their contribution at the fuel extraction stages – that is coal mining and fracking stages. As shown in Table 2, the ING alternative does not have an Aquifer Contamination risk because extraction and processing occurs outside SA. Likewise, Water Use, Land Use, and Waste impacts for ING occur outside SA. Both, ING and FGW have similar criteria air pollutant emissions because both alternatives are a gas fired power plant. The risk of displacement is highest in BPC because of the risk of displacement due to future coal reserves in higher populated areas. The Karoo region has a very low density population, thus the risk of displacement are much lower. Lastly, the Global Warming Potential in this study reflect life-cycle emissions- from raw material extraction until combustion. See Appendix for further detail and references for data collected.

Data Collection Case Study 2: Fracking Options

The Fracking Case study utilizes the same FGW alternative as Case Study 1 and it compares them to FSW (where water is sourced from the ocean), and FMW (where fracking fluid utilizes coal mine waste). The Job Creation criteria in this case study represents the additional job generated from the *additional* transportation of fracking fluid, which is considered to be negligible in the case of FGW. The cost of transportation fuel for fracking fluid includes only the cost of diesel priced at R11.3/l and R11/l for inland and coastal prices respectively. Air pollutants vary slightly depending on the additional emissions during the fracking fluid transportation. The water use for FSW and FMW is zero because it does not use water that is apt for human consumption. The risk of contamination is higher in FSW and FMW because lower quality of water is estimated to promote faster degradation of castings, and if contamination occurs implications are worse. Given than FMW utilizes the lowest quality “water” its aquifer contamination risk is the highest.

Table 3. Case 2 performance data

Criteria	Unit	FGW	FSW	FMW
Global Warming Potential	kg CO_2 eq. /MWh	440	441.314	443.888
Water use	m^3/MWh	0.0275	0	0
PM 10	kg/MWh	0.0008	0.00085	0.00097
NOx	kg/MWh	0.0629	0.06438	0.0675
SOx	kg/MWh	0.002	0.002143	0.00245
Aquifer Contamination	Qualitative Scale	Low	Medium	High
Job Creation	#jobs/MWh	0	0.00148	0.00148
Cost of Fracking Fluid Transport	R/MWh	0	115.899	375.207

Results. Each simulation in both case studies was run with and without random midpoint variation of the single attribute value function. However, negligible changes were observed because the data tends to fall closer to either the lower or upper ends of the value function. Results are shown in Figures 3 and 4 for case studies 1 and 2 respectively.

The x-axis represents the rank of an alternative with “1” being the most preferred rank and “3” being the least preferred. The y-axis represents the probability of each alternative to position at a certain rank. Each of the plots represents a different decision maker. Each of these results aggregates a total of 5000 Monte Carlo simulations. For example, in Figure 3, BPC labeled as “Coal” positions last consistently according to all decision makers. It is important to note that although BPC is a difficult selection to make, given the availability of natural gas resources (ING and FGW) it is unlikely that they will be able to replace coal entirely. Instead, this study looks at the most feasible replacement feedstock whenever possible.

