Development of a National Water-Energy System Model with Emphasis on the Power Sector for South Africa

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A comprehensive archive of information and data pertaining to the development process is available via the Energy Research Data Portal for South Africa. The portal hosts technical reports and data fully describing the model development, estimation of costs and technical parameters; and that of stakeholder engagement for model validation and scenario critique. ***http://energydata.uct.ac.za/organization/erc-water-energy-nexus*** Environ Prog, 37: 132–147, 2018
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INTRODUCTION

South Africa's existing water supply resources are at their limit with ca. 97% of supply already allocated with Agriculture estimated to demand the bulk of available supply (60%) followed by Domestic use (27%), Industry (3%), Mining (3%), Power (2%) with the remainder comprising other smaller consumers (Figure 1) [1,2]. The majority of the population (55%) is deemed to live below the accepted poverty line of ZAR441 or USD34 (2017) per month [3]. The country's Water for Growth and Development Framework recognizes water security as key to achieving developmental goals [4]. In particular the promotion of agricultural activity to counter rural poverty where livelihoods are most adverse could potentially expand water-use within the sector which, without integrated planning to encourage water-efficient agro-industrial expansion could further strain future supply options [5–7].

In order to stimulate economic growth to address widespread poverty, expanding the existing energy supply is also deemed a priority while maintaining affordable access to energy and adhering to international and national environmental commitments [8–10].

Historically low cost and low calorific coal has accounted for ~74% of primary energy supply and responsible for ca. 95% of electricity production and ca. 30% of transport liquid fuels via coal-to-liquids production (Figure 1) [2]. Societal development requires adequate water and energy as a foundation. Although the concomitant flow of these resources are acknowledged [11–17], planning for future growth in both water and energy supply in South Africa still largely occurs in separate planning spheres [18–20]. Water planners typically estimate regional requirements (including those of the energy sector) but do so without necessarily a holistic consideration of technology options (e.g. water-intensity and efficiency), inter-regional development paths and future climatic impacts [20,21]. In a similar manner, energy planners account for water without sufficient information of water availability, accessibility, the required timing of supply infrastructure and alternative options that emerge when additional criteria are considered [18,19,22].

Regional disparities in water and energy resources further requires timeous water supply infrastructure to develop new regions of energy supply. Figure 2 illustrates the regions of interest for existing and new energy supply development in South Africa. The figure depicts the primary basins (variegated-shading) and water management areas (WMA) to contextualize the necessary water transfers. The dependence of water exports from the neighboring country of Lesotho is also shown. Each WMA represents a distinct water supply zone. This regional disparity in water supply may be exacerbated by Climate Change, as climate models suggest (Figure 3). The figure displays the uncertainty in regional water supply in 2050 relative to an unconstrained GHG emissions energy and land-use scenario [23].

Recent legislation requires the use of emissions control technologies to comply with stricter environmental releases [10]. For example, to limit the emission of SO_2 from fossil fuel combustion would require additional water supplies and increased investment costs to retrofit existing technologies, and acid mine drainage, a by-product of coal mining, requires additional investment and energy to remediate process water for environmental release [24–26].

The water-for-energy and energy-for-water interplay in a context of growing demand for both energy and water is of particular concern for South Africa given the lack of an integrated approach to resource planning and regulation enforcement [27] in a country regarded as arid receiving less than half the global average rainfall. High rainfall areas are dislocated

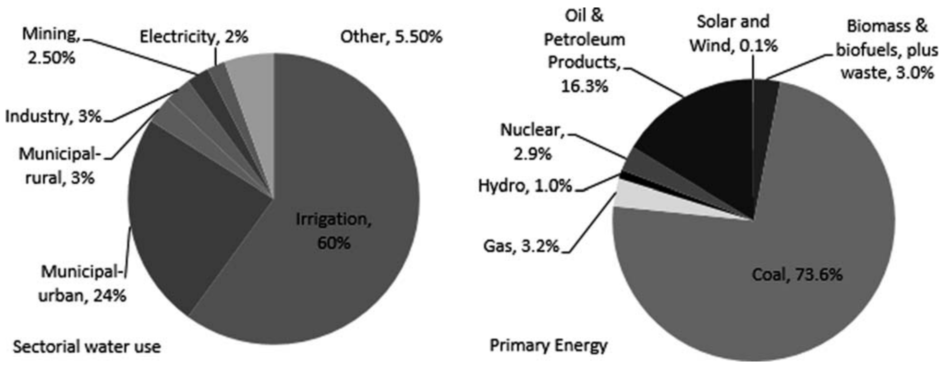


Figure 1. Water and primary energy supply for South Africa [1,2].

