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Estimating the opportunity cost of water for the Kusile and Medupi coal-fired electricity power plants in South Africa

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Abstract
In South Africa, water is considered a limited source, not only because of the country's arid nature, but also because of the relatively skew distribution of the resource and the fact that 98% of the resource is already allocated. Eskom, the South African electricity supplier, commenced with the construction of two new coal-fired power stations namely Kusile and Medupi. The question is: what is the opportunity cost of investing in these power stations from a water perspective? We do not argue here against the need for power plants and additional electricity generation capacity per se, but consider the opportunity cost of using this specific technology. We estimate the shadow price of water for different power generation technologies as an indicator of the opportunity cost of water.
We apply a production function approach for a baseline case (coal-fired power generation using the Medupi and Kusile parameters), and four alternative technologies. The only alternative that performs worse than the baseline case is the traditional wet-cooling coal-fired power process. The baseline case, however, does show a high opportunity cost when compared to renewable alternatives (solar, wind and biomass) ranging from R0.66/kWh (biomass) to R0.83/kWh (solar) to R1.31/kWh (wind).

Keywords: opportunity cost, water, coal-fired energy generation, Kusile, Medupi

1. Introduction

Accessible and affordable water of high quality is considered to be one of the scarcest natural resources on our planet. The World Water Council (n.d.) argues this point by stressing that although the global population tripled during the 20th century, the water consumption increase was six fold. Increasing industrialisation, including the need for more power generation, and urbanisation only add to the already burdened conditions. Also, the most common form of power generation is by means of coal combustion which has various implications for water quality and quantity. While it is important to take note of the negative side effects of coal-fired power stations, electricity in and by itself plays an extremely important role in any economy: firstly, as a supplier of an essential input to all other economic sectors and, secondly, as an employer and service provider for households. Eskom, South Africa's power utility, has embarked on an infrastructure expansion programme. As part of this programme, two coal-fired power stations, Medupi and Kusile, will be added to the country's existing capacity.

Given that water is a limiting factor to development (Blignaut & Van Heerden, 2009), the question is: What is the society-wide cost of this water consumption? This is an important question, as water's administered prices do not capture society's welfare impact due to externalities (Spalding-Fecher & Matibe, 2003). The water tariff, therefore, does not have any signalling power for the actual social cost. To aggravate matters, the water tariff is only in rare cases reflective of the full cost of delivering the water. As an alternative the shadow price is estimated as an indicator of the opportunity cost of water to society when engaging in coal-fired electricity generation. Shadow prices are usually relevant when real prices cannot represent the actual loss of welfare to society (Moolman *et al.,* 2006).

The main purpose of this paper is to estimate the opportunity cost of water for the two prospective power stations. In order to do so, the shadow price of water has to be estimated for electricity generation based on the technology to be used by the

two power stations. This shadow price then has to be compared with the shadow prices of water, assuming that alternative technologies were employed. This assessment here is purely economic – considering the value of water and the opportunity cost thereof is not equal to financial costs. Rather, opportunity cost here is the value of the societal losses not being implemented.

To do so, a literature review is described, followed by a profile of the water sector in South Africa as well as the two new power stations. This will be followed by the research method, the data and the results. The final section discusses the findings and concludes. It should be noted that this analysis excludes the contribution to externalities of other parts of the coal chain, such as health, plant construction and the coal mining operation itself (see Riekert and Koch 2012, Inglesi-Lotz and Blignaut 2012 and Nkambule and Blignaut 2012 for these).

2. Literature review

Water is an important consideration for all developing countries that experience shortages linked to poverty and other social challenges (Asthon & Haasbroek, 2002; Van Heerden *et al.,* 2008). On the other hand, water is considered an important natural capital resource that is becoming scarcer by the day (Aronson *et al.,* 2006), affecting the economy's growth and development.

Literature on the environmental concerns related to the selection of different power generation technologies has been increasing over the last few years (Roth & Ambs, 2004; Feeley *et al.,* 2008; King *et al.,* 2008). Electricity-generating power stations have an impact on the environment while being constructed, as well as while operating (generating electricity, using fuel). Spalding-Fecher and Matibe (2003) summarise the main externalities by classifying them in three categories, as in Van Horen (1996). Water quality issues are considered unlikely to be serious (see further discussion), while water consumption and pricing are classified as being potentially serious, but not readily measurable. Its seriousness is exacerbated by climate change related issues, as the frequency and severity of climate-related events are likely to affect water provisioning in the future. Feeley *et al.* (2008) also argue that, in the future, the competition for water will increase among water-intensive sectors such as agriculture, power generation and the residential sector.