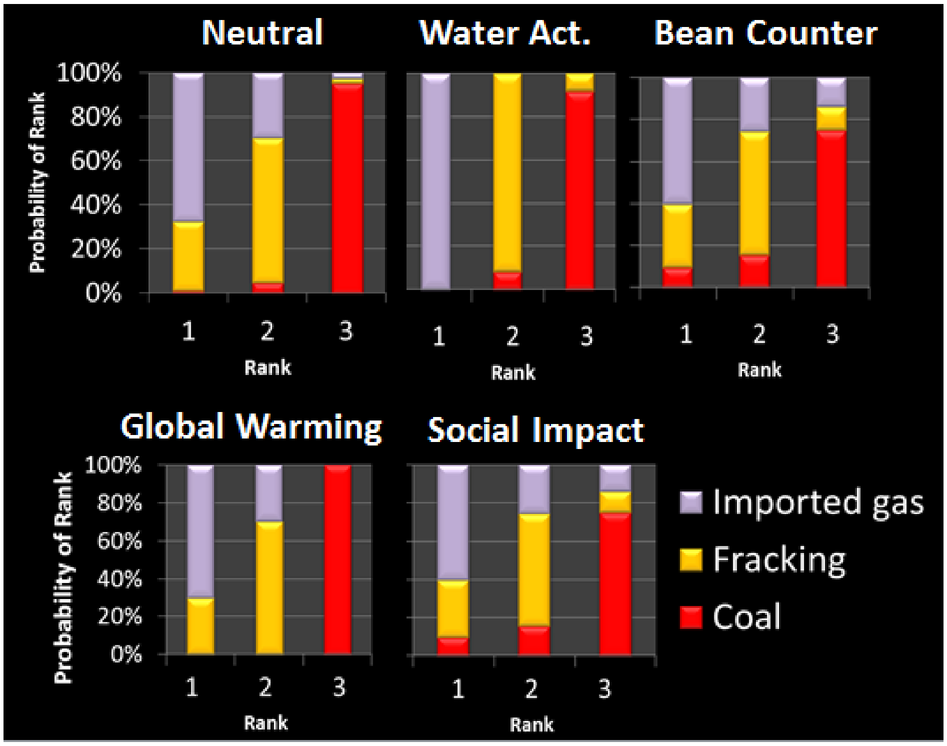

Figure 3. Probability of ranking of fuel alternatives (Case Study 1) according to decision makers.

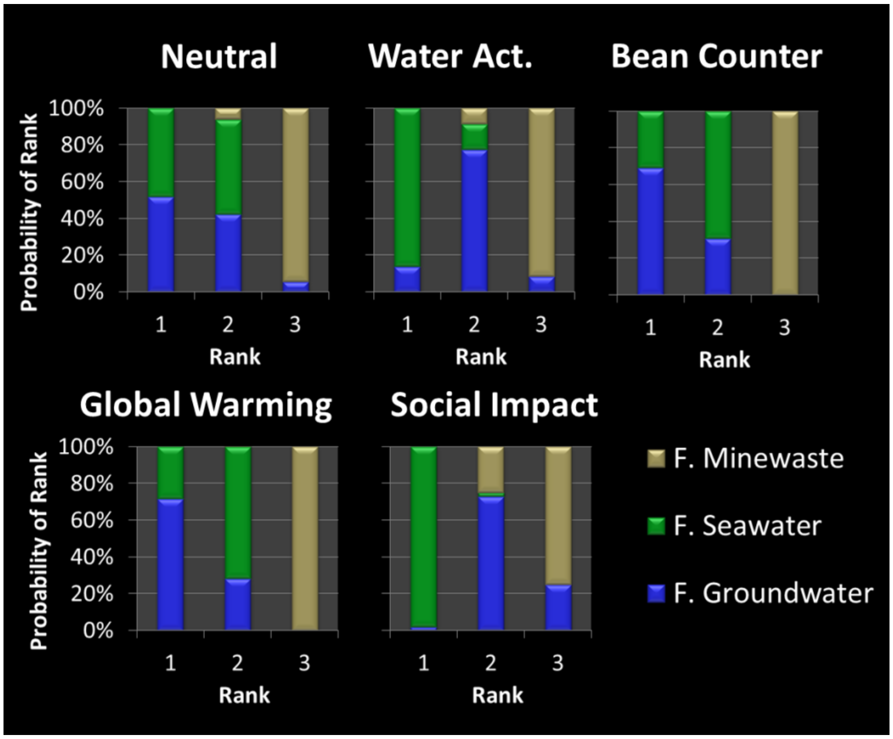

Figure 4. Probability of ranking of fracking alternatives (Case Study 2) according to decision makers.

