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Water Constrains South Africa's Energy Future: A Case Study on Integrated Energy-Water Nexus Modeling and Analysis

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Abstract: *This research involves integrating a representation of water supply into an energy systems model to better reflect the interdependent nature of the energy-water nexus in South Africa; the water challenges facing the energy system are therefore of primary interest. The research methodology developed focuses on embedding the various water supply options in a least-cost optimization platform, so that the cost of water is fully captured as energy sector investments are planned, and any changes in these investments due to implementing this nexus approach can be quantified. The results of this investigation demonstrate the process and type of tools that can be employed to examine the water-energy nexus and the insights that can be gained from integrated energy-water planning. A number of relevant energy-water policy scenarios in South Africa were explored, and the results show that specific energy sector policies can have significant implication for both new investment in water supply infrastructure and in some cases, can lead to stranded water supply investments, and vice versa, reinforcing the importance of planning the water-energy nexus in an integrated manner. A key finding of the study is that a national-level energy systems optimization model can be readily regionalized in terms of energy resource supply and power plant locations, and the regional costs and limitations for water supply can be incorporated into the energy model to create a water-smart energy sector planning tool. Recommendations for further development of the SATIM-W model and its application for energy and water planning have resulted in additional areas of improvement of the model and further expand the coverage and insights that can be obtained. This work has demonstrated the importance and value of employing an integrated planning platform to properly assess the energy-water nexus challenges in South Africa towards robust hedging strategies and ensure that these critical long-term aspects of sustainable development are intelligently planned in a least-cost manner.*

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I. Background

The basic need for understanding of the interdependencies between energy, water and food is growing in importance as the challenges of ensuring the sustainable and secure provision of these vital systems increase. Stress on these systems arises due to both biogeophysical (natural system) factors and social, political and economic (human system) issues that affect the allocation, availability, and use of energy, water and land resources. Complexities in such coupled human-natural systems manifest in the form of interdependencies and feedbacks, non-linear dynamics and thresholds, time lags and legacies, and tradeoffs and unintended consequences (Liu et al. 2007ab). Although complexities have been theoretically explored by particular disciplines (e.g., social or ecological sciences), far less research has empirically examined these dynamics in real-world contexts driven by planning, policy, and management decisions (Liu et al. 2007ab; Brunner, 2010; Pahl-Wostl, 2007; Bazilian et al. 2011; Rodriguez et al. 2013; Perrone and Hornberger, 2014; Miralles-Wilhelm, 2016).

Several regions of the world are already experiencing serious energy-water scarcity challenges, and there is already evidence of the effects of climate change on the availability of and demand for energy and water, especially in fast-growing countries (Shah et al. 2009; Voinov and Cardwell, 2009; WWAP, 2012; Schornagel, et. al. 2012; Perrone and Hornberger, 2014).South Africa is one of such countries struggling to achieve an ambitious development agenda while consuming its resources in an unsustainable and emissions intensive manner using aging infrastructure (Gaunt, 2010). The electricity supply capacity crisis of 2007-8 led to power shortages with a direct impact on economic growth (Eberhard, 2008), and the current electricity supply system is highly vulnerable to water availability and droughts (Davies, 2012). Although power generation accounts directly for only about 2% of the total water demand of the country, it represents about 15% of GDP. At the same time, existing water supply systems are at or approaching their capacity with 97% of existing water supply systems allocated. Agriculture consumes 60% of water withdrawals (DWAF 2004). As shown in Figure 1, the national water allocation masks regional disparities in water supply. Also, a national summary does not reflect regional sectoral composition. For example, in the northern Limpopo (Waterberg) region where vast new coal deposits are located, energy supply activity accounts for close to half the water withdrawals and may grow to be the dominant regional water consumer should coal-based energy supply expand; whereas in the populous industrial heartland of the Vaal region, the energy sector is an almost insignificant consumer on a relative basis accounting for less than one percent of withdrawals. Shortfalls in regional water supply are compensated for by the construction, existing and planned, of large scale water transfers. Thus, to ensure that the country's growth aspirations remain viable, prudent coordinated planning for future energy and water supply and use is essential.

Despite growing concern over the trends and scenarios envisioned for energy and water systems over the near future (e.g., Hejazi et al. 2014ab; McLaughlin and Kinzelbach, 2015), decision makers often remain ill-informed about these systems and ill-equipped to deal with the range of plausible outcomes.South Africa has established long-term infrastructure planning processes for the supply of both energy and water in the public domain under the auspices of their Department of Energy and Department of Water and Sanitation. The planning of both resources has considered cost and scarcity of the other to various degrees, but to date integrated modeling of both systems has not been undertaken. In this national planning context, the complexity of the energy-water nexus requires a more systematic approach that considers the existing interactions and dependencies between these sectors. South Africa is therefore uniquely positioned as a candidate to develop and demonstrate an advanced integrated energy-water planning exercise.

This spatial disparity in the availability of water and energy resources in South Africa implies the need for improved quantitative tools used to capture the discrete water supply and transfer schemes that will be necessary for the energy sector in the different regions of the country. This research involves integrating a representation of water supply into an energy systems model to better reflect the interdependent nature of the energy-water nexus in South Africa; the water challenges facing the energy system are therefore of primary interest. The research methodology developed focuses on embedding the various water supply options in a least-cost optimization platform, so that the cost of water is fully captured as energy sector investments are planned, and any changes in these investments due to implementing this nexus approach can be quantified.

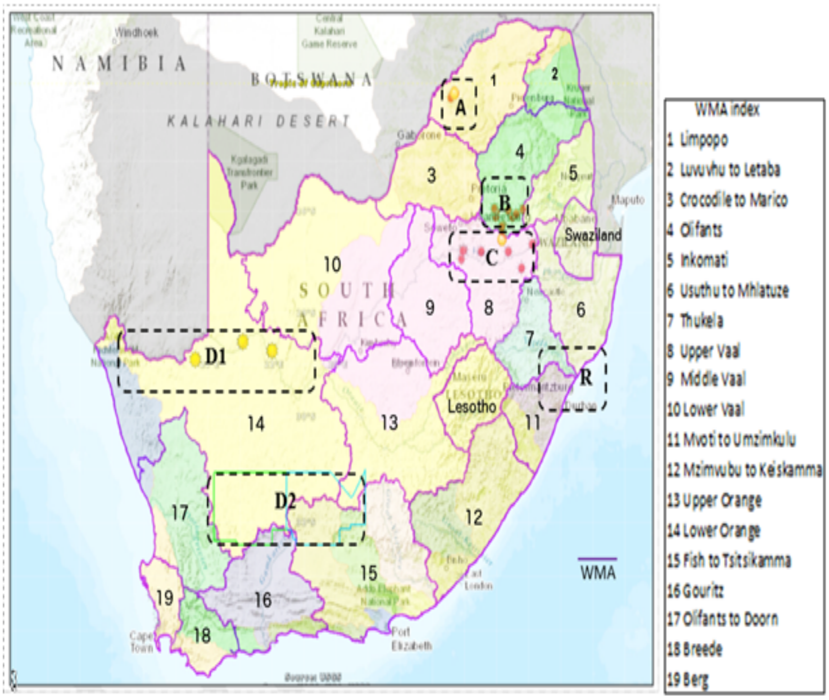

Figure 1: South Africa Water Management Areas and Energy Producing Regions (A: Waterberg (Lephalale); B: Mpumalanga, Witbank; C: Mpumalanga, Secunda; D1: Northern Cape, Upington; D2: Northern Cape, Karoo; R: Richards Bay Coal Export Terminal)

II. Methodology: Integrating Water and Energy Planning

2.1 The SATIM Energy Model

SATIM is a single-region national representation of the energy system in South Africa. SATIM is an instance of the TIMES (The Integrated MARKAL/EFOM System) modeling platform developed, promoted and used under the auspices of the International Energy Agency's Energy Technology Systems Analysis Program (IEA-ETSAP). It is a detailed full-sector representation of the supply and demand components of the national energy system from resource extraction to end-use services (e.g., heating, cooling, lighting, passenger travel, industrial motor drive). SATIM includes the extraction, transmission and distribution of gas and coal for electricity generation; the transmission and distribution of electricity; and the consumption of electricity by end-use technologies to supply energy services, including the energy requirements for water pumping and water treatment. Technologies are linked by commodities and characterized by techno-economic parameters such as efficiency, investment along with capital and operational costs. Technologies are further organized by use subsectors (supply, refining, power, buildings/households, industry, and transportation) and type (e.g., power plants by fuel and technology type and various types of vehicles). The model solves for the optimal configuration of technologies and resources that will satisfy the growth in demand for electricity and other energy commodities at the subsector level in equilibrium assuming perfect foresight and competition (e.g., electricity and/or biomass demand for the Pulp and Paper sub-sector in Industry). In this way, the model determines the size and sequencing of long-lived energy infrastructure investments, the rates of utilization of available resources, and the short-lived devices that are needed to deliver the energy services to the consumer in each period, so as to meet energy services demand at the lowest present-value-cost over the planning horizon examined. Because SATIM solves for the least-cost chain of supply extending from resource extraction to transmission, distribution and end-use demand devices, the model was readily modified to incorporate the representation of water infrastructure as a component of the energy system supply chain for integrated planning purposes.

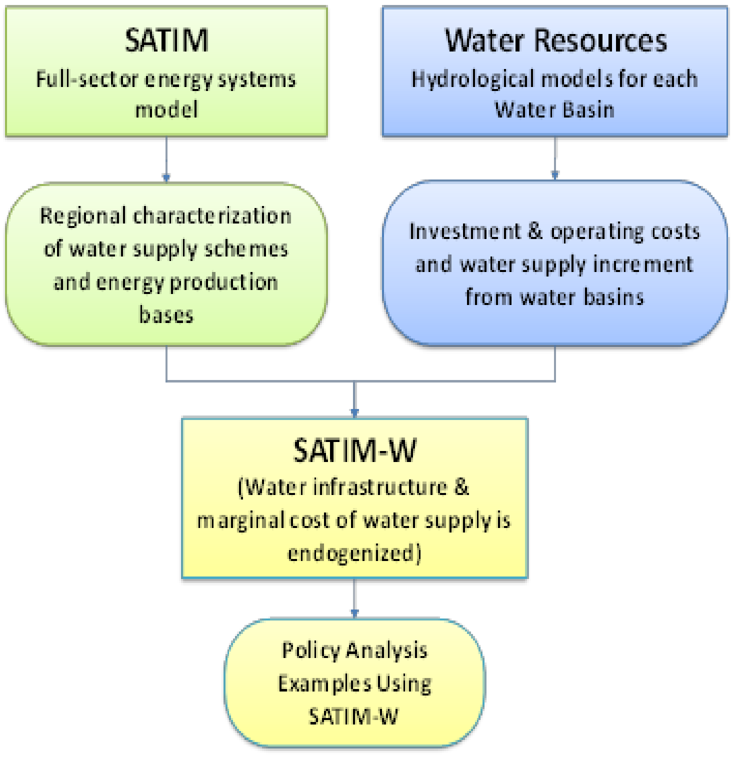

Figure 2: South Africa Water-Energy Nexus Modeling Framework

2.2 The SATIM-W Water-Energy Model

The modeling of water consumption within SATIM is limited to accounting for the water consumption of the power sector by including the estimated water use intensity of power plants. This implementation does not consider regional disparities in water supply and costs, nor the water usage by non-electricity generation energy technologies such as coal mining and shale gas production; nor does it include water treatment requirements. To remedy this shortcoming, individual water supply options, include major investments in dams and transfer projects and water supply energy needs, were incorporated into the SATIM-W model (Figure 2) to capture the water-energy interplay. Incorporating a regional cost and quality for water allows the model to examine potential tradeoffs arising from:

- fuel extraction and processing (e.g. coal washing and shale gas extraction);
- consumption and treatment of water for the cooling and steam circuits in thermal plants;
- cleaning and other water services required by all types of power plants;
- additional (marginal) treatment required for water of poorer quality entering the supply system as new water supply schemes are implemented in response to growing demand; and
- meeting air quality emissions standards, with end of pipe technologies, such as Flue Gas Desulphurization (FGD), that require water.

Figure 3 illustrates a section of the water-energy diagram for SATIM-W, showing the supply, conversion and end-use processes for supply of energy and water to the power sector. Specifically, this partial illustrative SATIM-W water-energy diagram shows the various facets of how the water-energy complexities were handled including, from left to right, top to bottom:

- Regional water supply cost curves (including the cost and incremental supply of new infrastructure) from which the marginal cost of water supplied in each region and for each period is endogenously determined;
- Water and energy requirements for coal mining and cleaning, as well as the treatment of discharged water;
- Coal is transported and water is moved as necessary to meet the demands;
- Power and liquid fuel sector water consumption demands are endogenously determined, while non-energy water needs are fixed exogenously, the combination of which determine how much water ultimately needs to be delivered, and
- The electricity, liquid fuels and renewables (not shown) then provide the final energy needed to meet the energy service demands in each of the end-use sectors (agriculture, residential, commercial, industry and transport).

The updated model, SATIM-W, allows these activities to be represented so that the model is responsive to the regional cost and availability of water and energy supply, which is connected to a single national representation of the energy demand sectors providing integrated coverage of the water-energy nexus.