An additional concern is the appropriate rates and tariffs paid for water by coal-fired power stations. Spalding-Fecher and Matibe (2003) raise the question of whether the administered water prices include the opportunity cost of water. The real costs of water should be based on the capital costs of the infrastructure, added to the operation and maintenance costs. They suggest that to achieve accuracy in the pricing of water, the opportunity cost for each catchment area should be estimated. While this is not yet considered in South Africa, the opportunity cost of water for industries such as agriculture has been estimated (Moolman *et al.,* 2006). It has, however, not been done for the power generation industry.

In the literature, there are three main directions towards an improvement of the water requirements for power generation. Firstly, there are studies that suggest technological advancements in order to reduce the water intensity of the current techniques of electricity generation (Feeley & Ramezan, 2003; Feeley *et al.,* 2008). Secondly, a number of studies recommend a combination of innovative technologies with regard to fossil fuel-fired power stations with a switch to renewable technologies (Larson *et al*., 2007; Sovacool & Sovacool, 2009). Thirdly, studies such as that of Von Uexkull (2004) support the notion that the only solution for the future of power generation is the switch to cleaner renewable energy technologies that are also benefiting water users.

3. Background

3.1 South African water sector

From a supply point of view, South Africa is considered a water-limited country. The average annual rainfall is 497 mm, which is much lower than the global average of 860 mm per annum[1] (Turton, 2008). Only 8% of the country's rainfall is caught in dam outlets and rivers that are controlled by water authorities, while a large amount of the precipitation is lost through evapotranspiration and deep seepage (Van Heerden *et al.,* 2008). The water resources in the country are also distributed unevenly. More than 60% of the river flow comes from 20% of the land area (DWAF, 1997). Groundwater is scarce, since most of the country is underlain with hard rock formations that lack major water aquifers. This fact also adds to the risks of major shortages in the case of overexploitation (DWAF, 1997).

As Blignaut and Van Heerden (2009) point out, the balance of water resources remaining for development is declining while Turton (2008) specified that more than 98% of the country's water has already been allocated. This decline can be attributed to demographic and socioeconomic pressures, the change in climate and the allocation of water to higher value-added industries such as the electricity sector (Blignaut *et al.,* 2009). It is expected that the available water resources will not be sufficient to meet the future water requirements, especially with the current rates of population and economic growth (Eberhardt & Pegram, 2000). This is confirmed by the fact that the country has started importing water and with several catchments already in deficit (Wassung, 2010). This increasing

scarcity necessitates an investigation as to the opportunity cost of water where this is defined as the cost of any activity in terms of the best alternative forgone.

3.2 Medupi and Kusile power stations

The site preparation activities for the Medupi power station started in May 2007 (Eskom, 2011). The first unit was expected to be completed in 2012, while the overall station is expected to reach its full capacity by 2015. Kusile consists of six units of approximately 800 MW electricity generation capacity each, giving an aggregate estimated supply of 4 800 MW. The first unit is scheduled to begin operation in 2014, while the remaining ones will be ready by 2018. Both power stations will have a capacity of approximately, 4 800 MW each (Eskom, 2011) and a lifespan of 50 years (Eskom-Medupi power station, n.d., Action Sierra Club, n.d.).

Medupi is located in Lephalale. It lies in the Mokolo River Catchment that drains into the Limpopo River, and the specific site where the power station is situated measures 883 ha. The area is relatively flat, approximately 920 m above sea level. Approximately 87% of the water in the catchment was previously used for agricultural activities, game and cattle grazing (Eskom-Medupi power station, n.d.) as well as for industrial, mining, power generation and domestic water supply (AfDB, 2009).

The Kusile power station is located on the Hartbeesfontein and Klipfontein farms in eMalahleni, Mpumalanga, and extends over 1 355 ha (NCC Environmental Services, n.d.). The area was previously used for agricultural activities and cattle grazing (Frontiers Insight, n.d.). Water required for the Kusile power plant will be supplied from the Vaal River system (and not the catchment area). From the Vaal River water sources used locally in 2000, 64.5% was used for irrigation and by urban and rural consumers, while the rest was used for mining and power generation (DWAF, 2004).

The Medupi and Kusile power stations will use a variety of new technologies in all stages of the electricity generation process. The country's power stations have been using three types of systems for cooling purposes (Eskom, 2010): wet-cooling (the most conventional type), direct and indirect cooling. Only the Koeberg nuclear power station uses a completely different cooling system. Kusile and Medupi are designed to have dry-cooling systems due to the water scarcity and limited water availability at the location (AfDB, 2009). The difference in water requirements between direct and indirect dry-cooling systems is substantial. The water needed for the dry-cooling process is 0.160 m^3/MWh of electricity sent out. In addition to this, water for coal washing (0.150 m^3/MWh) and, if necessary, carbon capture and storage (CCS) (0.100 m^3/MWh) should be added. This brings the total requirement to 0.410 m^3/MWh (DoE, 2011).