Discussion

Case Study 1

For the neutral decision maker BPC always places last, and ING tends to be preferred. However, if FGW is less than half the cost of ING, the FGW alternative becomes a more viable option. For the Water Activist cost makes little difference, given that the water impacts of Importer Gas in SA are negligible, ING continues to be preferred despite price changes. Even with water issues as a priority, fracking is still preferred over coal (surprising) because according to the data, BPC consumes more water than FGW. The higher risk of aquifer contamination in FGW does not counteract with BPC's larger water footprint. For the Bean Counter BPC does not win even if it orders of magnitude cheaper than ING and FGW. The Bean Counter is most sensitive to the relative prices of ING vs. FGW. Whichever is cheaper is preferred. For the Global Warming Activist ING always wins because fuel extraction CO_2 is emitted outside South Africa's national borders. The preference is so high that even if ING is 100 times more expensive than FGW and BPC it still wins. At this point, FGW gets 30% chance of ranking first at most. There is a valid discussion whether it is ethical to export environmental externalities to other Southern African countries because Global Warming accounting happens at a national scale, but the effects of climate change are global. Therefore, it depends what the motivation for accounting for global warming is: policy compliance or actual global warming mitigation strategies. Regardless, it puts into question carbon accounting methods that limit the analysis to national borders. For the Social Focused decision maker, even though BPC generates more jobs (through mining) it ranks last most of the times because it has a much higher environmental footprint, and it performs worse at the "risk of displacement" criterion – A priority for this decision maker. In addition, ING places first because of the reduced environmental emissions and because it has a lower risk of displacement. However, FGW is competitive with ING when it is cheaper.

Case Study 2

For the Neutral decision maker FGW and FSW are equally competitive at first place and FMW which has the most transport and aquifer contamination risk, places last. If the risk of FMW and FSW get closer together, FGW becomes more viable. However, for the Neutral decision maker, FSW presents a good compromise of medium aquifer contamination risk and no potable water consumption. With respect to the Water Activist, FSW is preferred 80% of the times, FGW places second also with about a 80% probability. However, if FSW has the same risk of contamination as FMW (both four times greater than FGW), FGW is preferred. The Water Activist faces the challenge of protecting the aquifer vs. conserving water, and it depends on the relative risk of aquifer water contamination. The Bean Counter prefers FGW because is cheaper (less transport). FSW is the second preferred alternative. As aquifer contamination risks get closer together, the preference of FGW increases. For the Global Warming Activist FGW takes the first place 70% of the times because it has the least transport (less CO_2 emissions) and the least aquifer contamination risk. Lastly, the Social Focused decision maker sees FSW as the best compromise because it generates more jobs without having the most risk of contamination. In fact, the preference of FSW is 97%. Even if the risk of aquifer contamination is the same as FMW, it generates less emissions overall because of the reduced transportation distances.

Conclusion

Case Study 1

BPC is the least preferred alternative even if cost is the most important criterion, and the price difference is cheaper by orders of magnitude. BPC's poor performance in almost every criteria makes it a very problematic choice for all decision makers. However, variations in the cost of production change the viability between ING and FGW. Therefore, more accurate information with regards to the relative cost between these alternatives can bring clarification between these two options. Furthermore, it may be worthwhile to include environmental impacts outside SA.

Case Study 2

FMW ranks last consistently because it requires the most transport and it has the highest risk of aquifer contamination. The FGW and FSW are highly competitive in the first and second place because of the water use vs. water contamination tradeoff. In this case further refinement of the value functions and the weights for these two criteria could clarify the choice.

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Supplementary Information

Value Measurement Analysis of Energy Tradeoffs in South Africa

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1. Data Collection by criteria for Case 1: Fuel Options

Global Warming Potential: The life cycle greenhouse gas (GHG) emission data measured in CO2 equivalents at a 100 yr time frame for BPC, FGW and ING was obtained from the JISEA, 2012 study where they perform a comparative analysis of GHG emissions. The measure of CO2 equivalents allows for the representation of GHG to be aggregated based on their potency to trap heat. Therefore, the lifecycle CO2 equivalents include all GHG emissions (carbon dioxide, methane, nitrous oxides etc.) during extraction, processing, distribution and combustion.