2.3 Regional Water Supply Cost Curves

The cost of water supply for energy is determined from four separate components: the supply; infrastructure, delivery (transmission and distribution); and treatment requirements, presented here as amortized annual costs, for the latter three:

$$\textbf{Scheme Supply Cost} = \textbf{Capital}_{\text{(Scheme + Delivery)}} + \textbf{Fixed OM (\%Capital)}_{\text{(Scheme + Delivery)}} + \textbf{Var OM}_1\ \textbf{(Energy cost of conveyance (endogenous))}_{\text{(Scheme + Delivery)}} + \textbf{Var OM}_2\ \textbf{(Administrative \& Water Treatment charges))}$$

The capital, fixed and variable operating and maintenance (OM) components are calculated separately in each water supply region (WSR) for each water supply scheme (e.g., dam, inter-basin transfer) as part of determining the potential regional water supply cost (WSC), also called the Unit Water Cost (UWC) in traditional water basin models; this considers the current and future water supply options that have been identified for each region (DWA, 2010). SATIM-W then weights each water supply and delivery option (or scheme) and chooses the combination and timing that delivers the needed water at least-cost, resulting in the determination of the marginal water supply cost (MWSC). As a result, the MWSC is determined with the model and varies from period to period and in response to constraints placed on the system by specific policy scenarios.

Looking more specifically at the components of the WSC, each individual component is determined in R/m^3 on an annual basis as described below. The cost of each scheme, organized by WSR, is the sum of all component costs, where: **Capital** consists of the i) water supply scheme infrastructure costs, which cover the development and use of bulk water supply infrastructure including the cost of planning and design, capital loan repayment, and annual depreciation, and ii) water supply delivery costs, which include the capital costs for transporting water from the nearest bulk water source to the location of a power generation plant or mine; **Fixed O&M** consists of the i) water resources management charges, which cover the charges required to manage water resources within the designated WMA, and ii) water supply delivery O&M costs for transporting water from the nearest bulk water source to the location of a power generation plant or mine.

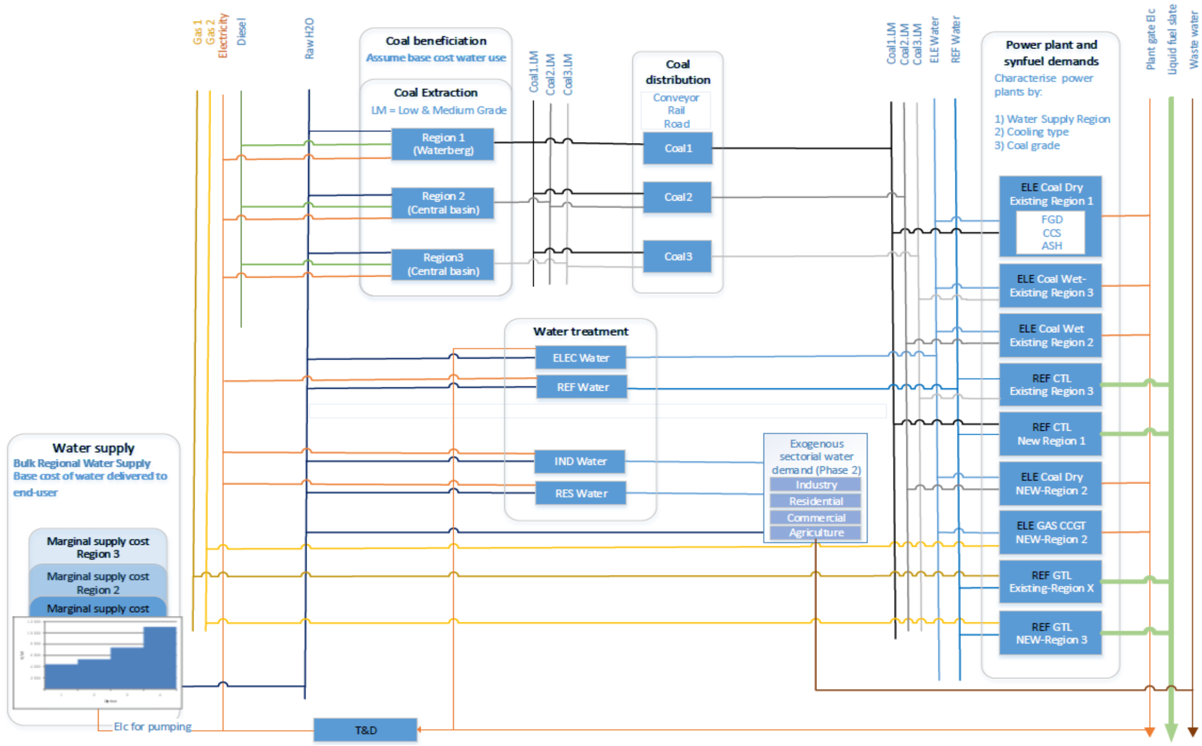

Figure 3: Partial Illustrative diagram of the SATIM-W water-energy model

Var O&M$_1$consists of the water supply energy costs, which include the cost for pumping water of both i) the raw water supply scheme and ii) the delivery of water to the power station or mine. The electricity cost for water supply is calculated within SATIM-W based on the power sector technology and fuel choices made in each scenario. Var O&M$_2$ consists of the following additional charges as appropriate: i) waste discharge mitigation charges, which cover the charge for discharge of water containing waste into a water resource or onto land, and ii) primary and secondary water treatment costs, which include the additional cost of treating water to a basic water quality standard (primary) plus the additional treatment (secondary) of a portion of the water requirements to a higher level of quality through for example the use of reverse osmosis (RO) to reduce the salinity of the source water.

Table 1 presents the estimated infrastructure costs for the bulk supply of water for various schemes identified by DWS in each region. The table also includes a breakdown of the estimated unit water cost (UWC) for each water supply scheme in terms of capital repayment (CUC), depreciation (ADC), O&M costs (OMC) and energy costs (EC), which for these estimates are based on the weighted average cost of generation. Note that the data for each step represents the incremental cost and supply for implementing that step. The Net UWC is the weighted average of the all water schemes up to that point. Table 2 provides similar information for major water delivery schemes to the four regions critical to future power generation.

Interesting to note is the relative high cost of pumping from the Orange River to a CSP plant (R 4.07/m^3) compared to gravity pipelines from the Lephalale River based infrastructure to prospective new coal power plants in the Waterberg (R 0.39/m^3). On the other hand, the cost of future bulk water supply infrastructure in the Waterberg is an order of magnitude higher for lower yields compared to the Orange River supply schemes, emphasizing the sometimes extreme regional disparities in the cost of water supply. The tables also show how the water supply cost can rise steeply with the deployment of discrete schemes that need to be implemented to meet the total water supply requirements. It's also worth noting the very high costs of water delivery from the Orange River for hydraulic fracking – either by truck or pipeline. Finally, the desalination energy requirement includes the energy needed to pump water from the coastline. Hence it is significantly higher than just the energy required for the desalination alone.

2.4 Incorporating the Cost of Water into SATIM-W

The SATIM-W model is a tool devised towards an integrated water-energy planning approach that can help to ensure timely investments and delivery of water supply and treatment infrastructure for the energy sector. Specifically, it is an energy sector planning tool that considers water supply as a critical component that needs to be taken into consideration as part of decision-making process. However, SATIM-W is not a tool that could be used for water planning (which needs to be conducted at a more granular basin level). Furthermore, in

Table 1: Estimated UWC for Planned Bulk Water Supply Infrastructure

Water Supply Region	Scheme Description	ID	Scheme Yield (2010) (M.m^3/ year)	Energy Requirement (kWh/m^3)	Capi-tal Cost (R 10^6)	Annual O&M Cost (R 10^6)	CUC* (R 10^6)	ADC$ (R 10^6)	OMC (R 10^6)	EC# (R 10^6)	UWC (R/m^3/ year)	Net UWC (R/m3 /year)	No-tes
Waterbe-rg (Lephala-le)	Existing	A0	25									0.60%	
	Mokolo Phase 1	A1	29	0.85	1759	4.7	224	13	5	12	8.9	8.89	
	Mokolo-Crocodile Phase 2	A2	75	0.8	8174	21.7	1042	61	22	30	15.4	15.40	
	Reuse and transfer from Vaal	A3	126	0.87	1216	3.2	155	9	3	55	1.8	10.98	1
	Transfer from Vaal	A4	90	1	2562	6.8	327	19	7	45	4.4	13.64	1
	Desalination of seawater	A6	100	13.82	20896	55.4	2664	157	55	691	36	33.67	2
Upper Olifants	Existing	B0	400									1.42%	5
	Vaal Eskom transfer	B0-X	230									1.42%	5
	Olifants Dam	B1	55	0	1241	3.3	158	9	3	0	3.1	3.11	
	Use of acid mine drainage	B2	31	2.2	1637	4.3	209	12	4	34	8.4	6.37	2
	Transfer from Vaal River	B3	190	1.07	4281	11.3	546	32	11	102	3.6	8.06	3
	Desalination of seawater	B5	100	13.82	14210	37.7	1812	107	38	691	26	24.47	3
Upper Vaal	Existing	C0	3523									0.44%	
	LHWP II (Polihali Dam)	C1	437	0	11947	31.7	1523	90	32	0	3.8	3.76	4
	Use of AMD	C2	38	2.51	1820	4.8	232	14	5	48	7.8	5.85	2
	Thukela-Vaal Transfer	C3	522	3.35	21976	58.2	2802	165	58	874	7.5	7.47	
	Orange-Vaal transfer Boskraai Dam (55%)	C4	289	1.99	15671	41.5	1998	118	42	287	8.5	8.47	
	Mzimvubu transfer scheme	C5	631	4.38	41568	110.2	5300	312	110	1382	11.3	11.26	
	Desalination of seawater	C7	100	13.6	7831	20.8	998	59	21	680	18	15.58	2
Lower Orange	Existing	D0	4131									0.17%	
	Boskraai Dam (55%)	D1	515	0	2678	7.1	341	20	7	0	0.7	0.72	
	Boskraai Dam (full yield)	D2	422	0	3286	8.7	419	25	9	0	1.1	1.07	
	Mzimvubukraai Transfer	D3	165	5.26	4370	11.6	557	33	12	434	6.3	6.28	
	Desalination of seawater	D4	100	14.1	11175	29.6	1425	84	30	705	22	22.43	

Notes:
* Annual capital loan repayment over a period of 25 years at 12% interest
$ Assumes 30% depreciation portion and an average lifetime of 40 years
# Based on R0.50 /kWh electricity cost.
% Reflects tariff
Prices in 2010 ZAR
1 Requires additional cost of transfer to Lephalale (~ 9.2 ZAR/m^3)
2 Excludes R2/m^3 water treatment cost
3 Additional cost of water from LHWPII (~ 9.2 ZAR/m^3)
4 Excludes cost for hydropower station
5 Generation-weighted average cost of water to power stations applied

SATIM-W the non-energy water needs are inputs to the model and are currently fixed. However, the water needs for energy often determine timing and provide critical capital for expansion of the water infrastructure.

So, it is the impact of changes in water needs for energy that can be examined with SATIM-W now. The cost of water supply is shown in Figure 4, in the form of WSC curves for each region, which plot the UWC for the series of supply schemes identified. These WSC curves show the incremental increase in water supply attained and the cost of the next water supply scheme necessary to meet increasing demand in each of the critical water resources areas considered in this study.

Table 2: Estimated UWC for Delivery of Water from Major Supply Schemes to Power Plants

Region	Description of Final Delivery from Bulk water scheme to power plant	ID	Annual Supply (M. m^3)	Capital Cost (R x 10^6)	O & M Cost (R x 10^6/ year)	Energy Requirement (kWh/m^3)	Fuel Cost (R 10^6)	CUC* (R 10^6)	ADC$ (R 10^6)	OMC (R 10^6)	EC# (R 10^6)	UWC (R/m^3 /year)
Waterberg (Lephalale)	Gravity pipeline from Lephalale	A1	30	73.6	0.20	0		11	0.55	0.20	0	0.39
Upper Olifants	Pipeline from Olifants Dam	B1	30	2656.5	7.04	0.41		400	19.92	7.04	6.15	14.44
	Import Vaal Dam - pipeline from dam in Upper Olifants	B2	30	405.8	1.08	0.41		61	3.04	1.08	6.15	2.38
	Reuse AMD - pipeline from dam in Upper Olifants	B3	30	405.8	1.08	0.41		61	3.04	1.08	6.15	2.38
	Zambezi water - pipeline from Mokopane	B4	30	3165.2	8.39	1.38		477	23.74	8.39	20.7	17.66
Lower Orange	CSP - Pipeline pumping directly from Orange River	D1	0.27	5.6	0.01	0.32		1	0.04	0.01	0.0432	4.07
	Hydraulic fracturing – road transport	D2	0.015	1.3	0.06		1.6	0	0.01	0.06	1.63	113.38
	Hydraulic fracturing – pipeline	D3	3	8173.8	21.66	1.3		341	61.30	21.66	32.5	9.13
	Hydraulic fracturing – groundwater	D4	0.1	2.6	0.01	4.01		0	0.02	0.01	0.2005	2.27

*Annual capital loan repayment over a period of 25 years at 12% interest

$Assumes 30% depreciation portion and an average lifetime of 40 years

#Using R0.50 /kWh electricity cost.