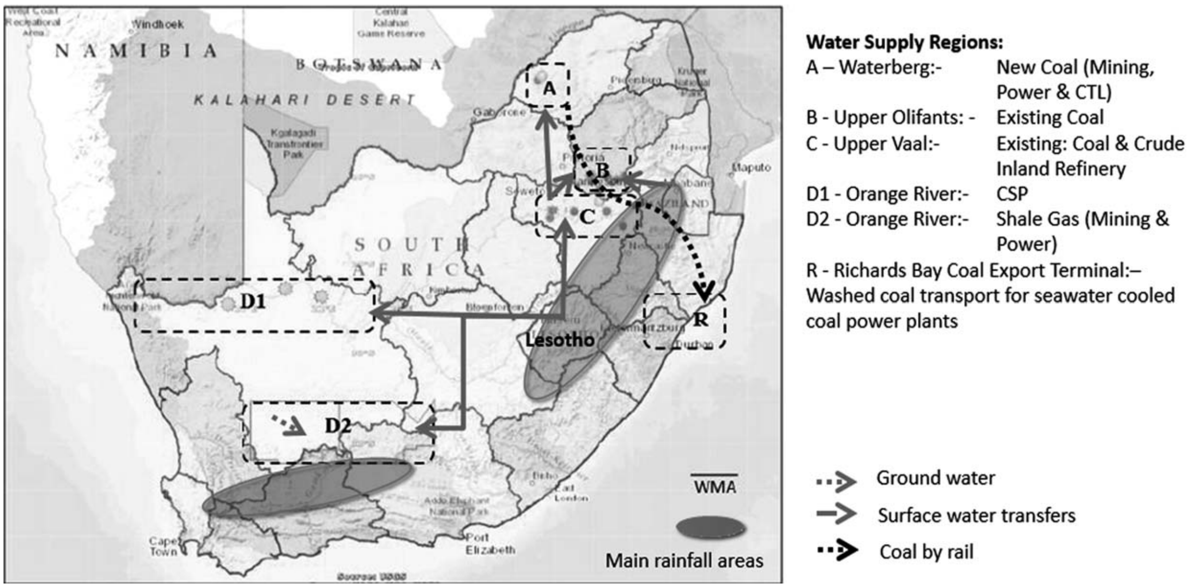


Figure 2. A schematic depiction of the water-energy supply regions modeled for South Africa.

from economic hubs with 20% of the land mass providing most of the 70% country's surface water runoff [28].

Existing long-term planning tools and studies have previously addressed regional or components of water-energy planning in South Africa in isolation. That is, perturbations along the supply and distribution linkages of economic sectors (e.g. Transport) on the energy system are not fully accounted; or lack a rich and flexible technology base of options that enable choices that compete economically on both water and energy resource utilization.

To address the silo approach of current planning tools we present in this paper a novel approach using an existing linear optimization least cost energy systems model which incorporates an endogenous water supply infrastructure component. The resultant water-for-energy model allows national strategic planning of future energy supply fully accounting for regional water availability in terms of quantity, quality and cost of developing supply infrastructure.

METHODOLOGY

The SATIM Model

The Energy Research Centre hosts a national energy-economic system model referred to as the South African TIMES (or SATIM) model [29], developed over several years with the TIMES modelling platform [30]. TIMES is a partial equilibrium linear optimization framework capable of representing the entire energy system which minimizes the cost of satisfying demand for energy services.

SATIM is a technology rich, non-spatial (single node) national representation of energy commodity flows, energy transformation technologies and incurred costs and emissions (Figure 4).

Table 1 provides a summary of key data sources required to populate the optimization model.