The BPC value was obtained from the JISEA, 2012 reported value of coal practices in the US. Since BPC relies in the newest technology, we found it appropriate to estimate the new generation of power plants in SA to have similar emissions than those in the US. The harmonized study of life cycle GHG emission of coal power plants (980 kg of CO2 eq /MWh) comes originally from Whitaker et al, 2012. The values for FGW were taken from the values of regular fracking in the US estimated at 440 kg of CO2 eq /MWh (JISEA, 2012). For the ING value we used the value from JISEA, 2012, 520 kg of CO2 eq/ MWh with a reduction to discount the emissions occurring outside SA. According to a study from the same research group, Heath et al, 2012, 80% of all life cycle GHG emissions from conventional gas occur at combustion. Therefore, we calculate the final value to be 416 kg of CO2/ MWh (520*0.8 kg of CO2/ MWh) to only account for the combustion stage.

Water use: Since all alternatives, BPC, FGW and ING have thermal generation plants, the water used at this stage was not accounted for because it is estimated it is the same across all fuel options. Therefore, ING has no water impacts since its extraction and processing occurs outside SA. The water use for coal was obtained from Fthenakis and Kim, 2010 where they report the water quantities at all stages of coal electricity production for open cast and underground practices. SA performs 50% of its coal mining undergrounds, with the remaining 50% open cast (Eberhard, 2011). Therefore, we did a weighted average of the water use and included washing. In the end, we concluded that the extraction and washing of coal in SA required 0.12 m3/ MWh. The water required for shale gas extraction for the FGW alternative was obtained from Clark et al, 2011 based on their reported average water requirements per well per fracking event (3.2 million gallon), the number of fracking events in a wells life time (2), and the estimated ultimate recovery (EUR)of a well (3Bcf) with a high heating value of 1030 Btu/cf, we calculate a water use of 0.27 m3/MWh.

Land use: This indicator covers the extraction stage of energy generation because the combustion is estimated to be the same for all fuel options. For BPC, the value was based on the SA coal mining practices, which is half open cast, half underground (Eberhard, 2011). According to Fthenakis and Kim, 2009, open cast and underground coal mining use 400 m2/GWh and 200 m2/GWh respectively. We calculate 0.3 m2/MWh as shown in Table 2. For FGW, we use Clark et al 2011 study which estimates a quarter square mile per well and an EUR of 3Bcf. Therefore, FGW uses 0.14 m2/MWh of land during extraction. ING has most of its land use impacts outside SA, therefore for the purposes of this analysis it has not land use impacts.

Waste: According to ESKOM 2011, ash generated in 2011 amounted to 36,220 tons and produced 237,430 MWh of electricity. Therefore we estimate 152.5 kg/MWh of waste from coal electricity. Waste from FGW corresponds to the amount of flowback water that comes back up to the surface after fracking. Lewis, 2012 studies waste from natural gas practices in the SU (conventional and unconventional) and estimates an average of 1.3355 Mgal of waste and 1,031 MMcf of gas production during a 4 year span. Liquid waste is composed of fracking chemicals, water and brine, and we assume a density equal to that of water. At the end, we estimate a total waste production of 16.5 Kg/MWh. Waste generation for ING occurs outside SA, thus is not accounted for in this analysis.

PM10, NOx and SOx: All critical air pollutant values form Table 2 come from Argonne's National Lab estimates (Cai et al., 2012). For this criterion we include combustion, because there is a significant difference between coal and natural gas in the production of critical air pollutants. However, criteria air pollutant generation values are the same for FGW and ING because both these alternatives utilize the same fuel at combustion. Even though the extraction of shale gas in SA will release criteria air pollutants, there is to date no comprehensive estimate of these.

Mercury: Coal burning in SA is one of the leading causes of anthropogenic mercury emissions. It is unclear how best practices will mitigate them, because even though they will implement new technologies, SA burns low grade coal. Therefore, BPC's value comes from total mercury emissions from coal burning in 2006 according to Masekoameng and Dabrowski, 2010 (38.85 ton Hg/ yr) and the total amount of electricity generated from coal in SA from the Department of energy in 2006 (220,991 GWh) (SA Energy Digest, 2009). Alternatively, ING and FGW generate negligible mercury emissions.