Prices in 2010 ZAR

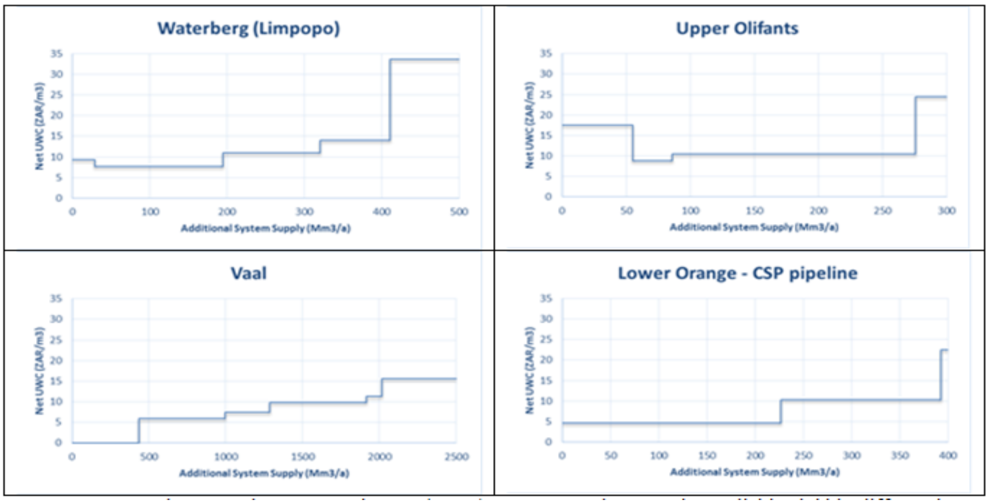

Figure 4: Increasing net unit water supply cost (UWC) necessary to increase the available yield in different key water resources areas of South Africa to meet increasing demands including future power generation water requirements.

This illustrates the estimated costs of water supply based on fixed assumptions about the price of electricity required for the treatment and transport of water and the implementation timeline of specific supply schemes. Note that in some cases a more expensive scheme must precede a less expensive one to deliver additional water (e.g., second step in both Waterberg and Upper Olifants). Water supply components are incorporated into SATIM-W that are characterized by the WSC curves in each region, thus directly representing the supply and infrastructure costs for the delivery of water. This approach allows for a scenario-specific dynamic cost curve to be calculated since the price of energy supply is endogenously determined and water supply schemes are commissioned as necessitated to meet the requirements of the energy system and the fixed non-energy demands. Thus, by choosing the appropriate schemes, SATIM-W constructs the MWSC that enables the model to determine least-cost solutions to water-energy nexus planning. SATIM-W also represents inter-regional water transfers schemes by linking specific regional supplies to water demands throughout the country. The commissioning of schemes is predicated within a national energy supply system. In this manner, the investment choice and timing of energy supply technologies are influenced by the cost and timing of water supply schemes. The reciprocal water-energy investment decision cycle occurs simultaneously resulting in the least-cost configuration for the integrated water-energy nexus across the entire planning horizon.

III. Results and Discussion: Exploration of South Africa's Water-Energy Planning Challenges

3.1 Scenario Development

The primary value of integrated water-energy planning is to support the decision-making process. This is done here through the exploration of scenarios that simulate the impact of possible policies and technology choices of significance to the country. In this investigation, a series of scenarios shown in Table 3 were designed to capture the main areas of investment uncertainty in water and energy supply in South Africa. The analysis of these scenarios showcase how SATIM-W can be used to advise the energy sector policy formulation and decision-making process, and its inter-dependency with that of water infrastructure planning. The following discussion summarizes the results through answers to a series of questions, arising from key decisions that could shape the future of South Africa's energy and water systems. For each of the scenario clusters a Summary Metrics table (Table 4) highlights the cumulative change in key results over the 2010 to 2050 planning horizon.

Table 3: South African Water-Energy Case Study Scenarios

Scenario Name	Description
Reference (No Water Cost)	Reference scenario, which assumes a continuation of status quo planning, but does not include the cost or availability of water supply.
Reference (Water Cost)	Reference SATIM-W scenario, which assumes a continuation of status quo planning, but includes the cost and availability of water supply.
Shale	Shale-gas extraction occurs in the Orange River region. A total of 40 Tcf of gas is estimated to be economically recoverable.
Dry Climate	Regional water supplies and the non-energy water demands in the Reference scenario are adjusted to reflect a drier climate (increasing water demand and decreasing water supply), affecting the unit water supply cost of regional schemes.
WaterQ	Water quality of transfers from Regions B and C to Region A is lower than local supplies, requiring additional treatment costs for demineralized application.
Env. Compliance	This scenario entails: • Retrofitting existing coal power plants with wet-FGD. • Fitting existing and new CTL refineries with semi-dry CFB-FGD technology. • Operating all CCGTs with wet NOx control in accordance with EPRI data submitted to Eskom. • Including the increased costs to coal mines associated with the treatment of water discharged to the environment. • Includes the WaterQ scenario
Dry & Environmental Compliance	A dry climate with environmental compliance scenario. The scenario represents a water stress case with elevated water demands across sectors and increased costs associated with water usage; includes the WaterQ scenario
CO_2 Cum Cap 14GT	The imposition of "Peak-Plateau-Decline" NDC emission pathway, a carbon budget limiting cumulative national GHG emissions to 14Gt by 2050.
CO_2 Cum Cap 10GT	The imposition of a stricter carbon budget limiting cumulative national GHG emissions to 10Gt by 2050.

Table 4: Summary Metrics Description

Metrics	Units	Description
System Cost	2010 MZAR (x1000)	Total discounted cost of the entire water-energy system
Expenditure - Supply	2010 MZAR (x1000)	Payments for energy
Primary Energy	PJ	Total primary energy supply (including imports, PJ equivalent account for renewables
Final Energy	PJ	Total final energy consumed to meet all energy service demands
Power Sector CO_2 Emissions	Mt	Total CO_2 emission for the power sector
Power Plant Builds	GW	Total gigawatts of new capacity added
Power Plant Investment	2010 MZAR (x1000)	Total cost of new power plants
Water to Power Plants	Mm3	Amount of water delivered for the power sector
Total Water for Energy	Mm3	Total water consumed by the energy system

3.2 What are the key features of the Reference (Water Cost) scenario?

The SATIM-W Reference scenario with water costs included, referred to as Reference (Water Cost), is the modeled evolution of the integrated water-energy system in the absence of alternative policies or technology advancement, and assuming water demands and yields are not significantly affected by climate change over the study time horizon. It serves as the point of comparison against which the costs and benefits of the alternate scenarios will be evaluated.

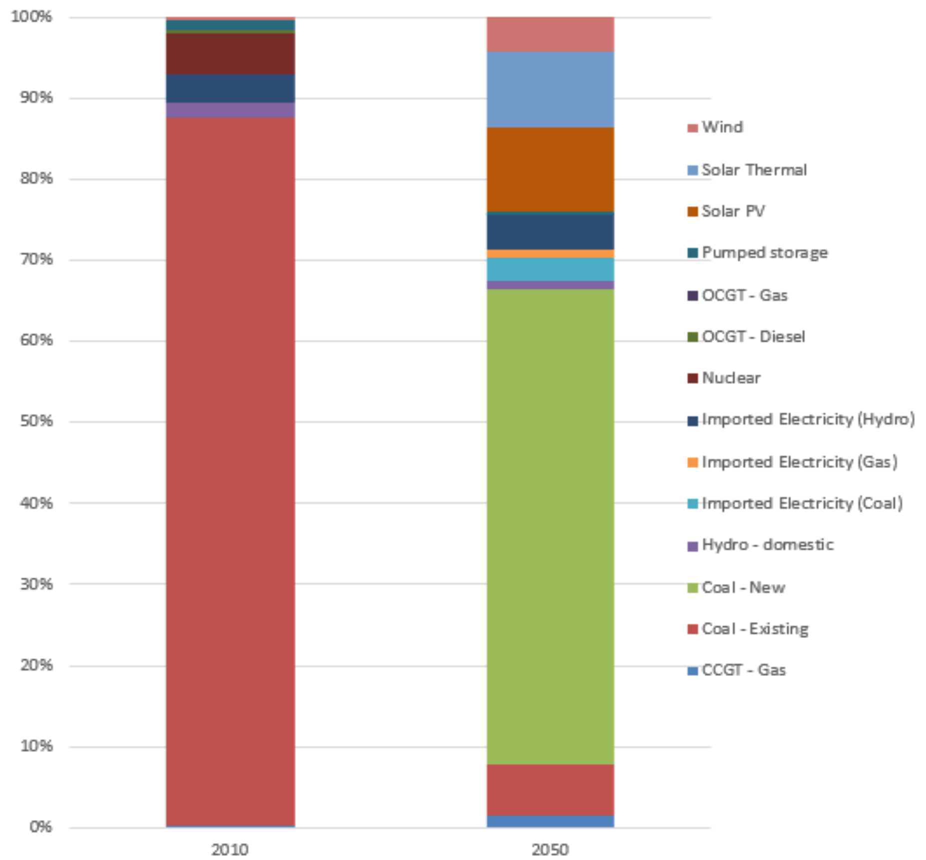

Figure 5: Comparison of Reference (Water Cost) Electricity Generation Shares for 2010 and 2050

The evolution of the South Africa electricity generation mix between 2010 and 2050 in this scenario is shown in Figure 5. The 2010 mix is almost 90% coal based with a variety of renewable, nuclear, natural gas, and oil technologies supplying the remainder. By 2050, the share of coal based power has diminished from almost 90% to 65% while the renewable share, comprised of concentrating solar, solar PV, wind and hydropower technologies, accounts for 25% of generation. Imported electricity grows from 3.4% to 8.2%, while nuclear shrinks from 5% to less than 1%, given the costs assumed for this scenario. The portfolio of technologies supplying this electricity comprises 42 GW of new supercritical coal, 3 GW of Fluidized Bed Combustion (FBC) generation capacity which utilizes discard-coal, 9 GW of wind, 30 GW of utility and distributed solar PV, and 10 GW of CSP with storage. Note that hydropower, both domestic and imported, remains the same, at about a 5% share.

Regional water supply in the Reference (Water Cost) scenario varies significantly in both volume and end-use applications by region, as shown in Figure 6. The Waterberg region has the lowest total consumption and the greatest share of water going to energy activities, growing from 36% in 2015 to 82% in 2050, split between power plant cooling, coal mines and CTL plants. The Olifants region, which initially has 10 times the amount of consumption, sees water for energy decline from about 50% to about 7% in 2050 as the new coal power plants are dry-cooled. In both the Vaal and the Orange River regions, water consumption is 4 to 8 times that in the Olifants region, and water for energy in both regions is an insignificant percentage of the total. The price of water supply also varies significantly by region as shown in Figure 7. The prices in the Waterberg are up to a factor of 10 higher than other regions primarily due to the lower volumes of water being supplied, and the price also fluctuates with periodic investments, which increase unit water cost in steps, followed by declining unit costs as demand increases over time.

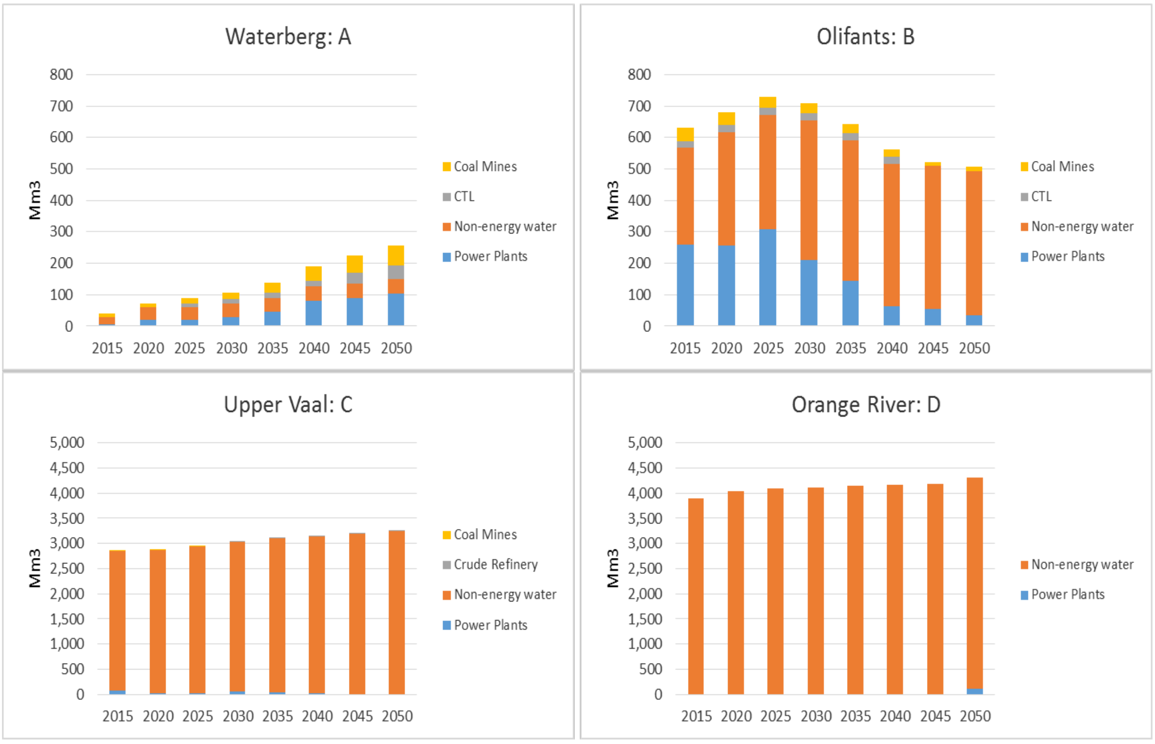

Figure 6: Reference (Water Cost) Regional Water Consumption

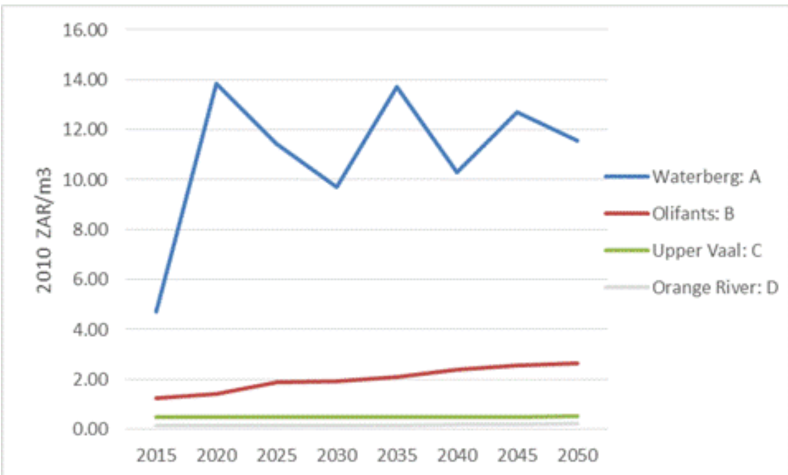

Figure 7: Reference (Water Cost) Regional Water Supply Prices

3.3 Is the Current Policy of Dry-Cooling for Coal Power Plants Economically Justified?

Due to water security concerns, South Africa's first foray into dry-cooling for coal thermal power plants occurred in the late 1960s, and dry-cooling for new coal thermal plants is ESKOM current policy. In the Reference (No Water Cost) scenario, water supply costs and constraints are not factored into planning. Figure 8shows electricity generation by fuel and plant type, along with water intensity of electricity generation (liters per kWh). The scenario shows a clear preference for new wet-cooled coal power plants due to their higher operating efficiencies and lower capital costs. However, the Reference (Water Cost) scenario, where full consideration is given to including the costs of water supply to power plants and energy resource industries, there is an all-outshift to dry cooling, as shown in Figure 9. This result reinforces the understanding that Eskom's decision to employ dry cooling for new coal power plants is indeed the least-cost policy for the country.