Technologies are linked by commodity flows and characterized by associated efficiencies, costs, plant life, and other salient techno-economic parameters. For example: the extraction, transmission and distribution of gas and coal; the transformation to electricity; the transmission and distribution of the electricity; and the consumption of the electricity by end-use technologies such as an electric vehicle for transport or an appliance for residential cooking. Figure 5 provides a simplified schematic of the Power Sector implementation in SATIM illustrating the generation, transmission and distribution of electricity to consumers while Figure 6 illustrates the typical parameterization of a specific technology type without ancillary water consumption.

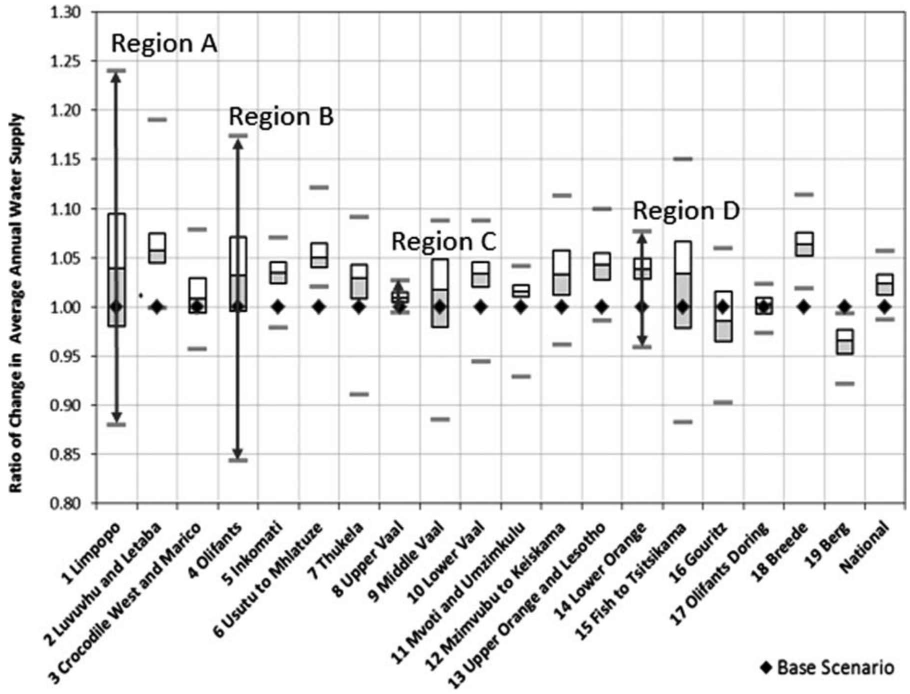


Figure 3. Forecasted uncertainty in regional water supply by 2050 [23].