Another innovation that will be used in the two new power stations is a flue gas desulphurisation (FGD) mechanism. This process is responsible for removing sulphur dioxide (SOx) from the exhaust flue gases in coal power stations. These gases are primarily responsible for the phenomenon of acid rain and causes substantial deterioration of water quality. FGD will increase the water requirement (an extra 0.250 m^3/MWh is needed) to 0.66 m^3/MWh. This requirement, although considerable, is almost half the average of South African power stations in 2012, namely 1.35 m^3/MWh of electricity sent out (Eskom, 2011). This means that the two power stations, once fully operational, will require approximately 52.3 million cubic metres per annum[2]. This amount of water will represent 14% of the total water consumption of Eskom, while Kusile and Medupi will produce 23% of the power.

According to Ninham Shand (2007), the new power stations will not influence the quality of the regional water supply substantially because they will operate under Eskom's Zero Liquid Effluent Discharge (ZLED) policy. The main purpose of this policy is to ensure that the quality of water discharged into the receiving bodies should be at least as good as before it was used (Spalding-Fecher & Matibe, 2003). However, the ZLED policy will only be put into effect when the all the power units are fully operational. The overall expected result from this is no conscious discharge of pollutants into existing water resources or riparian zones. It should be noted that ZLED is a policy implemented through different technologies, depending on the specific power station. No formal evaluation of the policy has been published yet.

4. Research approach and materials

4.1 Methodology

To determine the true scarcity value of the water, we had to estimate its shadow price and compare these shadow prices of water using different technologies. The way in which we propose to estimate the shadow price reveals the net marginal revenue of water, that is the additional revenue generated by using a cubic metre of water. The higher the net marginal revenue (NMR), the more efficiently water is used, that is, the greater the marginal value of the water. The difference between the net marginal revenues is the opportunity cost of using one technology above the other. This approach has successfully been applied within the agriculture sector as described in Moore and Dinar (1995), Moore (1999) and Moolman *et al.,* (2006). According to Moolman *et al.* (2006), for example, the NMR of sugar cane is several orders of magnitude lower than mangoes. The opportunity cost, from a water perspective, of planting sugar cane is the difference

between mangoes and sugar; that is the forgone value (opportunity cost) of using water on sugar rather than on mangoes.

To estimate the opportunity cost of water for the Kusile and Medupi power stations and in accordance with Moore (1999), a panel data analysis is used. The logic behind the use of a revenue function lies in the literature that estimates water as a fixed input (Moore, 1999). Owing to the fact that water prices are set as administrative prices, they serve neither a rationing nor an allocating function (Moore, 1999; Rausser & Zusman, 1991). Two earlier studies (Moore & Dinar, 1995; Kanazawa, 1993) confirmed the hypothesis that water is a quantity-rationed input and revenue function models water appropriately. According to Moolman *et al.* (2006), the marginal revenue function for water is obtained from the total revenue function. The revenue function is estimated by using a production function approach. The total revenue of electricity is a function of the price of the product (electricity), the quantity of water consumed for the generation of electricity and a number of other variables, such as the total expenses for the use of necessary coal per power station. In this case, the total revenue is calculated by multiplying the price of electricity with the quantity of the net electricity sold per power station and, hence, neither of them can be included as an explanatory variable. Therefore, the total revenue function is defined as follows:

Equation 1

$$TR = f(\text{water, total expenses}) \quad (1)$$

where TR is the *total revenue* calculated by multiplying the net quantity of electricity supplied with the price of electricity, *water* is the water used in electricity generation, and *total expenses* is the overall costs of each power station for coal (price of coal times the quantity of coal) plus other operational costs when we estimate the model assuming coal-fired power stations; or total expenses is the sum of fixed and variable costs with regard to the electricity generation of alternative options, such as solar, wind or biomass. The total revenue function is estimated using a quadratic functional form as proposed by Moore (1999). This form is defined as follows:

Equation 2

$$TR = \alpha + \sum_{i=1}^{m-1} \beta_i \text{totalexpenses}_i + \beta_w \text{water} + \sum \beta_{ij} \text{totexpenses}_i * \text{totalexpenses}_j + \beta_{ww} \text{water}^2 + \sum \beta_{w\ \text{totalexpenses}_i} \text{water}_i * \text{totalexpenses}_i$$

Equation 3

$$\sum_{i=1}^{m-1} \beta_i \text{totalexpenses} = \beta_i * \text{totalexpenses}_i + \beta_j * \text{totalexpenses}_j$$

Equation 4

$$\sum \beta_{ij} \text{totalexpenses} * \text{totalexpenses}_j = \beta_i * \text{toalexpenses}_i^2 + \beta_j * \text{totalexpenses}_j^2$$

Equation 5

$$\sum \text{water} * \text{totalexpenses} = \beta_{w\ \text{totexc,med}} w_{med} * \text{totexc}_{med} + \beta_{w\ \text{totexc,kus}} w_{kus} * \text{totexc}_{kus}$$

where *i* denotes Kusile power plant or its hypothetical (renewable) equivalent and j denotes Medupi power plant or its hypothetical (renewable) equivalent.