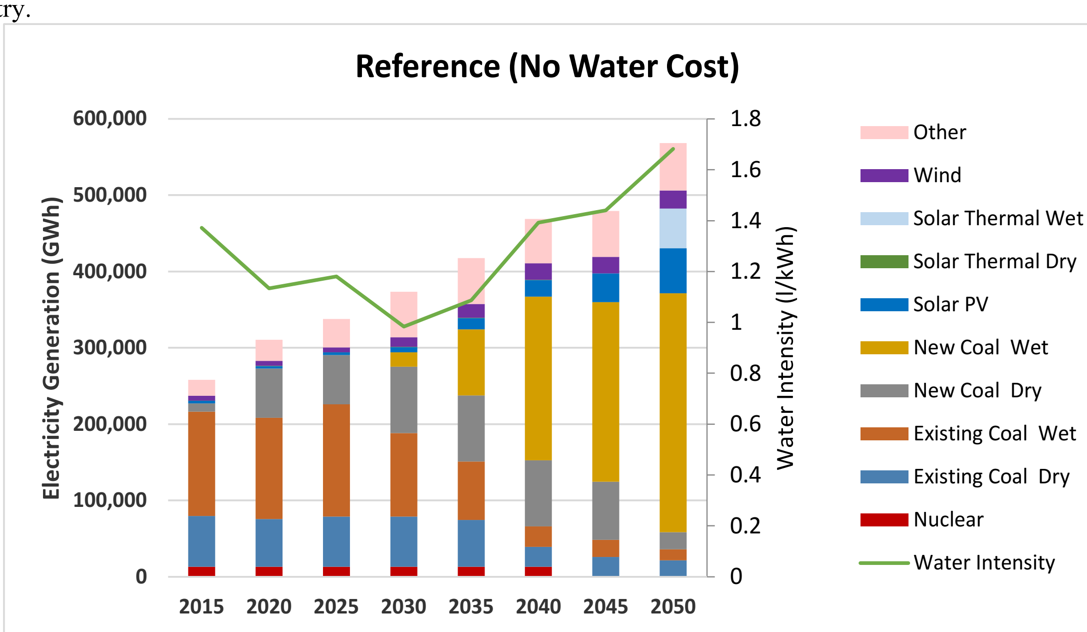

Figure 8: Reference (No Water Cost) Electricity Generation by Type (with Water Intensity)

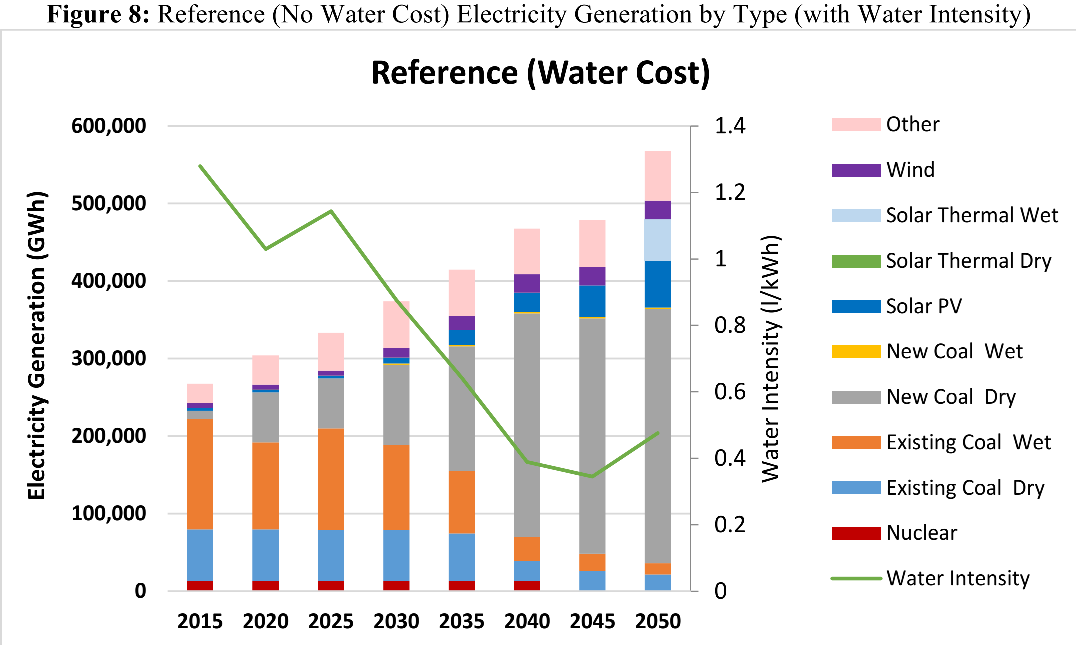

Figure 9: Reference (Water Cost) Electricity Generation by Type (with Water Intensity)

Figure 8 also shows that in the Reference (No Water Cost) scenario, the water-intensity of generation increases from an average value of 1.4 l/kWh in 2015 to 1.7 l/kWh in 2050. Although the average water-intensity of generation decreases from 2015 to 2030, as existing wet-cooled plants are retired and 8.6 GW of committed dry-cooled plants are commissioned, the fact that all new coal plants after that date are wet-cooled causes the water intensity of generation to increase steadily. However, in the Reference (Water Cost) scenario

(Figure 9), the preference for dry-cooled technology leads to a dramatic decline in water-intensity as the dry-cooled coal power plants replace the retiring wet-cooled stock. This modal shift to dry-cooled technology is primarily driven by the availability of relatively cheaper coal in the water-scarce Waterberg region. Expensive water transfer investments would be required to support building wet-cooled coal power plants in the Waterberg region. Therefore, when water costs are considered, the most cost-effective option is new dry-cooled power plants that utilize cheap coal in the Waterberg.

Given the large share of water going to the energy sector in the Waterberg, many of the following results will focus on that region, which often showed the greatest response to the scenario being examined. Figure 10 shows the breakdown of total water consumption in the Waterberg region for the Reference (No Water Cost) scenario. Power plant water consumption dominates, and by 2050 approaches 80% of total supply. Figure 11 shows that when water costs are included, power plant consumption drops by a factor of seven, while coal mines consume very slightly less (as coal remains the main power plant fuel, only the cooling technology switches), and the other sectors are unaffected.

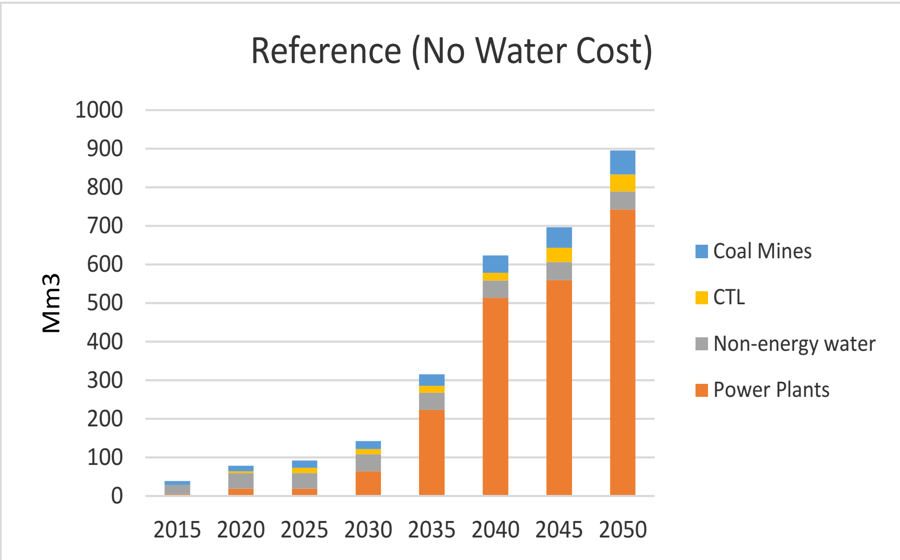

Figure 10: Waterberg Region Water Consumption by Type - Reference (No Water Cost)

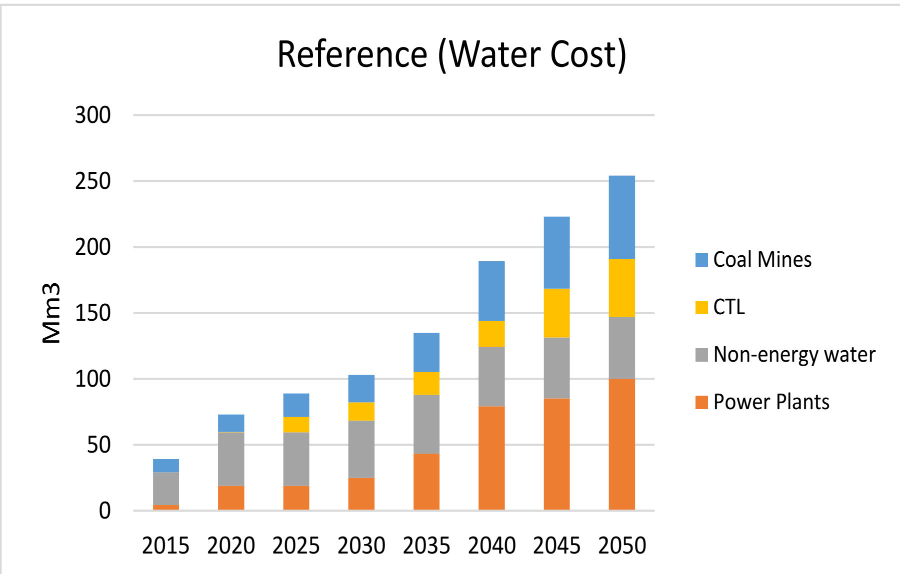

Figure 11: Waterberg Region Water Consumption by Type - Reference (Water Cost)

Table 5 summarizes the key cumulative metrics (2010 to 2050) from the two Reference scenarios. The total system cost, energy supply expenditures, and primary and final energy consumption are quite similar, with the most dramatic difference being the water consumed by power plants, which is cumulatively 77% lower (over

9300 Mm^3) in the Reference (Water Cost) scenario. Interestingly, this does not result in significantly higher power plant investment costs. Also, the Reference (Water Cost) produces slightly more CO_2 emissions despite generating 1.3% less electricity with coal and 2% more with RE technologies. This results from the higher unit emissions that are associated with the dry-cooled coal plants that are adopted when water costs are considered.

Table 5: Summary Metrics for Reference (Water Cost) and Reference (No Water Cost) Scenarios (Cumulative values 2010 to 2050)

Scenario Results	Units	Reference (Water Cost)	Reference (No Water Cost)	% change
System Cost	2010 MZAR (x1000)	7,646	7,582	-0.84%
Expenditure - Supply	2010 MZAR (x1000)	11,650	11,639	-0.09%
Primary Energy	PJ	335,500	336,508	0.30%
Final Energy	PJ	157,084	157,039	-0.03%
Power Sector CO_2Emissions	Mt	13,756	13,751	-0.03%
Power Plant Builds	GW	134	131	-1.84%
Power Plant Investment Difference	2010 MZAR (x1000)	2,670	2,639	-1.14%
Water to Power Plants	Mm3	12,074	21,412	77.34%
Total Water for Energy	Mm3	16,265	25,412	57.82%

3.4 How do stricter environmental controls impact coal investments in the Waterberg?

Economical coal deposits in the Waterberg region are the key driver for siting new coal mines, coal power plants and CTL plants in the region. Measures to improve air and water quality, as embodied in the Environmental Compliance scenario requiring that FGD be installed for existing coal power plants and all CTL plants. This impacts the operating efficiency and water intensity of both types of plants, which is particularly critical in the Waterberg. Although the Reference (Water Cost) scenario grows CTL plants to a capacity of over 500 PJ per year, the Environmental Compliance scenario limits the capacity to 100 PJ/year, as shown in Figure 12. The figure also shows the impact of the water quality, which is a component of the Environmental Compliance scenario, slightly reduces new CTL plants capacity due to the increased water supply costs. However, the greatest impact is due to the FGD requirements. For this study, only wet FGD systems were modelled, based on the detailed information from the Medupi plant, and Eskom's current preference for the proven wet technology.