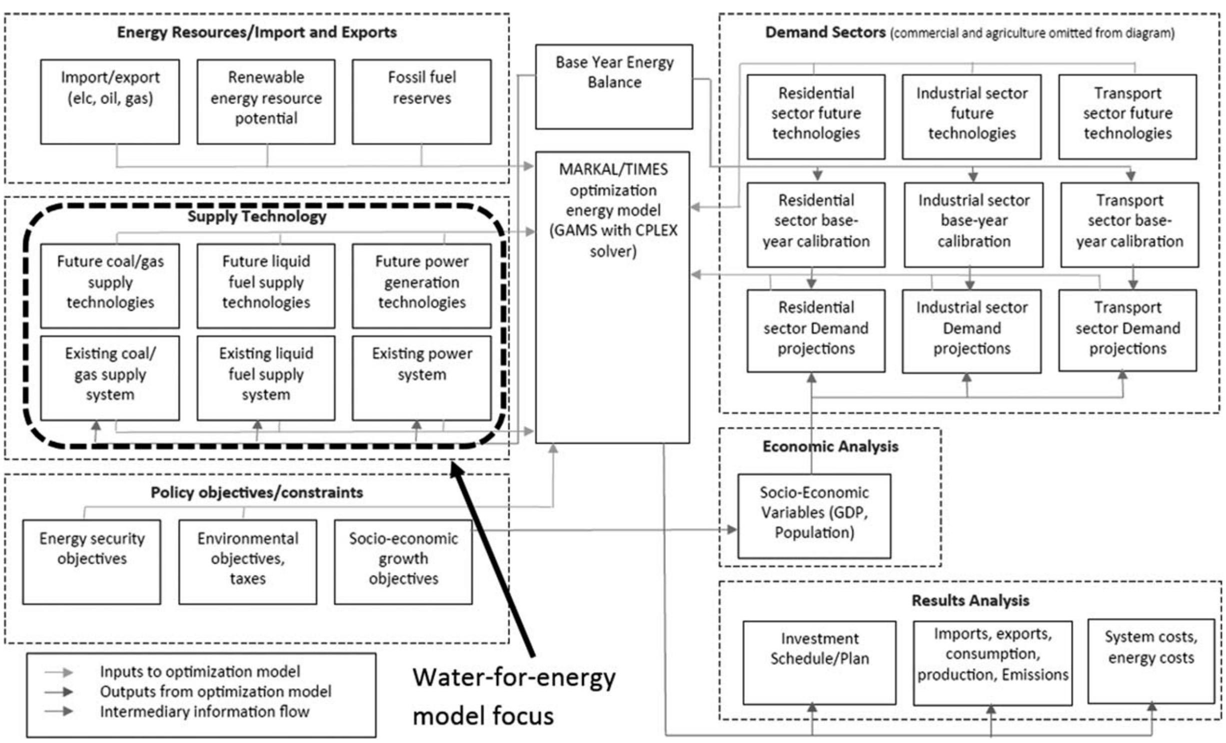


Figure 4. A process flow schematic of the SATIM energy systems model with the water-for-energy development focus highlighted.

Incorporating Water Supply Infrastructure and Spatial Information

To address water-energy scenarios of interest in the context of energy supply the existing SATIM model is restructured to include water abstraction and consumption by process and technology. Figure 6 thus incorporate additional input flows of "primary" and "high quality" water commodities which are differentiated by their energy requirements and bulk regional cost of supply. The model referred to as SATIM-W, introduces new nomenclature in order to attribute supply and demand processes to a particular region (Figure 2). For clarity, the salient features of the integrated water supply system are depicted in Figure 7. The figure excludes additional model processes and commodities necessary to effect the dynamic supply allocation. The figure illustrates the diversion or allocation of water to specific regions which could vary by regional climate or demand scenario.

A complete illustration of the SATIM-W water supply system is too large to display with clarity. Instead parameterization within the model is depicted in Figure 8 subset of supply schemes in Region A which depicts keys features. For example, in the figure, the pipeline (U2WAT-A) supplying Region A with water supply (WA01-A) requires electricity (ELC) for the necessary conveyance. Also shown are the additional ancillary (or dummy) commodity variables (WAXC0, WAXC1) required within the model structure to implement interbasin (or inter-regional) water transfers from specific supply schemes in Region C (C0, C1).

Table 1. Summary of data and key sources for SATIM model.

Data requirement	Source
Energy Balance	Department of Energy, International Energy Agency
Electricity and Natural Gas Balances	Eskom, SASOL
Power sector	Eskom*, EPRI (IRP), SASOL**, Energy Research Centre, STATSSA
Industry	Industry Publications (e.g. Annual Reports, Technical Reports)
Transport	
Residential and Commerce	
Agriculture	
Existing power plants	Eskom*
New power plant types (e.g. wet-cooled supercritical, sea-water open-cycle cooled)	Key data and assumptions for non-IRP power plants are documented in the Thirsty-Energy Task 2 SATIM-W method report available at the online data portal.

*Eskom is the country's main electricity utility responsible for 95% of current average annual generation.
**Sasol operates the country's sole coal-to-liquids facility and is the dominant supplier of natural gas.

Rather than including predefined water supply costs, supply options are modelled as discrete infrastructure projects within the model. Scheme costs including the energy requirements are incorporated as given below with the required parameterization summarized in Table 2.

Scheme Supply Cost = Capital (Scheme + Delivery) **+ Fixed_OM** (%Capital) (Scheme + Delivery) **+ Var_OM1** (Energy cost of conveyance (endogenous)) (Scheme + Delivery) **+ Var_OM2** (Administrative charges)

Pre-computed water supply costs include estimates of the monetary cost of energy for conveyance and treatment and the resultant static supply curves are invariant to the effect of varying scenarios of regional demand in an interconnected supply system which may affect regional average costs and therefore do not necessarily capture changes to investment preferences for individual water supply projects.