The marginal revenue function of water determines the unit cost as the opportunity cost. As already noted, the marginal revenue function for water is derived as in Moore and Dinar (1995):

Equation 6

$$\lambda\,(\text{totexc}, w) = \beta_w + 2\,\beta_{ww} w_i + \sum \beta_{w\ \text{totexc}} \text{totexc}_i$$

Equation 7

$$\sum \beta_{w\ \text{totexc}} \text{totexc}_i = \beta_{w\ \text{totexc}_{med}} \text{totexc}_{med} + \beta_{w\ \text{totexc}_{kus}} \text{totexc}_{kus}$$

Before proceeding, it is imperative to clarify that water as an input to production is not unlimited, but highly contested within the specific catchment. Water values are not universally transferrable but geographic and project specific. Hence, the method chosen is considered appropriate under conditions of contestability.

4.2 Data

Since neither of the two power stations is currently operational, only projected information on the variables can be used. The data used is based on information collected from various reports describing the two power stations and assumptions in order to estimate the time series for a period of 20 years. A two-decade period was selected because it is approximately half the estimated lifespan of the power stations in question. Six models will be estimated to calculate the differences between the chosen technology for the two power stations (baseline) and five alternative options. These are as follows:

- Baseline: dry-cooling process, with FGD, as proposed for Medupi and Kusile

- Alternative 1: dry-cooling process without FGD
- Alternative 2: conventional wet-cooling South African power plant using Eskom's average (2010) water consumption figures
- Alternative 3: concentrated solar power (CSP) with parabolic trough, with 9 hours energy storage (as in Macknick *et al.* 2011).
- Alternative 4: wind
- Alternative 5: forest residue biomass

For each of these models, the assumptions are as follows:

Total revenue=price of electricity x quantity of electricity sold (net quantity of electricity)

• ***Price of electricity:*** The real average price for Year 1 is assumed to be the same as the average 2010 price, which was equal to R0.416/kWh (Eskom, 2011). For the rest of the sample, the base case scenario of the Integrated Resource Plan (IRP) of Electricity 2010 (RSA, 2011) is followed. It is noted here that according to this estimation, the real average price for electricity will decrease slightly after it reaches the ceiling of R1/kWh. We use the IRP time series, although it might not necessarily be viable.

• ***Quantity of electricity:*** In the Medupi power station, only one unit is assumed to be operational in Year 1. According to the Eskom annual report of 2008 (Eskom, 2009), an extra two units will be operational in Year 2, another one in Year 3 and another two in Year 4. In the Kusile power station, one unit will become operational every eight months, according to Eskom (Eskom, n.d.). For this study, the frequency of the data is annual, so the assumption is that one extra unit becomes operational every year. The gross capacity per unit is 794 MW for Medupi and Kusile (Eskom, 2011), but their net capacities (after deductions for internal use) is 723 MW (Eskom, personal communication). Further-more, the amount of electricity that can finally be supplied by each unit is equal to its net capacity times its operational load factor (85%).

For the solar and wind alternatives, the net production of electricity is calculated as the gross quantity produced multiplied by their load factors: 43% and 29%, respectively (RSA, 2011). For biomass, the net production takes into account that 10% of the production is used within the power plant and from this only 85% (load factor) is finally sent out for consumption.

Total expenses for coal=price of coal x quantity of coal

• ***Price of coal:*** The information is derived from the Quantec database (Quantec, 2011) and the series is called *Local sales: Coal (Unit: Rand/ton)*. For Year 1, the price of coal is assumed to be equal to the average 2010 price (January to December) and for Year 2, the estimated average price of coal for 2011. For Year 3 to Year 7 it will be a two-year moving average. From there onwards until the end of the sample, we assume that the price of coal will increase by 2% every year, thus capturing the increasing resource shortage.

Quantity of coal: According to the report by the African Development Bank (AfDB, 2009), the coal requirement will be 17 million tons per annum once the overall project is functioning. Hence, it can be assumed that one functioning unit will require 2.8 million tons per annum. In the first years, the requirements will be dependent on the number of operational units. After that it remains the same.

Operational, fixed and variable costs

• ***Coal-fired:*** Other operational costs are also taken into consideration for the baseline and the first two alternatives (coal-fired technology). In Eskom's annual report for 2011, the operational costs per kWh for 2010 were said to be 28.23 cents, to which we added the amortisation costs of the new power plants.[3] Hence, the operational cost ratio is multiplied with the amount of electricity produced for each year.

• ***Solar:*** The fixed operating and maintenance cost for this type of technology is R635 000 per MW per year (RSA, 2011), to which we added amortisation costs, assuming a technology of concentrated solar power (CSP) parabolic trough with nine hours of storage capacity. This ratio is multiplied with the amount of electricity sent out by the hypothetical solar power plant.