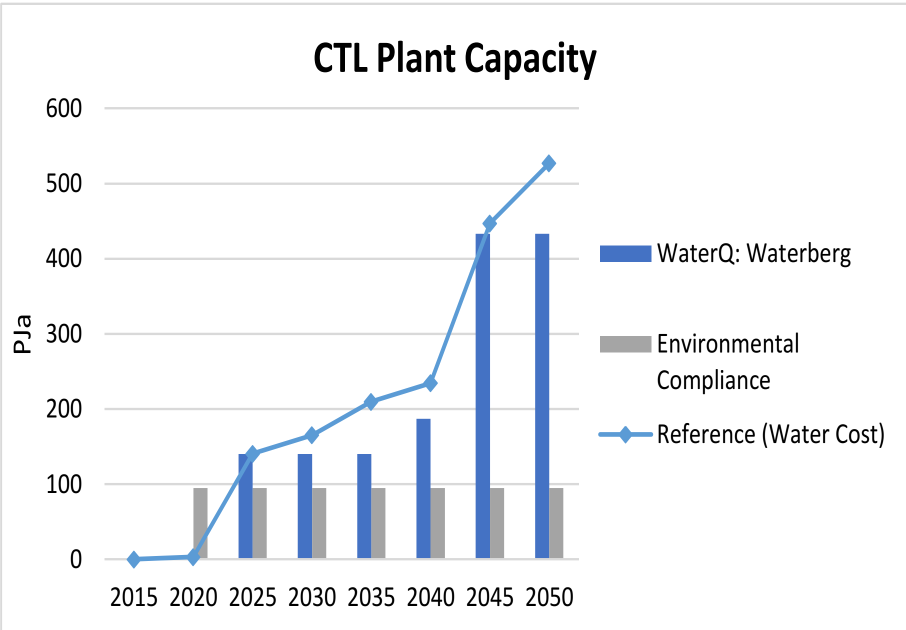

Figure 12: New CTL Capacity

Figure 13 shows that the lack of new CTL capacity under the Environmental Compliance scenario reduces the requirement for new water supply schemes in the Waterberg as compared to the Reference and WaterQ scenarios. Figure 14 shows the impact on new coal power plant capacity in the Waterberg where the increased cost of treatment begins to decrease the new coal plant capacity from 2040 resulting in a drop of ~7 GW from the Reference (Water Cost) scenario. However, in the Environmental Compliance scenario, which includes water quality, the new coal power plant capacity is slightly higher because of water freed up by the CTL plants that are not built. This somewhat intuitive result highlights the fact that the value of employing a full multi-sector energy system planning model is to capture and quantify the interplays between the sectors.

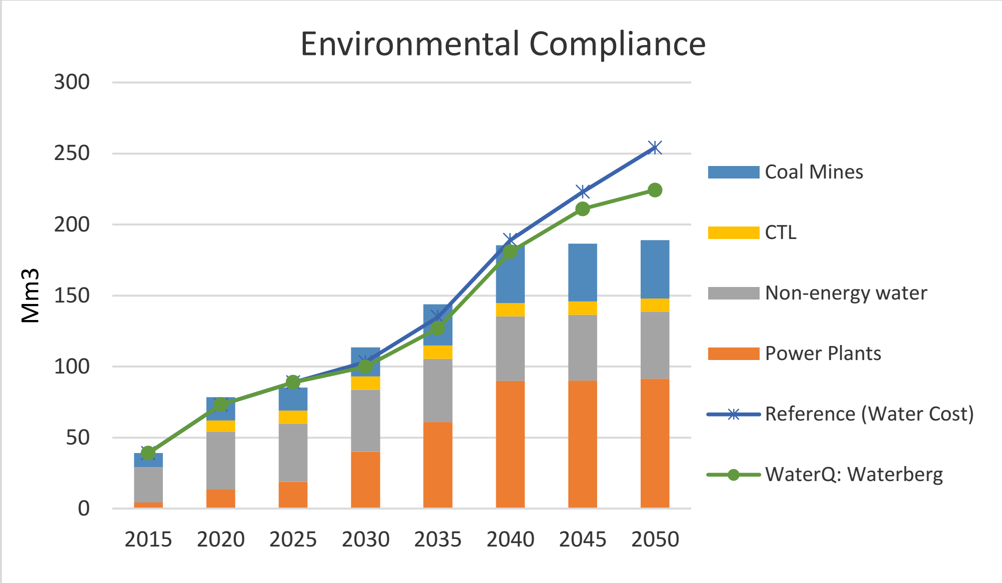

Figure 13: Water Demand in the Waterberg under Reference and Environmental Compliance scenarios

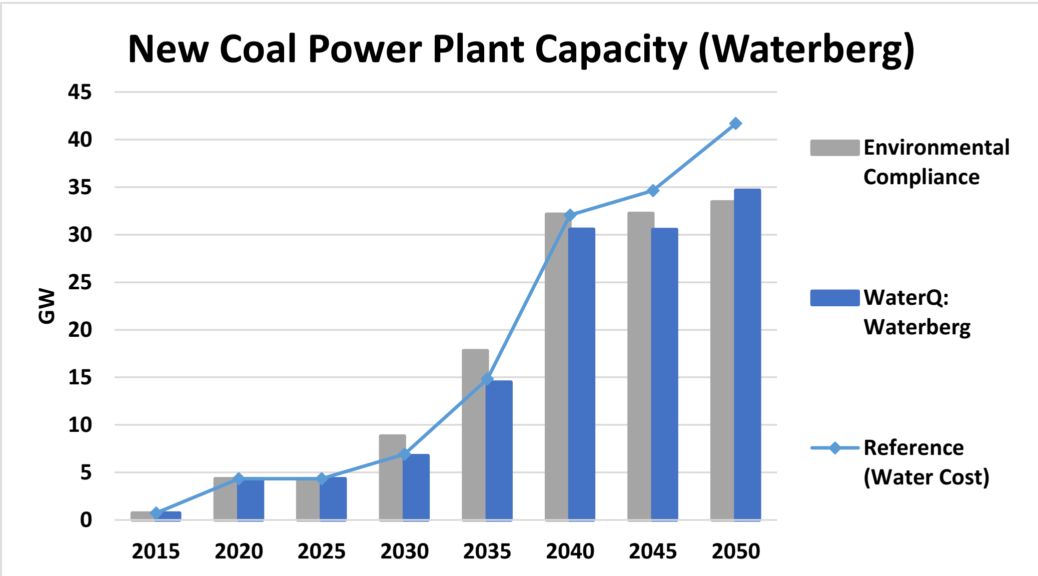

Figure 14: New Coal Capacity in the Waterberg in the Env. Compliance Scenarios

3.5 How does a Dry Climate impact coal investments in the Waterberg?

The Dry Climate scenario has a CTL build-out similar to the Reference (Water Cost) scenario. Similarly, the Dry and Environmental Compliance scenario also limits the construction of CTL plants to 100 PJ/year. The Dry Climate scenario alone has little impact on new CTL capacity, largely because of the limited impact of climate change on bulk water supply. One impact of the Dry Climate scenario is early retirement of wet-cooled coal capacity in the Olifants and Upper Vaal regions due to increased water demands by the non-energy sectors, and Figure 15 shows that this results in an additional 2 GW of dry-cooled coal capacity in the Waterberg in 2050 relative to Reference (Water Cost) scenario.

However, this small change in capacity hides the change in the coal power plant mix that results from the Dry Climate scenario, particularly starting in 2030. Figure 16 shows the difference in coal power plant capacity between Dry Climate and Reference (Water Cost) scenarios. All the existing wet-cooled plants and the older, less efficient, dry-cooled plants, as well as the 800 MW of new wet-cooled plants, are instead replaced by new dry-cooled plants. This is primarily influenced by the competition for water from the non-energy sectors, which increases by an average of 11% from 2030 to 2050 in the Central Basin, where the existing plants are located. In the Dry and CO_2 constrained scenarios, there is almost no new investment in coal-fired generation and so there is no significant impact of a Dry Climate on investment in coal-fired power generation.

Table 6 summarizes the key cumulative metrics (2010 to 2050) from the Dry and the Environmental Compliance scenarios. The Dry scenario accelerates the shift to dry-cooled coal plants through early retirement of existing wet cooled plants, and the cumulative water use decreases by 6.4%. On the other hand, the Environmental Compliance scenario reduces investment in new both new coal and new CTL capacity in the Waterberg, which reduces the requirement for new water supply schemes in that region, but new generation (coal and CSP) is shifted to other regions and water for power generation increases although the scenario results in a 1.6% decrease in overall water for energy.

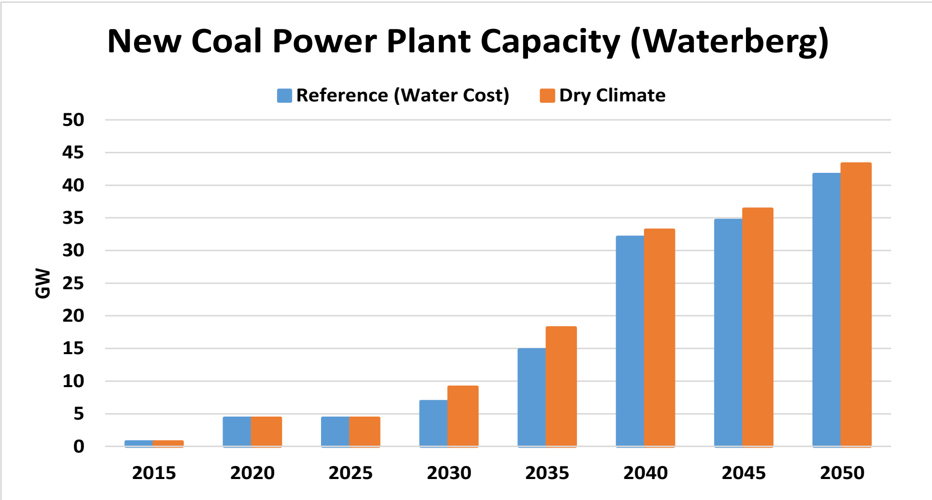

Figure 15: New Coal Capacity in the Waterberg under Dry scenarios

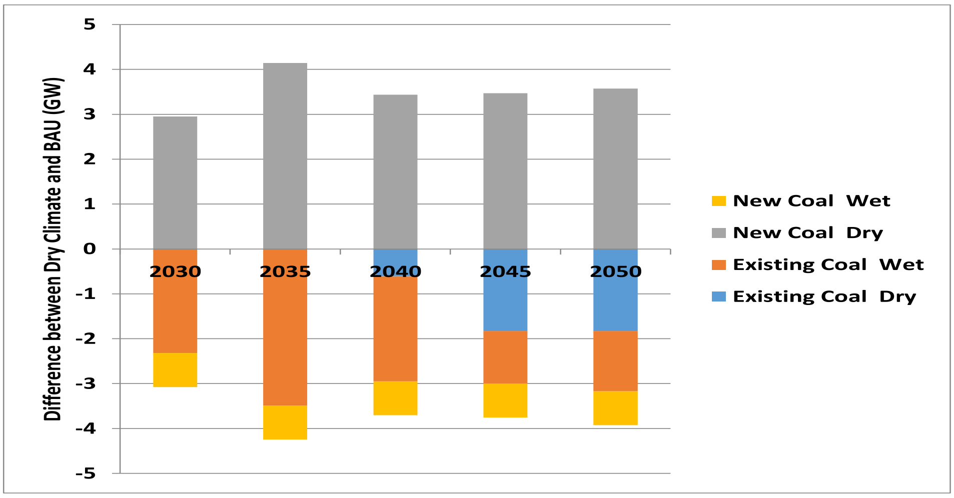

Figure 16: Difference in Installed Capacity between Dry Climate and Reference (Water Cost) Scenarios

3.6 How does the cost of water impact shale gas production?

For this investigation, the data on water supply costs (initial trucking in the water) was suspect and no data was available for the cost of treating shale gas return-flow effluent in South Africa. Therefore, the current SATIM-W treatment of shale gas production, and the following scenario results are considered preliminary. Under the shale gas scenario, shale gas production increases to just over 15 billion m3 per annum, and accounts for over 6% of total primary energy.

Figure 17 shows the water requirements in the Shale Gas scenario. There is an initial reliance on groundwater (~ 1 Mm^3/year) and trucking (~300 km per round-trip) for water delivery in the absence of a pipeline, which results in a relatively expensive water supply cost. The construction of a water supply pipeline in 2030, at an investment cost of R7.5 billion (US$600 million), dramatically lowers cost of water and accelerates shale gas development in the region. However, because of the lack of data, the costs of treatment and disposal of flow-back effluent from shale gas exploration and extraction are not fully reflected in the current analysis. The updating of the water supply cost and treatment of these wastewater streams is a planned improvement to the SATIM-W model.