Modeling discrete projects therefore has the flexibility to reflect impacts to the integrated water supply system resulting from changes in energy prices and regional water demand. This in turn influences regional investment choices in energy supply where water costs are higher. Technical and economic parameterization of the regional supply augmentation options are summarized in the supplemental appendix with technical and economic data used to populate the model available online.

Figure 9 for example, illustrates the water supply region WSR for Region A: the Waterberg area in the Limpopo WMA. The identified water supply regions each comprise a portfolio of candidate water supply options that together provide planners with estimates of the marginal cost of new water supply in the context of water supply [10].

Figure 9 further displays additional processes that characterizes a water supply system in SATIM-W. Thus a water supply system for each inland region is constructed featuring regional nuances such as, for example, truck delivery of surface water requiring diesel rather than electricity; and groundwater usage for shale-gas extraction (refer to supplemental).

Water Quality

Water quality is not emphasized in this paper but introduced to adequately describe the model components depicted in Figure 10. A comprehensive analysis of time varying water quality impacts was not investigated in this phase and it is proposed for future research. Further research is required to fully assess regional water quality and its effect on water supply investment decisions for energy supply. At present water quality is represented as indexed grades (i.e. 0, 1) in which Index 0 refers to

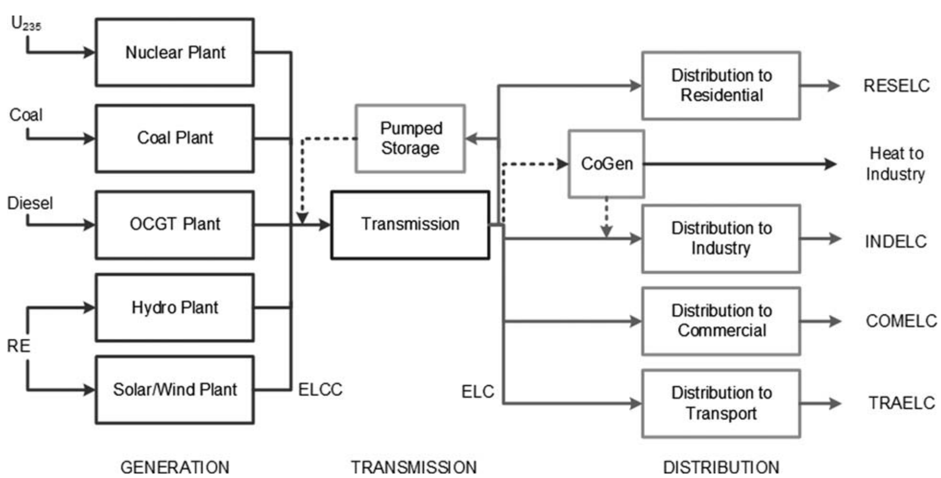
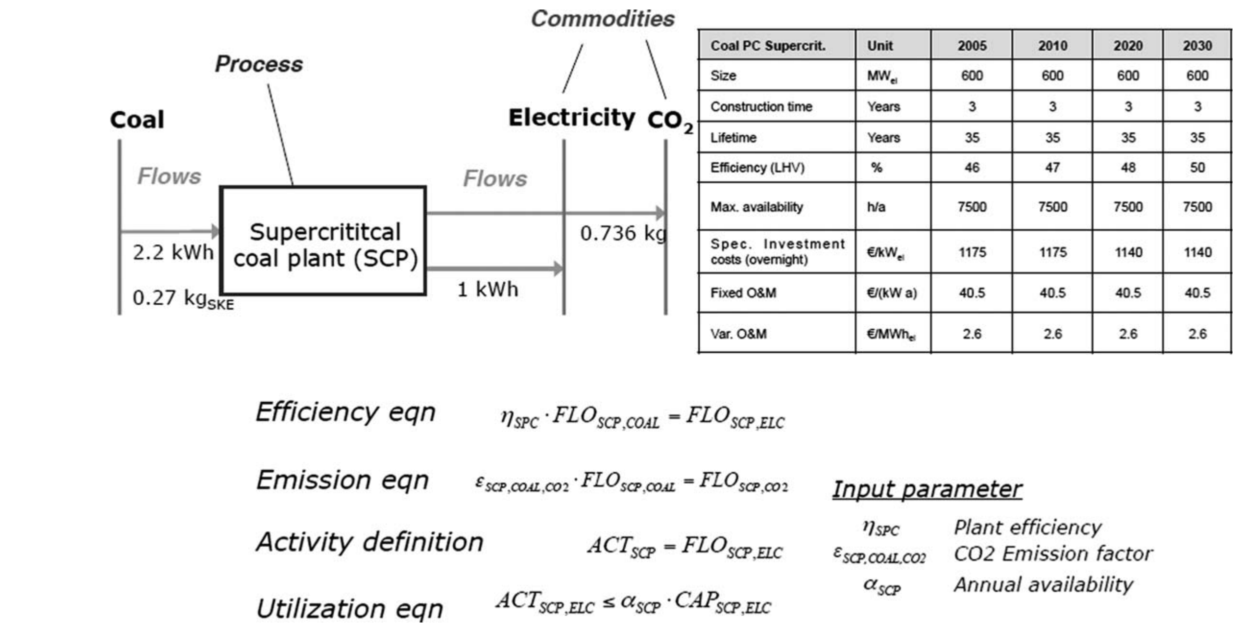