• ***Wind:*** The fixed operating and maintenance cost for this type of technology is R266 000 per MW per year (RSA, 2011) plus amortisation costs. This ratio is multiplied with the amount of electricity sent out by the wind power plant.

• ***Forest residue biomass:*** The fixed operating and maintenance cost for this type of technology is R972 000 per MW a year (RSA, 2011) plus amortisation costs. The variable operating and maintenance costs for such a technology are R31.1/MWh a year. This ratio is multiplied with the amount of electricity sent out.

Water requirements

The water consumption differs substantially from technology to technology. Table 1 presents the assumed water requirement ratios per unit of electricity produced for the different alternatives. We multiply these by taking into account that a power station is not used at its full capacity, that is there is an underutilisation of 5%.

Table 1: Water requirements for each of the alternatives

Technology	*Water requirement*	*Source*
Baseline: Dry cooling process with FGD	Dry-cooling = 0.16 m^3/MWh Coal washing = 0.15 m^3/MWh FGD = 0.25 m^3/MWh CCS[a]= 0.1 m^3/MWh Total = 0.66 m^3/MWh	Department of Energy, 2011
Alternative 1: Dry cooling process without FGD	Dry-cooling = 0.16 m^3/MWh Coal washing = 0.15 m^3/MWh CCS*= 0.1 m^3/MWh Total = 0.41 m^3/MWh	Department of Energy, 2011
Alternative 2: Conventional South African power plant (wet-cooling)	1.35 m^3/MWh	Eskom, 2011
Alternative 3: Concentrated solar power with parabolic trough[b]	0.296 m^3/MWh	Macknick *et al*., 2011
Alternative 4: Wind0.0038 m^3/MWh	Macknick *et al*., 2011	
Alternative 5: Forest residue biomass	0.36 m^3/MWh	Dennen *et al,*, 2007

Notes:
a) Carbon capture and storage (CCS) is a new technology that has not been tried or implemented yet.
b) Dry-cooling CSP is assumed here for comparison purposes (to the baseline).

5. Empirical results

The study uses a panel data set for 20 years, not linked to calendar years, with two cross-sections, namely Kusile and Medupi. The only restriction in the estimation is that, according to theory, the marginal revenue function of water (Equation 7) should be positive. Hence, as Moolman *et al.* (2006) suggest, the function should have a negative slope and a positive intercept. Limited cross-section heterogeneity is present, so pooled effects are also considered, but based on Moore and Dinar (1995) we should allow for variation in some of the factors of the components of the estimation and hence we proceed with a seemingly unrelated regression (SUR). The problem of hetereroskedasticity in the estimation was corrected by using White's cross-section heteroskedastic structure on the error term. The results of the baseline estimation are presented in Table 2.

The adjusted R-squared of 0.986 gives the indication that the model is a good fit to the data. The coefficient of water squared should be negative, based on economic theory, because it determines the slope of the marginal revenue function. In this estimation, the coefficient is equal to -1.17*e*-10 and statistically significant at the 1% level of significance confirming our *a priori* expectations. All the coefficients of the interaction variables (the ones contain-

Table 2: Baseline results

Dependent variable: total revenue
Total pool (balanced) observations: 40

Variable	*Coefficient*	*Standard error*	*t-Statistic*	*Problem*
WATER	0.00100	0.00049	2.02546	0.0512
$WATER^2$	-1.17E-10	0.00000	-3.35963	0.0020
TOTALEXPENSES_KUS	-0.74343	0.67089	-1.10812	0.2761
TOTALEXPENSES_MED	-0.86218	0.72696	-1.18601	0.2444
$TOTALEXPENSES\_KUS^2$	-0.00013	0.00003	-4.02579	0.0003
$TOTALEXPENSES\_MED^2$	-0.00013	0.00003	-4.12669	0.0002
TOTALEXPENSES_KUS*WATER_KUS	0.00000	0.00000	4.25711	0.0002
TOTALEXPENSES_MED*WATER_MED	0.00000	0.00000	4.50861	0.0001
Rsquared	0.989	Mean dependent variable		26883.950
Adjusted Rsquared	0.986	SD dependent variable		9251.171
SE of regression	1078.609	Akaike info criterion		16.982
Sum squared resid	37228729.000	Schwarz criterion		17.319
Log likelihood	-331.632	Hannan-Quinn criterion		17.104
Durbin-Watson stat	1.084			

ing water) that affect the intercept of the marginal revenue function are also all significant at the 1% level of significance and their combination yields a positive intercept. The function, therefore, is in accordance with economic theory.