Table 6: Summary Metrics for Dry Climate (DRY) and Environmental Compliance (ENV) Scenarios (Cumulative values 2010 to 2050)

Scenario Results	Units	Reference (Water Cost)	Dry Climate	% change	Environmental Compliance	% change	Dry &Env Compliance	% change
System Cost	2010 MZAR (x1000)	7,646	7,647	0.00%	7,703	0.78%	7,703	0.74%
Expenditure - Supply	2010 MZAR (x1000)	11,650	11,622	-0.24%	11,955	2.62%	11,934	2.43%
Primary Energy	PJ	333,500	333,514	-0.59%	322,607	-3.84%	321,995	-4.03%
Final Energy	PJ	157,083	156,993	-0.06%	157,051	-0.02%	156,905	-0.11%
Power Sector CO_2Emissions	Mt	13,756	13,533	-1.62%	13,359	-2.89%	13,249	-3.34%
Power Plant Builds	GW	134	130	-2.82%	131	-1.7%	132	-1.77%
Power Plant Investment	2010 MZAR (x1000)	2,670	2,747	2.90%	2,664	-0.22%	2,673	0.14%
Water to Power Plants	Mm^3	12,074	11,302	-6.39%	12,356	2.34%	11,783	-2.41%
Total Water for Energy	Mm3	16,265	15,453	-4.99%	16,007	-1.59%	15,428	-5.14%

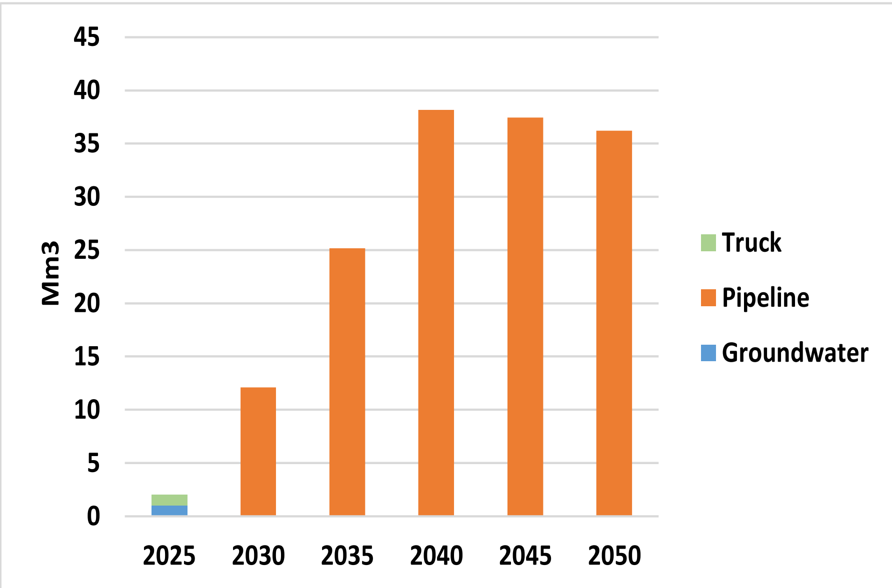

Figure 17: Water Supply by Mode for Shale Gas Production

As shown in Figure 18, the Shale Gas scenario significantly increases power generation from natural gas compared to the Reference (Water Cost) scenario. Figure 19 shows that the growth of shale gas utilization for power generation occurs at a similar rate for the Shale Gas and Shale Gas with No Water Cost scenarios. The slight increase in capacity that occurs for shale gas power plants when water costs are included, results from the decrease in coal power plant capacity that occurs when water costs are included. The new CCGT plants built under the Shale Gas scenarios are all dry cooled, as CCGT plants have lower water requirements and suffer less efficiency loss with dry cooling. However, this result might change once more accurate water cost data and the cost of treating shale gas return-flow effluent is included in the SATIM-W model.

Table 7 summarizes the key cumulative metrics (2010 to 2050) from the Shale gas scenario. It's interesting to note that the cumulative water supply to shale gas production is only 9.8% of the total water use for energy in that scenario, and 8.8% of the Reference (Water Cost) scenario's use of water for power. The overall water needs for energy drops slightly as less water is devoted to the coal industry and power plants.

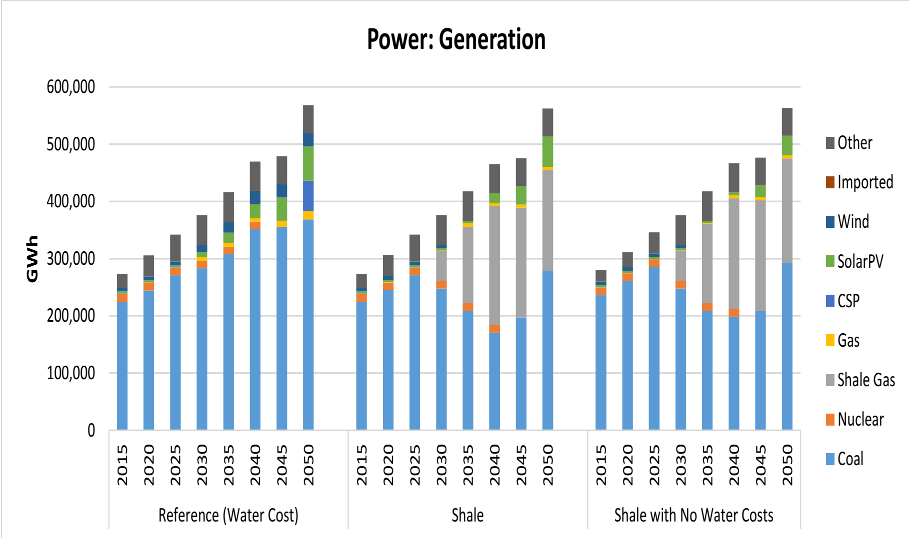

Figure 18: Electricity Supply Portfolio with Shale Gas

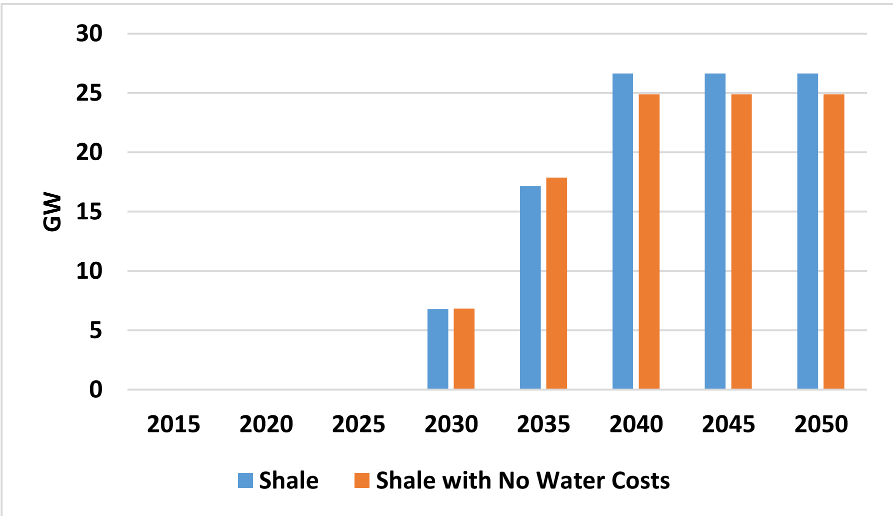

Figure 19: New Shale-Gas Power Plant Builds with Shale Gas Availability

Table 7: Summary Metrics for Shale Gas Scenario (Cumulative values 2010 to 2050)

Scenario Results	Unit	Reference (Water Cost)	Shale Gas	% change
System Cost	2010 MZAR (x1000)	7,646	7,597	-0.65%
Expenditure - Supply	2010 MZAR (x1000)	11,650	12,217	4.87%
Primary Energy	PJ	333,500	331,025	-1.33%
Final Energy	PJ	157,083	157,453	0.24%
Power Sector CO_2 Emissions	Mt	13,756	12,540	-8.84%
Power Plant Builds	GW	134	117	-12.42%
Power Plant Investment Difference	2010 MZAR (x1000)	2,670	1,935	-27.52%
Water to Power Plants	Mm3	12,074	10,275	-14.90%
Water to Shale Production	Mm3	0	1,435	NA
Total Water for Energy	Mm3	16,265	14,677	-9.76%

3.7 In a carbon constrained world, what is the likelihood of stranded assets?

A system-wide carbon constraint in the form of a cumulative CO_2cap was used in SATIM-W to help identify the most cost-effective path to mitigating energy sector CO_2 emissions in response to international climate change obligations and national policy. Two scenarios were investigated: a 14 Gt CO_2 equivalent cumulative cap by 2050, which is in line with the current 'Peak, Plateau and Decline' policy (Altieri et al. 2015) used in the South Africa NDC, and a 10 Gt CO_2 equivalent cumulative cap, which models a more aggressive policy that might be followed if South Africa's trading partners mitigated aggressively and applied pressure to limit embedded emissions in their exports. These scenarios highlight the potential impact of these policies on energy sector investments, as well as on water supply investments, and the potential for stranded assets.

Regarding energy supply investments, both scenarios have no new investment in CTL capacity, compared to over 500 PJ per year in the Reference (Water Cost) scenario. In addition, the operation of the existing CTL plant is impacted, as illustrated in Figure 20. The 14 Gt CO_2 Cap scenario reduces production at the plant to zero by 2040, which is5 years earlier than in the Reference scenario. If a 10 Gt CO_2 Cap is implemented, production at the plant is completely halted by 2025, 20 years prior to the scheduled decommissioning date. The reduction in CTL capacity is substituted by an increased reliance on imported petroleum products (Figure 21) and crude-oil (Figure 22).

The 10 Gt CO_2 Cap scenario is heavily reliant on early imports of refined petroleum products, substituting 80% of existing CTL production in 2025, with the remainder coming from increased production in the existing refineries. Although the 14 Gt CO_2 Cap scenario allows the existing CTL plant to operate at full capacity in 2025, there is still an increase in finished petroleum product imports owing to a lack of investment in new CTL in the Waterberg. The bulk of refinery capacity is situated along the coast (~80 %), and therefore does not impact the water supply system for this analysis.

In contrast to the CTL facilities, which have very high CO_2 emissions per unit output, the existing and committed coal power plants are less at risk under the 14 Gt CO_2 Cap scenario. In the Waterberg, the existing plants remain operational for their entire technical life, as shown in Figure 23, although their utilization stops in 2050. The CF lines in the figure show the coal plant average capacity factor. In the Central Basin (Upper Vaal and Olifants), existing coal plant utilization is highly variable from 2040 onward, only 4 GW of existing coal plants remain operational in the Central Basin comprising in roughly equal shares both wet and dry-cooled plants. The wet-cooled plants are effectively mothballed and generate very little and as such the capacity factor of the residual coal fleet increases in 2050 once these reach the end of life and the 1.22 GW of dry-cooled coal plant remains operational. On the other hand, there is indeed a risk of significant stranded coal assets under the 10 Gt CO_2 constraint, which requires early retirement of the existing coal plants, which are replaced by new nuclear plants. In addition, the 10 Gt CO_2 Cap scenario shifts electricity production from the Waterberg to the Orange River region. Although the capacity of wet-cooled stock in the Central Basin is similar to that of the Reference in 2025, a 30% decrease in electricity production occurs. Thereafter, the stock is retired by 2035 with idle capacity of 4 GW in 2040 onwards.

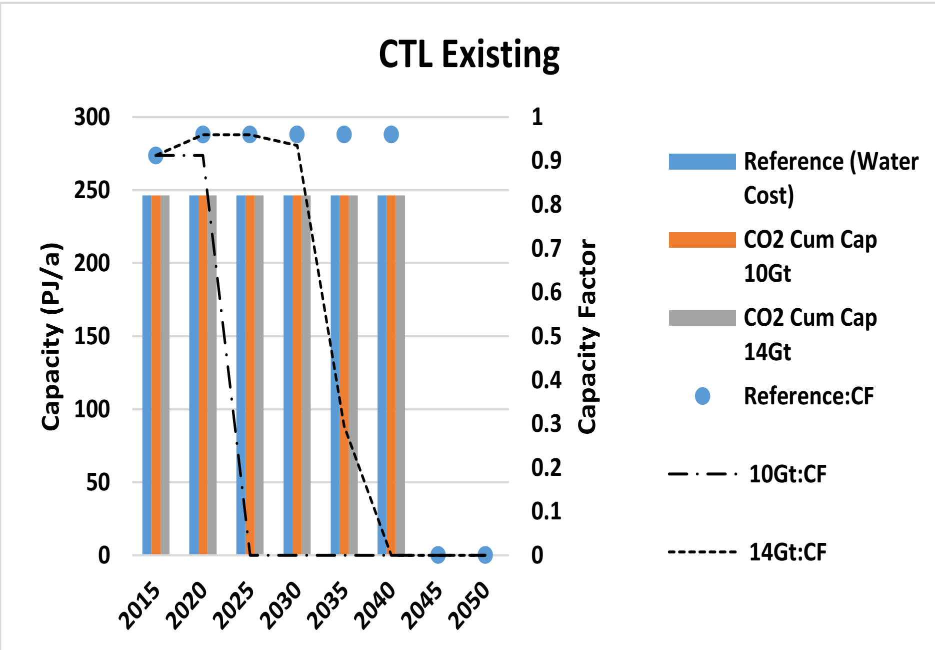

Figure 20: CTL Utilization under Carbon Constraints

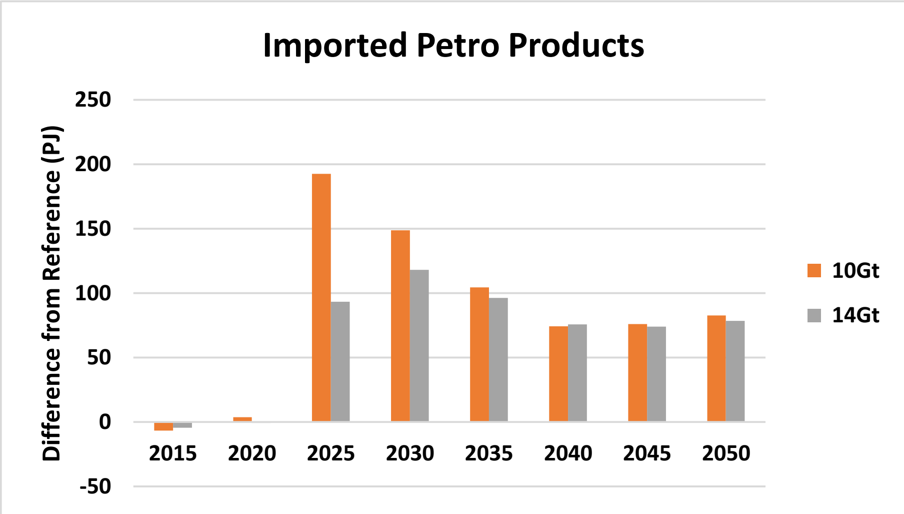

Figure 21: Imported Petroleum Products under Carbon Constraints - Difference from Reference (Water Cost)