Figure 5. Simplified representation of the power sector in SATIM.



Coal PC Supercrit.	Unit	2005	2010	2020	2030
Size	MW_{el}	600	600	600	600
Construction time	Years	3	3	3	3
Lifetime	Years	35	35	35	35
Efficiency (LHV)	%	46	47	48	50
Max. availability	h/a	7500	7500	7500	7500
Spec. Investment costs (overnight)	€/kW_{el}	1175	1175	1140	1140
Fixed O&M	€/(kW a)	40.5	40.5	40.5	40.5
Var. O&M	€/MWh_{el}	2.6	2.6	2.6	2.6

Figure 6. An example of technology parameterization in SATIM for a coal (pulverized fuel) powerplant.

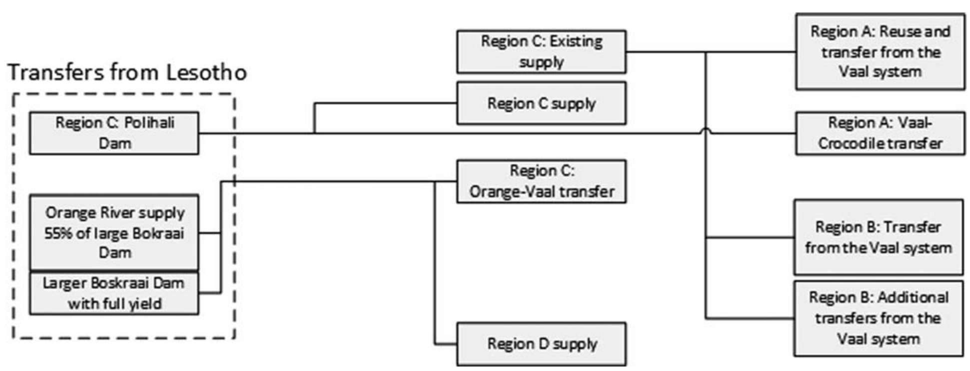


Figure 7. Schematic of the regional water supply network incorporated in SATIM-W.

the existing regional water quality. In the figure Grade 1 identifies changes to water quality that impact boiler feed water requirements which require pre-treatment in addition to existing treatment facilities [31]. Primary water, as introduced earlier is supplied from two quality grades (WA0-A; WA1-A). A super-critical coal-fired power-plant can be seen to consume, in addition low calorific coal (PWRCLE-A), both primary and high quality water (commodities). Also illustrated are fugitive emissions associated with coal mining and synthetic fuel production.

Water and energy consumption factors for energy sector technologies and processes such as, for example, shale gas extraction, coal mining and washing, water treatment plants, subcritical and super-critical coal power plants are obtained from literature review, personal communication with local utilities [32–46]. The portfolio of power plant technologies included are based on the local official strategic planning documents [18,19] and adapted to include additional options such as, for example, wet-cooled CSP or Sea-water cooled open cycle coal power plants [47].