Aquifer Contamination: The risk of aquifer contamination for the ING alternative is nonexistent because extraction occurs outside SA. This analysis considers the risk of contamination to be higher for FGW because of the unfamiliarity with shale gas extraction practices, and because the dolomite intrusions in the Karoo geology enable faster transport of underground fluid in case of case failures or fractures (Vermeulen, 2012). Comparing FGW to BPC, SA energy technologists and engineers have more years of experience and count with greater tacit knowledge surrounding all aspects of technology including waste management and remediation. Therefore, out of the three alternatives FGW has the highest risk of aquifer contamination

Job Creation: Job creation at the thermo electric generation plant was excluded, because it was estimated to be the same for all alternatives. Therefore, this criterion includes job creation at the fuel extraction stages. The number of direct jobs generated by coal mining in 2010 for electricity production comes from the Chamber of mines SA, 2012 (79766 job/Mt), plus the amount of coal that went into electricity production in 2010 (121.16 Mt) (Pooe 2011) and the amount of electricity generated from coal is based on ESKOM, 2011 (122.7 Mt/232 812 GWh). This study calculates 0.00035 jobs/MWh for BPC.

Cost of Production: This criterion was utilized as a way to perform sensitivity analysis. Data availability with respect to these future technologies is highly complex, so this study varies the relative costs according to the Department of Minerals and Energy, 2003, and ESKOM, 2012 to see how it would affect the alternatives' favorability. The main manuscript contains more details on the sensitivity analysis.

Risk of Displacement: This criteria reflects the potential (qualitatively) of alternatives to induce displacement of population due to their land use. Most of the Land Use of ING occurs outside SA, so the risks of displacement are negligible. FGW will occur in the Karoo Region which has a very low population density, so this risk is minimal compared to BPOC coal given the location of untapped coal reservoirs. In addition, coal mining is much more land intensive than unconventional gas extraction practices.

Energy Independence: This criterion reflects the contribution of an alternative to the robustness of SA energy systems. Imported energy as in the case of ING does not contribute to the robustness, nor resilience of energy infrastructure of SA because supply is directly related to the political and economic climate of other countries (most likely Mozambique and Botswana). Alternatively, FGW and BPC are both domestic resources and both contribute to Energy independence of SA.

2. Data Collection by criteria for Case 2: Fracking Options

Global Warming Potential: The global warming potential has the same definition as in Case 1, and in fact the performance of FGW remains the same. For the second case study, FSW and FMW has slightly greater Global Warming Potentials because of the additional transportation of the fracking fluid. This study utilizes transportation factors using GREET and assumes the transport of mine waste and seawater utilize a Heavy duty truck of 25 short tons capacity at a 5 mile per gallon of fuel efficiency. FMW gathers fracking fluid 1000km away from fracking site, and the FSW alternative gathers seawater from the coast at 300km. Therefore, the additional greenhouse gases reflect the emissions during transportation.

Water use: The water use remains the same for FGW in Case 2 than in Case 1. FSW and FMW have no water use because the water used for fracking fluid is not suitable for human consumption.

PM10, NOx and SOx: Similarly to the Global Warming Potential, FGW remains the same in terms of this criteria, but FMW and FSW have additional emissions due to transportations. Emission factors for PM 10, SOx and NOx were calculated according to GREET emission factors of a heavy duty truck.

Aquifer Contamination: Aquifer contamination was assessed qualitatively and was dependent on the type of water used for fracking. Even though FSW and FMW undergo cleaning prior to hydraulic fracking, the water quality is worse than in FGW. Therefore, out of the three alternatives FMW has the highest risk because if in the case of intrusion to the aquifer, consequences will be more severe. The magnitude and severity of consequences is less for FSW and are relatively less severe for FGW.

Job Creation: This criterion accounts for the additional jobs due to the transportation of the fracking fluids. This study assumes one job (driver) created per truck utilized. Each heavy truck with 25 short ton capacity and each well requiring a total of 0.0168 m^3 of fluid (mine waste or sea water) per fracking event and each well requiring 2 fracking events per lifetime of the well, and a total lifetime production of 905,586 MWh of natural gas. This way, it is possible to estimate the number of jobs per unit of electricity. This analysis assumes the transportation for the FGW has relatively negligible transportation and thus it does not generate additional transportation jobs.