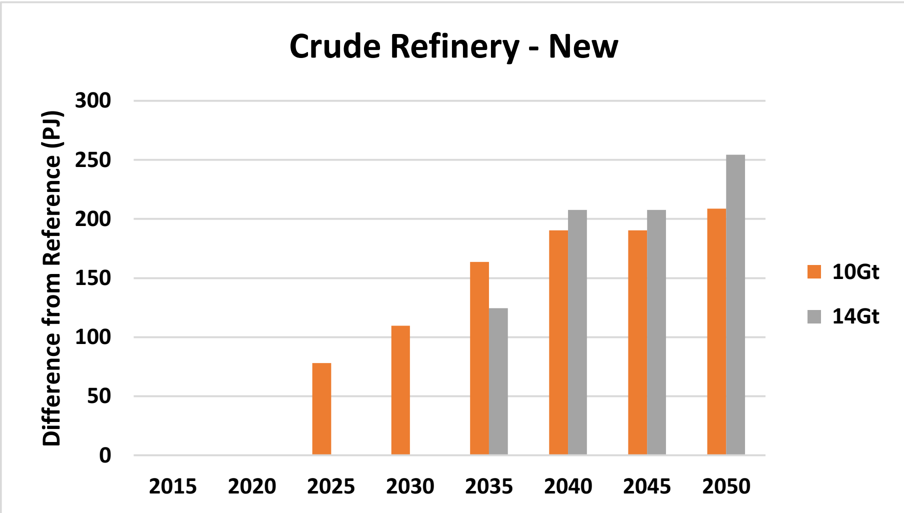

Figure 22: Crude Oil Production under Carbon Constraints - Difference from Reference (Water Cost)

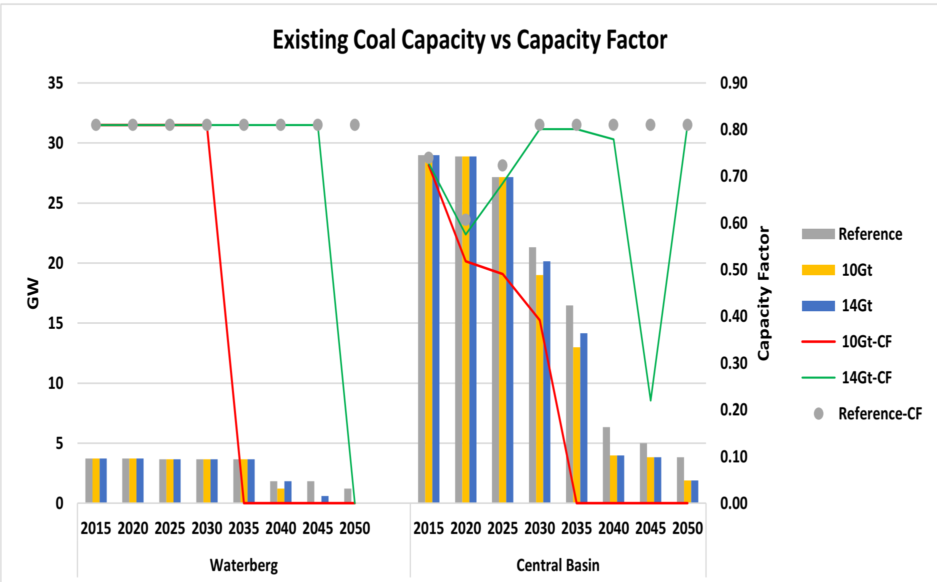

Figure 23: Existing Coal Capacity with Production Factors

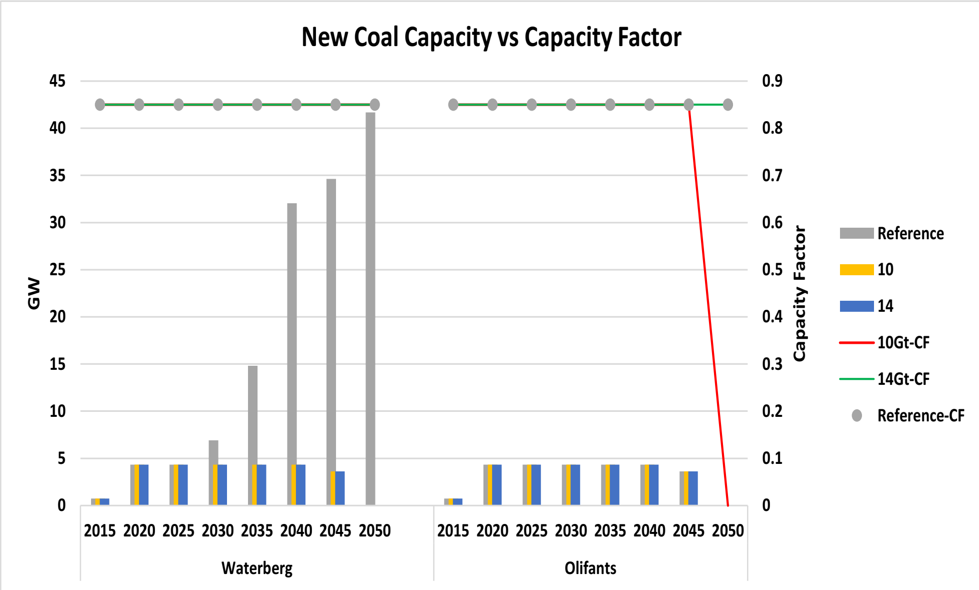

Figure 24: New Coal Capacity with Production Factors

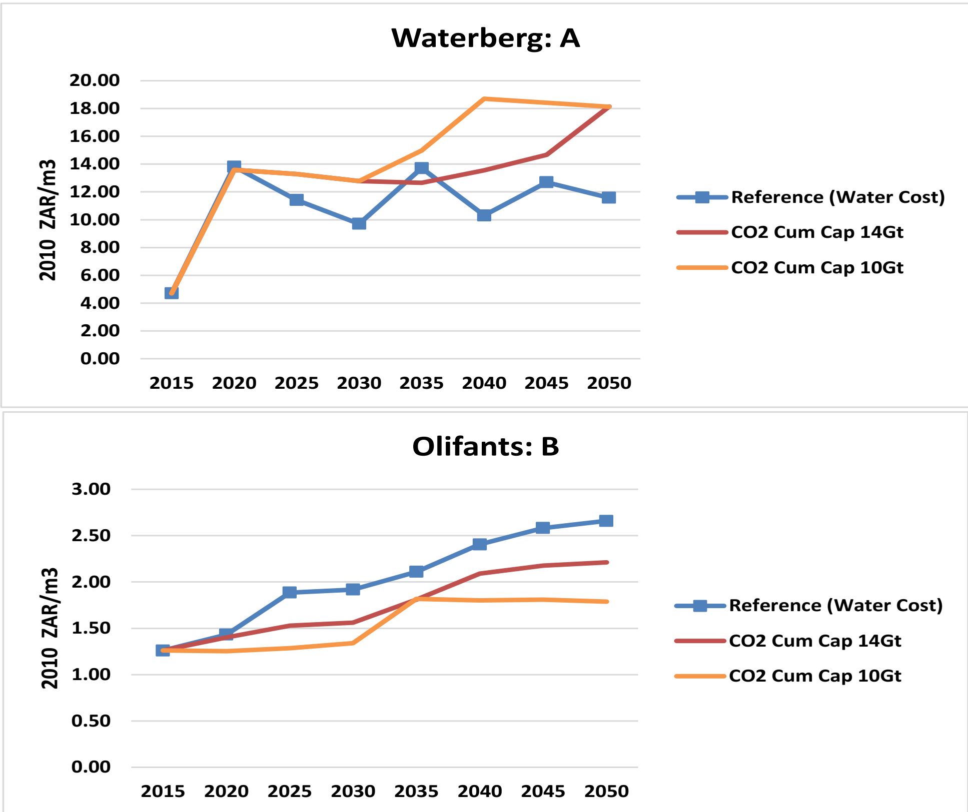

Figure 25: Water Supply Costs in Coal Rich Regions

New coal power plants in the Olifants appear most at risk under the 10 Gt CO_2 cap scenario, as they cease production earlier than plants located in the Waterberg (Figure 24). The regional coal price is a likely factor in the preferential early retirement of plants in the Olifants as Waterberg coal is more economical. In both scenarios, 3 GW of new Fluidized Bed Combustion (FBC) plants are built and operate over the planning period. Regarding water supply investments, Figure 25 suggests that water supply infrastructure for the Waterberg is also at risk of being under-utilized if CO_2 mitigation policy is carried through; the cost of water supply increases markedly after 2040 for the 14 Gt scenario and after 2030 for the 10 Gt Cap scenario because of the early closure of coal-fired capacity. This effectively increases costs for the remaining users as the supply system is being under-utilized. Conversely, the figure shows that the cost of water in the Olifants for the CO_2 cap

scenarios decreases relative to the Reference scenario with the stricter 10 Gt CO_2 cap also reducing costs relative to the 14 Gt cap in both cases due to the early retirement of the older existing wet-cooled coal plants.
The summary metrics for the two carbon cap scenarios relative to the Reference scenario are shown in Table 8. Notable are the large increases in power plant investments: 24% for the 14 Gt scenario and 82% for the 10 Gt scenario. The system cost differences, which aggregate and discount all supply and demand side costs show much smaller overall impact, although the 2.86% increase for the 10 GT scenario is significant relative to the impact of the other scenarios investigated. This is due to the power plant investments being offset by the reductions in primary energy use due to the increased role of renewables. There are significant increases in water consumption by power plants reflecting the shift to wet-cooled solar thermal in the Orange River Region where water is relatively cheaper although as discussed in the next section, when the stresses of a climate change and shale gas mining in the region are factored in, the model shifts to less water intensive dry-cooled CSP.

Table 8: Summary Metrics for 10 Gt and 14 Gt Cumulative CO_2Cap Scenarios (2010 to 2050)

Scenario Results	Units	Reference (Water Cost)	CO_2Cum Cap 14Gt	% change	CO_2Cum Cap 10Gt	% change
System Cost	2010 MZAR (x1000)	7,646	7,686	0.51%	7,865	2.86%
Expenditure - Supply	2010 MZAR (x1000)	11,650	11,765	0.98%	10,941	-6.90%
Primary Energy	PJ	333,500	284.385	-15.24%	266,639	-20,52%
Final Energy	PJ	157,083	156,008	-0.68%	154,452	-1.67%
Power Sector CO_2Emissions	Mt	13,756	9,330	-32.18%	6,120	-55,51%
Power Plant Builds	GW	134	189	26.49%	189	40.88%
Power Plant Investment	2010 MZAR (x1000)	2,670	3,318	24.28%	4,872	82.49%
Water to Power Plants	Mm^3	12,074	14,592	20.85%	15,073	24.84%
Total Water for Energy	Mm^3	16,265	16,941	4.16%	16,753	3.00%

3.8 Why does SATIM-W select CSP with wet cooling in the Orange River basin?

Several scenarios were examined to better understand why SATIM-W selects wet-cooled CSP in the Reference (Water Cost) scenario. In particular, two scenarios are illustrative. The 14GT CO_2 cap scenario also selects wet cooled CSP, but the Dry and 14 GT CO_2 cap scenario selects dry-cooled. However, the resulting reduced water demand is accompanied by an increase in water cost, as illustrated in Figure 26. The reason for the increased water cost can be understood by examining the investment decisions for water supply infrastructure in the Orange River region for these three scenarios. Figure 27 shows that a stricter carbon cap results in increased investment in water supply infrastructure in the Orange River region relative to the Reference scenario. These incremental water supply investments in the Orange River are due to a shift to CSP rather than coal under a Carbon Cap scenario, which shifts generation to the Orange River region. These investments begin in 2030 to support large-scale implementation of CSP starting in 2040. However, water demand in this region, which is still dominated by non-energy demands, requires a significant water supply scheme needs to be built, which happens is all scenarios; this water supply scheme is not operated at full capacity when the decision is made to invest in dry-cooled CSP. This suggests that the increased cost of water is a determinant in the choice.

Figure 28 shows the increased demand from the non-energy sectors under a Dry Climate scenario, which causes a degree of regional water stress in the Orange River region, and this stress is slightly exacerbated by the advent of shale gas extraction, which happens largely in this region. The increased demand triggers further investment in water infrastructure, which causes the average water costs to go up significantly enough, as shown in Figure 29, to move some of the investment in CSP to dry cooled technology. The summary metrics for the 14 Gt Cap scenario under the effects of climate change (‘Dry’ scenario) show a small reduction in the increased water intensity from the shift to CSP based production in the Orange River region caused by the cap. Essentially the water supply system appears to be resilient to the effects of climate change on water supply and demand as currently understood although there are changes to the cost optimal mix of wet and dry cooling coal and CSP technologies on the energy supply side in response to increased water costs. The summary metrics for these scenarios relative to the Reference scenario are shown in Table 9.