It is now possible to firstly construct the *lambda* functions for both power stations and subsequently substitute the figures for Year 15 of our sample. The reason why Year 15 is chosen is because it is towards the end of the sample and the two power stations will have reached their full capacity (after Year 6, both plants are expected to be fully operational). From this point of the analysis onwards, we will proceed by discussing only one power plant because in Year 15 the two power plants will be identical. So, the *lambda* function of the baseline scenario is as follows:

Equation 8

$$\lambda = 0.001001 + (-2.34E-10) * water + 2.87E-07 * totalexpenses_i + 2.87E-10 * totalexpenses_j$$

By substituting the values for water and total expenses for power station *i* (Kusile) and *j* (Medupi), we find that λ is equal to R0.0097mil/m^3. With exactly the same approach as mentioned, we estimate the models for the five alternatives. A summary of the total revenue regressions for all the alternatives considered is presented in Table 3.

Based on these estimations, Table 4 presents the λ (*lambda* – net marginal revenue) calculated for each alternative in column 1, column 2 shows the difference between each alternative with the baseline. Column 3 presents the water consumption for the baseline and each alternative in cubic metres, while column 4 shows the net generation output of electricity in MWh. Column 5 presents the overall societal loss or gain by alternative, while column 6 shows the opportunity cost or the forgone revenue per unit of electricity expressed in R/kWh.

From this table (and especially column 2), we can see that only the conventional generation of electricity has net marginal revenue (NMR) lower than the baseline, as could have been expected. The negative signs in column 2 show that for every cubic metre that is used the forgone revenue is

Table 3: Summary of total revenue functions of alternatives

Dependent variable: total revenue	*Alternative 1 Without FGD*	*Alternative 2 Conventional*	*Alternative 3 Solar*	*Alternative 4 Wind*	*Alternative 5 Biomass*
WATER	-0.000791	-0.00024	-0.003372	-0.388829	-0.004101
$WATER^2$	-1.57E-10	-1.44E-11	-4.13E-10	-1.13E-06	-1.14E-10
TOTALEXPENSES_i	1.43E+00	1.28E+00	3.02E+00	7.92E+00	7.53E+00
TOTALEXPENSES_j	1.27575	1.434426	3.165621	8.164694	8.007294
$TOTALEXPENSES\_i^2$	-0.000132	-1.26E-04	-3.36E-04	-1.98E-03	-6.36E-04
$TOTALEXPENSES\_j^2$	-0.000126	-1.32E-04	-0.000351	-0.00207	-0.000692
TOTALEXPENSES_i*WATER_i	3.29E-07	9.97E-08	9.41E-07	1.77E-04	6.68E-07
TOTALEXPENSES_j*WATER_j	3.28E-07	1.00E-07	9.48E-07	1.79E-04	6.81E-07

Note: i denotes a power plant equivalent to Kusile and j equivalent to Medupi

Table 4: Shadow prices for each of the alternatives

		-1	*-2*	*-3*	*-4*	*-5*	*-6*
Year 15 (= from Year 4 onwards)		*λ NMR of water*	*Difference*	*Water volume*	*Net generation output*	*Society-wide loss (+) or gain (-)[a]*	*Opportunity cost[b]*
		R/m^3	*R/m^3*	*m^3*	*MWh*	*Rmillion*	*R/kWh*
Baseline		9 717		26 166 365	32 300 748		
Alternative 1	No FGD	11 149	-1 432	16 254 863	32 300 748	-23 278	-0.72
Alternative 2	Conventional	3 399	6 318	53 522 111	32 300 748	338 154	10.47
Alternative 3	Solar	14 667	-4 949	5 405 495	18 237 164	-26 753	-0.83
Alternative 4	Wind	930 736	-921 018	45 989	12 102 466	-42 357	-1.31
Alternative 5	Biomass	11 210	-1 493	14 272 563	31 925 470	-21 305	-0.66

Notes:

a) Societal loss is calculated as the difference (column 2) times the water volume (column 3), divided by a million.

b) Opportunity cost is calculated as the societal loss (column 5) divided by the net generation output of the baseline (column 4) (32.3 TWh) times 1 000

R1 432 (alternative 1), R4 949 (alternative 3), R921 018 (alternative 4) and R1 492 (alternative 5). Column 6 shows the opportunity cost in R/kWh. For example, in the case of using solar instead of a dry cooling coal-fired generating process, for every kWh of dry-cooling electricity sent out, the forgone revenue is equal to R0.83, which subsequently can be converted to R26.7 billion per annum if the production of electricity is equal to 32.3 million MWh per annum. Hence, embarking on a non-renewable pathway equates to a significant societal loss (between R21 billion and R42 billion per year) and opportunity cost (between R0.66/kWh and R1.31/kWh). It should be noted that converting to dry-cooling implies a societal gain of R340 billion per annum relative to conventional coal-fired power stations.