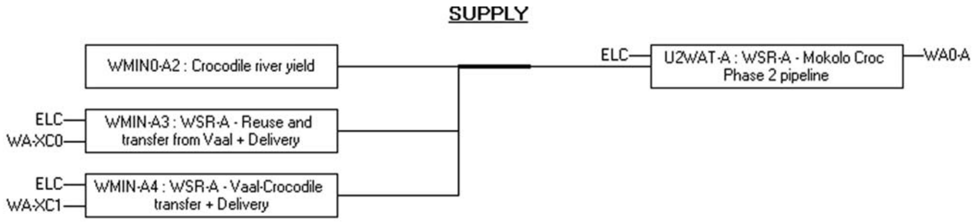
Table 3 summarizes water consumption factors for key processes and technologies in the model. Native model units of mm^3 per PJ of supply are shown for ease of comparison for different activities such as coal extraction and processing and power plant consumption. The consumptive use values are similar to abstraction for power plants as water is generally recycled through cascading reuse with brine effluent discharge to evaporation ponds (CSP) or coal ash dumps. Further research is required though to gauge the impact of wet FGD implementation (stated preferred option) on the current zero-liquid discharge practice. Direct-dry cooled thermal power plants typically have x10 less water requirements but incur ~10% more in capital with efficiency penalties in the order of 2%. FGD technology further increases water use at ~ 2 l/kWh (0.056 Mm^3/PJ) for the Wet option with an additional efficiency penalty of 0.5%–1% (new build super-critical or retrofit to subcritical plants.)

Wet (closed-cycle) cooled parabolic CSP is reported to be 10%–60% more water-intensive than central-receiver systems [44] potentially exceeding that of wet-cooled coal plants.

Estimated consumption factors for coal supply range from 0.05 m^3/ton to 0.27 m^3/ton of coal processed. Shale gas consumptive figures are based on literature reporting extraction activity in the USA [45].

Regional Water Demand

Typically water and energy planning is conducted in silos with water planning conducted regionally with different



Process	Parameter	Units	Commodity	Limit	Value
WSR-A MCWAP Phase-2	Variable costs associated with activity of a process	2010ZARm/uvol	-	-	0
	Bound on total installed capacity in a period	uvol/a	-	UP	332
	Process efficiency tied to primary commodity	dec fractn	Region D Reference Quality Water		1
	Investment cost for new capacity	2010ZARm/uvol/a	-	-	52.41
	Fixed operating and maintenance cost	2010ZARm/uvol/a	-	-	0.16
	Discrete capacity investment	2010ZARm/uvol/a			166.00
	Dependency linkage (pre-project requirement)	**WMIN-A1 (Phase 1)**			
	Lead-time required for building a new capacity	no. yrs	-	-	6
	Technical lifetime of a process	no. yrs	-	-	100
	Auxillary input commodity	Mm3/PJ	ELC	-	0.0031

Figure 8. Parameterization of a water supply project in SATIM-W. Key data is an upper limit on yield, name of the water supplied, investment cost for new infrastructure, operating cost, option dependency indicator (here WMIN-A1 must be built, though more expensive, before Phase-2), construction time, lifetime, and amount of electricity needed for unit of water produced. Note: Costs are in 2010 millions of Rands (ZARm); the unit volume (uvol) is Mm^3; and process efficiency is set to 1 as losses are accounted for in yield.

Table 2. Model parameters for incorporating water supply into the energy system model.

TIMES parameters	Scheme Supply & Delivery	Treatment
Time varying parameters		
NCAP_COST	Capital (ZAR/Mm^3)	Capital (ZAR/Mm^3/annum)
NCAP_FOM	Fixed OM (ZAR)	Fixed OM (ZAR)
PRC_ACTFLO	Energy commodity	Energy commodity
	Electricity or Diesel (kWh/m^3) or (L/m^3)	Electricity (kWh/m^3)
ACT_COST*	In SATIM-W included as a FOM cost	n/a
ACT_BND	Yield (Mm^3)	n/a
Time invariant parameters		
TOP-IN (Commodity input)	Electricity (ELC) or Diesel (ODS)	Electricity
TOP-OUT (Commodity output)	Water e.g. WA-P1-[i] (mm^3)	e.g. High quality boiler feed water WA-H1-[i] (mm^3)

*Variable costs are combined with FOM costs to ensure that the model is committed to a particular scheme once selected. This is necessary because the varying construction time of individual water supply projects (schemes) and the demands that may occur.