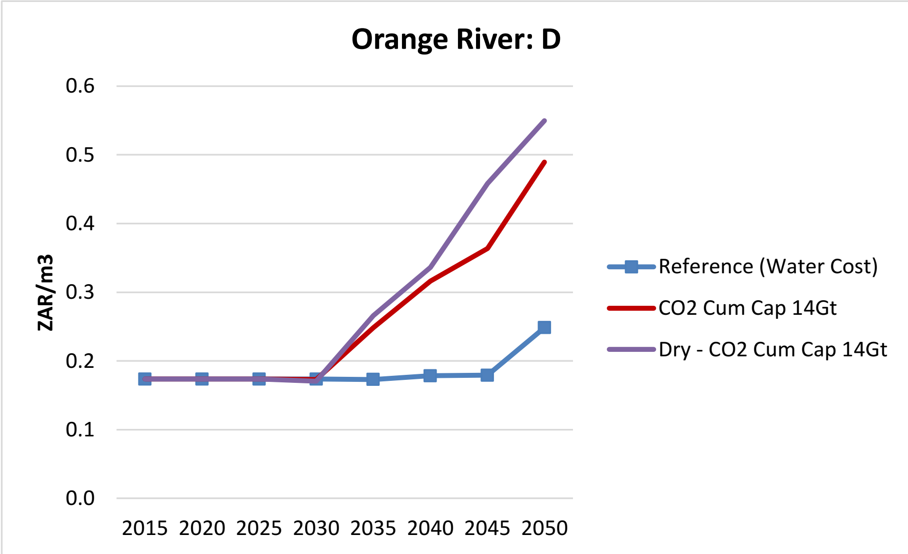

Figure 26: Water Supply Costs for Orange River

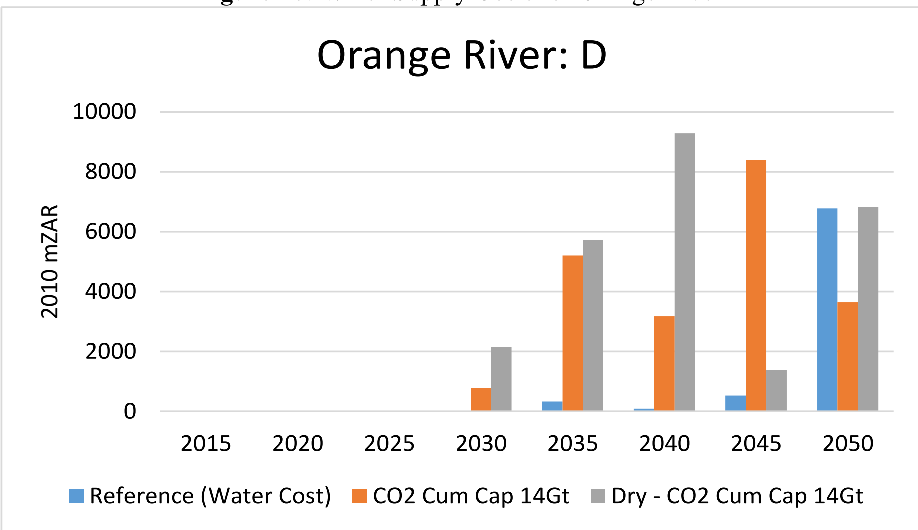

Figure 27: Water Supply Infrastructure lump sum investments for Orange River

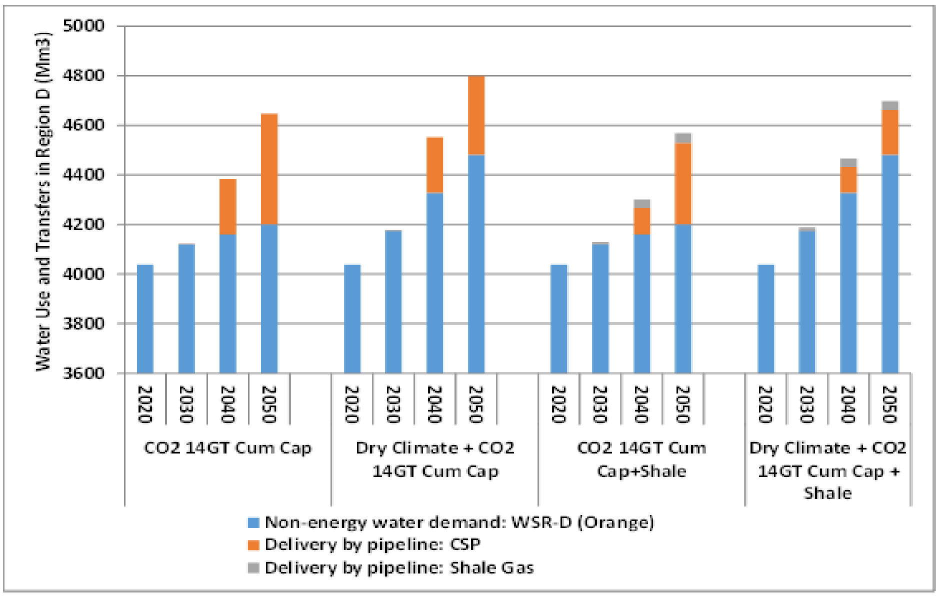

Figure 28: Water Use and Transfers for the Orange River WMA (Region D)

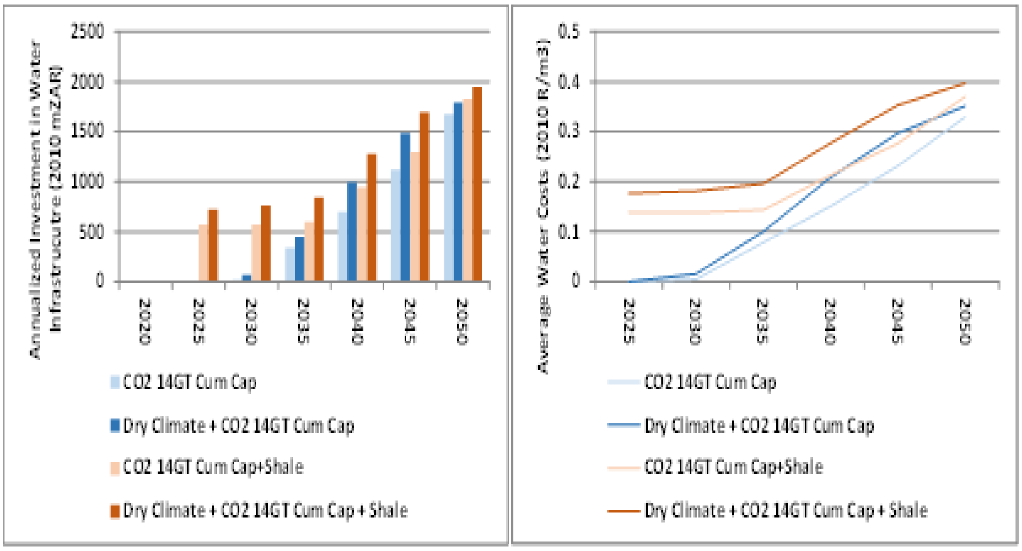

Figure 29: Annualized investment in water infrastructure in Orange Basin and the impact on the average cost of water

Table 9: Summary Metrics for the Combined Scenarios for the Dry, Shale and 14 Gt Carbon Cap (C14Gt) Scenarios

Scenario Results	Units	Reference (Water Cost)	Dry & C14Gt	% change	Shale & C14Gt	% change	Shale & Dry & C14Gt	% change
System Cost	2010 MZAR (x1000)	7,646	7,691	0.59%	7,635	-0.15%	7,631	-0.14%
Expenditure - Supply	2010 MZAR (x1000)	11,650	11,785	1.16%	12,124	4.07%	12,141	4.20%
Primary Energy	PJ	333,500	284,548	-15.19%	285,203	-14.99%	285,054	-15.04%
Final Energy	PJ	157,083	156,007	-0.69%	156,148	-0.60%	156,199	-0.56%
Power Sector CO_2 Emissions	Mt	13,756	9,337	-32.12%	9,294	-32.44%	9,299	-32.40%
Power Plant Builds	GW	134	170	27.08%	157	17.54%	157	17.42%
Power Plant Investment	2010 MZAR (x1000)	2,670	3,321	24.36%	2,759	3.35%	2,742	2.73%
Water to Power Plants	Mm3	12,074	13,801	14.31%	111,734	-2.81%	10,615	-12.08%
Total Water for Energy	Mm3	16,265	16,145	-0.73%	14,532	-10.65%	13,412	-17.54%

Concluding Remarks

The results of this investigation demonstrate the process and type of tools that can be employed to examine the water-energy nexus and the insights that can be gained from integrated energy-water planning. A number of relevant energy-water policy scenarios in South Africa were explored, and the results show that specific energy sector policies can have significant implications for both new investments in water supply infrastructure and in some cases, can lead to stranded water supply investments, and vice versa, reinforcing the importance of planning the water-energy nexus in an integrated manner. Furthermore, the approach used in this study can be readily adopted in other locations to tackle their water-energy management challenges in a more integrated manner.

A key finding of the study is that a national-level energy systems optimization model can be readily regionalized in terms of energy resource supply and power plant locations, and the regional costs and limitations for water supply can be incorporated into the energy model to create a water-smart energy sector planning tool. Planned options for future water supply infrastructure to the energy sector were explicitly represented with their costs and availability, and a representation of the full cost of water supply has been incorporated into a full-sector energy system expansion plan that considers the regional variability of water availability that needs to be addressed through the development of additional water supply infrastructure. A critical attribute of SATIM-W is the ability to understand: (i) which water infrastructure will be needed for the energy sector while meeting non-energy water needs as well; (ii) when and where investments will be needed, and (iii) what the cost of supply will be. Given that the planning, design, and construction of infrastructure requires long-term engagement, this study demonstrates that tools such as SATIM-W facilitate an integrated planning approach that can lead to timely investments and delivery of water supply and treatment infrastructure for the energy sector. A clear demonstration of the importance of more integrated water-energy planning is the fact that incorporating the cost of water supply infrastructure into the model produces significantly different energy technology investments compared to not including water supply costs. Dry cooled power plants are selected in water scarce regions and significant reductions in water consumption can be achieved along with modest reductions in GHG emissions, as including water costs are advantageous for certain renewable energy technologies.

Recommendations for further development of the SATIM-W model and its application for energy and water planning have resulted in additional areas of improvement of the model and further expand the coverage and insights that can be obtained. These include: (i) bringing more water allocation decision-making into the framework to examine, for example, if it is practical to model the trade-offs for transferring irrigation water rights to power sector use, considering crop reductions and economic losses that might result, as well as looking at water conservation opportunities; (ii) examining in more detail the economics of FGD retrofits for existing coal plants, which requires refinements to model the costs for FGD feedstock and disposal, and the reduction in plant availability during FGD retrofitting; (iii) evaluate the impacts of delays in the commissioning of water infrastructure on the energy sector; (iv) incorporating a more detailed disaggregated representation of non-energy water consumption into SATIM-W in order to examine water reallocation schemes, demand elasticity to cost, and the impact of water-use efficiency and DSM interventions; (v) incorporating wastewater streams, treatment plants and other related infrastructure(e.g., return flow effluent from shale gas production) from other sectors in addition to coal mining; (vi) linkage with an economic model to assess the impact of the energy-water nexus trade-offs on the economy as a whole including the impacts on jobs, GDP and affordability; (vii) developing water linkages to a variety of biofuel feed stocks and other aspects of land-use and food production in terms of both water and energy; (viii) explore approaches to incorporating the externality costs of power production including health and environmental impacts and the opportunity costs for water allocation and use; and (ix) better exploring the potential impacts and associated risks of future climate change.

A range of science challenges remain, however, in the development and use of integrated tools for energy-water-food nexus. First, although advances have been made in integrated modeling exercises such as this work, substantial technical advances are still needed. For instance, because integrated modeling requires representations of all three systems, and across regional scales, temporal and spatial resolution may frequently be sacrificed in the name of integration. Yet, carefully chosen focus areas of higher-resolution can substantially enhance the usefulness of integrated modeling for real world decision making. Major scientific questions remain about when, where, and how to create this higher resolution; when it matters and when it does not (Hibbard and Janetos, 2013; Kraucunas et al. 2015). Second, the successful development and use of modeling tools for decision making requires a two-way process in which decision makers are co-developers with the modeling teams (White et al. 2010; Strachan et al. 2016). Questions about when and where higher resolution is important or beneficial are dependent critically on the specific decisions and decision processes to be supported by modeling. This co-development, thus, requires the creation and strengthening of social networks that include decision makers and analysts (Crona and Parker, 2011). Third, and related, the development teams for models and for the use of models in decision making must consist not only of modelers, but also of *social scientists* that understand how different actors frame the problems and potential solutions (White, 2013) and how scientists, modelers and decision makers interpret key concepts such as uncertainty (White et al., 2015); data development experts that can create usable information from often incomplete sources and characterize the uncertainty in this information; visualization and other communication experts to bridge the divide between modelers and decision makers.

This work has demonstrated the importance and value of employing an integrated planning platform to properly assess the energy-water nexus challenges in South Africa towards robust hedging strategies and ensure that these critical long-term aspects of sustainable development are intelligently planned in a least-cost manner. This is particularly important as countries gear up to determine how their NDC commitments will be realized in a way the contributes directly to achievement of associated Sustainable Development Goals. These challenges are particularly acute in developing countries with less data and modeling infrastructure. Overcoming these challenges will be critical if the world is to address challenges like climate change while simultaneously making regional/local decisions that fulfill sustainable development goals (e.g., Sachs, 2012) and the Paris Agreement pledges (e.g., Fawcett et al. 2015, Iyer et al. 2015).

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