Cost of Fracking Fluid: This criterion accounts for the cost of diesel used in heavy trucks during transportation of fracking fluids. The FGW option has relatively negligible transportation, so the cost is set at zero. The cost for FSW is based on a distance of 300km (600km roundtrip), a coastal diesel cost of R11.06/L, a truck capacity of 25 short tons, a fluid requirement of 0.0168 m^3 per fracking event, and a total of 2 fracking events per lifetime of a well, with a total estimated ultimate recovery of 905,586 MWh. The same parameters apply for FMW except the distance which is 1000km (2000km roundtrip), and an inland diesel cost of R11.31/L.

3. Transportation

Transportation of fracking fluids for Case Study 2 are modeled according to Figure S1.

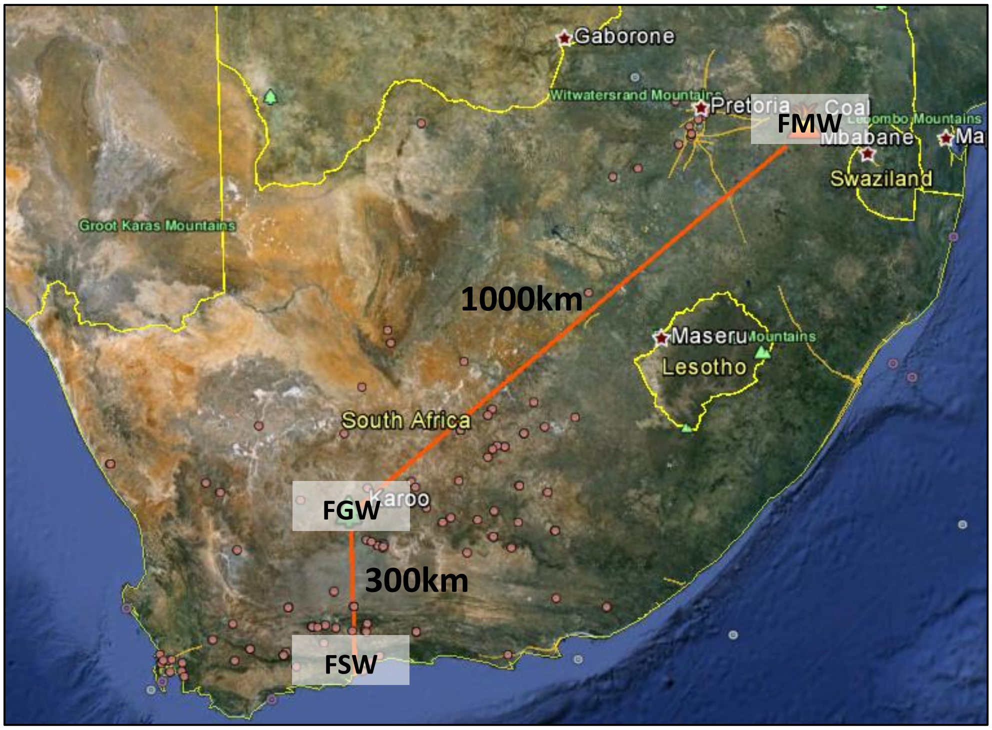

Figure S1. Transportation distance for FSW and FMW

4. GREET emission factors for FSW and FMW (Wang, 2011)

Pollutant	GREET Emission factor		Includes roundtrip distance			
			FMW	FSW	FSW	FMW
	g / gal of diesel	g /meter travelled per m^3 of fluid	g/m^3 fluid		kg /MWh	
Nitrogen Oxides	1.34E+01	7.34E-05	1.40E+02	4.41E+01	1.48E-03	4.70E-03
Particulate Matter of 10 microns (PM10)	5.00E-01	2.74E-06	5.21E+00	1.64E+00	5.53E-05	1.75E-04
Sulfur Oxides	1.30E+00	7.12E-06	1.35E+01	4.27E+00	1.44E-04	4.56E-04
Carbon Dioxide	1.07E+04	5.88E-02	1.12E+05	3.53E+04	1.19E+00	3.76E+00

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