6. Discussion and conclusion

South Africa is a country that is characterised as being prone to suffering from chronic water shortages. Amidst the already impaired water conditions of the country, the electricity sector uses large amounts of water for generation purposes. Eskom's new infrastructure programme includes the building of two new power stations, Medupi and Kusile, which will be fully operational in the next five to six years.

To determine the true scarcity value of water to be consumed in the two power stations, we estimate its shadow price and compare the shadow prices of water using different technologies. The way in which we estimated the shadow price reveals the net marginal revenue of water, that is the additional revenue generated by using a m^3 water. The higher the net marginal revenue (NMR), the more efficiently water is used. The difference between the net marginal revenues is the opportunity cost of using one technology above the other.

The baseline presents the chosen technology for the two power plants: a dry-cooling process with FGD. The other alternatives include dry-cooling process without FGD, conventional wet-cooling process, solar, wind and biomass. By using a production function approach, it was possible to estimate the opportunity cost of water. The only alternative that performs worse than the baseline, as expected, is the traditional wet-cooling process used by the majority of South African power stations. The renewable forms of electricity generation selected for comparison (solar, wind and biomass) use substantially lower amounts of water and hence the results show high opportunity costs of not considering the alternatives, ranging from R0.66/kWh (biomass) to R0.83/kWh (solar) to R1.31/kWh (wind).

Notes

1. For comparison purposes in the same geographic area as South Africa, the annual average rainfall of Botswana is 400 mm and of Namibia 254 mm.
2. The number is a summation of the water requirement for both power plants. Their gross capacity of electricity is estimated to be 9 528 MW, that is two power plants with six units each, and each unit has a capacity of 794MW.First the figure was multiplied by 8 760 hours of the year to convert it to MWh, then multiplied by 0.85to allow for downtime and then multiplied by $0.66m^3$.
3. The amortisation costs present the linear depreciation of the capital cost over 50 years.

References

Action Sierra Club. (n.d.). South African Kusile 4 800-MW coalfired power project background information and fact sheet. Available at: http://action.sierraclub.org/site/DocServer/Kusile_Power_Project_Factsheet.pdf?docID=5541 (accessed on 7 July 2011).

African Development Bank (AfDB) (2009). Executive summary of South Africa: environmental impact assessment for the Medupi power plant project of Eskom. Available at: ww.afdb.org/fileadmin/uploads/afdb/Documents/Environmental-and-Social-Assessments/ESIA%20Ex%20Summary%20of%20Medupi%20Coal%20Power%20Plant%20July%201%20revised%20Final-ram-1.pdf (accessed on 7 August 2011).

Aronson, J., Blignaut, J. & Milton, J.C. (2006). Natural capital: the limiting factor. *Ecological Engineering,* 28:1–5.

Asthon, P. & Haasbroek, B. (2002). Water demand management and social adaptive capacity: A South African case study. In Turton, A.H. (ed.). *Hydropolitics in the developing world: A southern African perspective*. African Water Issues Research Unit (AWIRU) and International Water Management Institute (IWMI).

Blignaut, J. (2012). Climate change: the opportunity cost of Medupi and Kusile power stations. *Journal of Energy in Southern Africa* 23(4): 67-75.

Blignaut, J. & Van Heerden, J. (2009). The impact of water scarcity on economic development initiatives. *Water SA*, 35(4):415 – 420.

Blignaut, J., Ueckerman, L. & Aronson, J. (2009). Agriculture production's sensitivity to changes in climate in South Africa. *South African Journal of Science*, 105:61 – 68.

Dennen, B., Larson, D., Lee, C., Lee, J. & Tellinghuisen, S. (2007). *California's energy-water nexus: Water use in electricity generation.* Santa Barbara: Donald Bren School of Environmental Science and Management University of California.

DoE (Department of Energy) (2011). *Water – 2010 input parameter data (externality)*. Pretoria, South Africa: South African Department of Energy.

DWAF (Department of Water Affairs and Forestry) (1997). *Overview of water resources availability and utilisation in South Africa*. Pretoria, South Africa:

Department of Water Affairs and Forestry.
DWAF (Department of Water Affairs and Forestry) (2004). Internal strategic perspective: Upper Vaal Water Management Area. Report number: P WMA 08/000/00/0304. Available at: www.orangesenqurak.org/UserFiles/File/National%20Water%20Departments/DWEA-DWAF/Upper_Vaal_ISP.pdf (accessed on 2 September 2011).
Eberhardt, R. & Pegram, G. (2000). *The water sector*. Midrand: Development Bank of Southern Africa.
Eskom. (2009). *Annual Report 2008*. Johannesburg: Eskom.
Eskom. (2010). Cooling techniques at Eskom power stations. Available at: www.eskom.co.za/content/CO_0005Cooling TechnRev7~1.pdf (accessed on 7 July 2011).
Eskom. (2011). *Eskom Integrated Report 2011*. Johannesburg: Eskom.
Eskom. (n.d.). Medupi power station. Available at: http://www.eskom.co.za/c/article/57/medupi-power-station/ (accessed on 11 July 2011).
Feeley, T. & Ramezan, M. (2003). Electric utilities and water: Emerging issues and R&D needs. Water Environment Federation, 9th Annual Industrial Wastes Technical and Regulatory Conference, San Antonio, 2003.
Feeley, T., Skone, T., Stiegel, G., McNemar, A., Nemeth, M. & Schimmoler, B. (2008). Water footprint of bio-energy and other primary energy carriers. *Energy*, 33:1 – 11.
Frontiers Insight. (n.d.). *Kusile power station*. Available at: www.frontiersinsight.com/ company_page.php?company=14837 (accessed on 6 July 2011).
Inglesi-Lotz, R. and Blignaut, J. (2012). Estimating the opportunity cost of water for the Kusile and Medupi coal-fired electricity power plants in South Africa. *Journal of Energy in Southern Africa* 23(4): 76-84.
Kanazawa, M. (1993). Pricing subsidies and economic efficiency: The US bureau of reclamation. *Journal of Law and Economics,* 36:205 – 234.
King, C., Holman, A. & Webber, M. (2008). Thirst for energy. Nature Geoscience, 1:283 – 286.
Larson, D., Lee, C., Tellinghuisen, S. & Keller, A. (2007). California's energy-water nexus: Water use in electricity generation. Southwest Hydrology, Sept – Oct: 20–22.
Macknick, J., Newmark, R., Heath, G. & Hallett, K. (2011). A review of operational water consumption and withdrawal factors for electricity-generating technologies. Washington DC: National Renewable Energy Laboratory, US Department of Energy.
Moolman, C., Blignaut, J. & Van Eyden, R. (2006). Modelling the marginal revenue of water in selected agricultural commodities: A panel data approach. *Agrekon,* 45(1):78 – 88.
Moore, M. & Dinar, A. (1995). Water and land as quantity-rationed inputs in California agriculture: Empirical tests and water policy implications. *Land Economics,* 74(4):445 – 461.
Moore, M. (1999). Estimating irrigators' ability to pay for reclamation water. *Land economics,* 75(4):652 – 578.
NCC Environmental Services. (n.d.). Environmental management for Eskom. Available at: www.nature-conservation.co.za/index.html?id=38 (accessed on 7 July 2011).
Ninham Shand (2007). *Proposed coal-fired power station and associated infrastructure in the Witbank area: Final environmental impact report*. Report No 4284/401281. Available at: http://recruitment.eskom.co.za/content/WitbankEIR.pdf (accessed on 2 September 2011).
Nkambule, N.P. and Blignaut, J. (2012). The external costs of coal mining: the case of collieries supplying Kusile power station. *Journal of Energy in Southern Africa* 23(4): 85-93.
Quantec. (2011). *Quantec: Mineral statistics*. Pretoria: Quantec.
Rausser, G. & Zusman, P. (1991). Organizational failure and the political economy of water resources management. In Dinar, A. & ZIlberman, D. (eds). *Economics and Management of water and drainage in agriculture*. Boston: Kluwer Academic Publishers.
Republic of South Africa (RSA) (2011). Integrated Resource Plan 2010 – 2030. *Government Gazette*. Pretoria: Government Printers.
Roth, I. & Ambs, L. (2004). Incorporating externalities into a full-cost approach to electric power generation life-cycle costing. *Energy,* 29:2125 – 2144.
Sovacool, B. & Sovacool, K. (2009). Identifying future electricity-water tradeoffs in the United States. *Energy Policy,* 37:2763 – 2773.
Spalding-Fecher, R. & Matibe, D. (2003). Electricity and externalities in South Africa. *Energy Policy,* 31:721 – 734.
Turton, A. (2008). Three strategic water quality challenges that decision-makers need to know about and How the CSIR should respond. CSIR Conference: Science Real and Relevant, Pretoria, South Africa, 2008.
Van Heerden, J., Blignaut, J. & Horridge, M. (2008). Integrated water and economic modelling of the impacts of water market instruments on the South African economy. *Ecological economics,* 66:105 – 116.
Van Horen, C. (1996). *Counting the social costs: Electricity and externalities in South Africa*. Cape Town: University of Cape Town Press and Elan Press.
Von Uexkull, O. (2004). Energy and water: The ignored link. *Refocus,* March – April**:** 40–44.
Wassung, N. (2010). Water scarcity and electricity generation in South Africa. Part 1: Water use in the coal-to-electricity process. MPhil thesis, University of Stellenbosch, School of Public Management and Planning, Stellenbosch, South Africa.
World Water Council. (n.d.). World Water Council: Water crisis. Available at: www.worldwatercouncil.org/index.php?id=25 (accessed on 7 August 2011).

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