Note: [i] ~ Region Identifier (e.g. A, B, etc) and ZAR = 2010 South African Rands.

scenarios of future water demands while energy planning conducted at a national level with aggregated forecasts [REF: technical report 1].

Therefore, data pertaining to regional water demand is adapted for inclusion in the SATIM-W model as follows:

- The energy sector components (e.g. coal mines, refineries, power plants, etc.) are subtracted as these are now incorporated in SATIM-W; and
- The remaining data is extrapolated and adjusted to approximate suggested values for the year 2050.

Figure 11 illustrates the resultant regional water demands as included in SATIM-W for the non-energy sectors.

The change in regional water demand is estimated from the uncertainty in the projected range in demand for each region [23] with a simple linear extrapolation applied to the 2050 value. Table 4 summarizes the climate change impacts on water supply and demand that are modeled for the four regions of interest and forms the basis for the Dry Climate scenario which is modeled.

Model Application

Figure 12 highlights key scenario and policy uncertainties that are believed to influence the decision process in the water-for-energy modelling framework outlined. These themes, identified by stakeholder consultation [50,51] explore the interaction of the various factors that would influence planning decisions in the energy supply sector from a water and energy perspective.

In this review, the key scenario factors and policy themes identified are summarized in Table 5 which is believed to

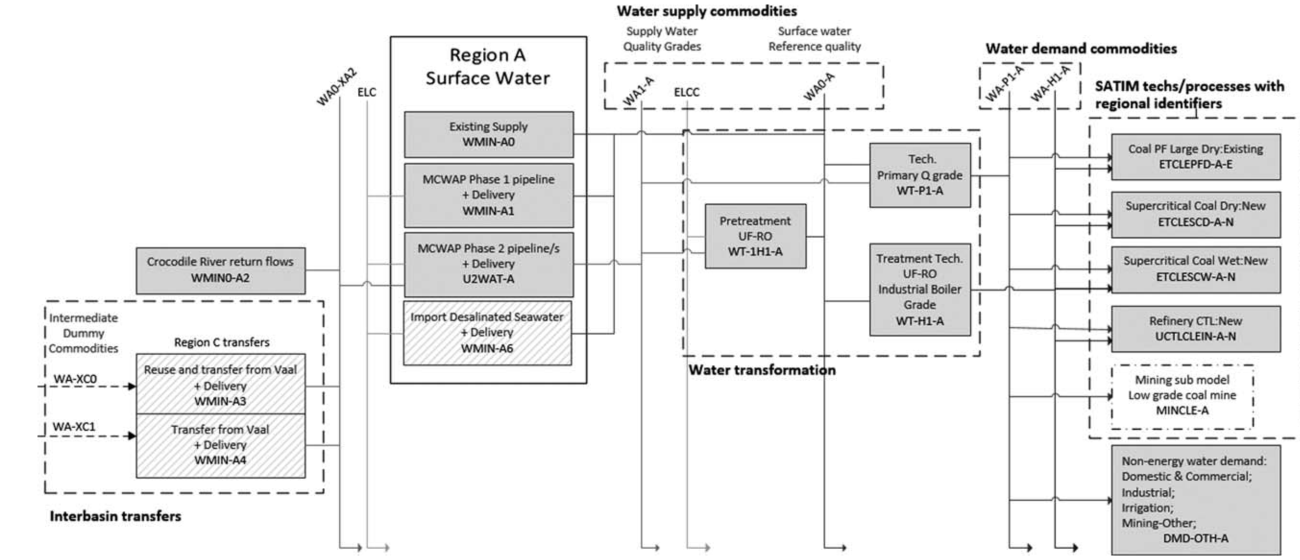


Figure 9. Incorporating water supply infrastructure in SATIM-W.

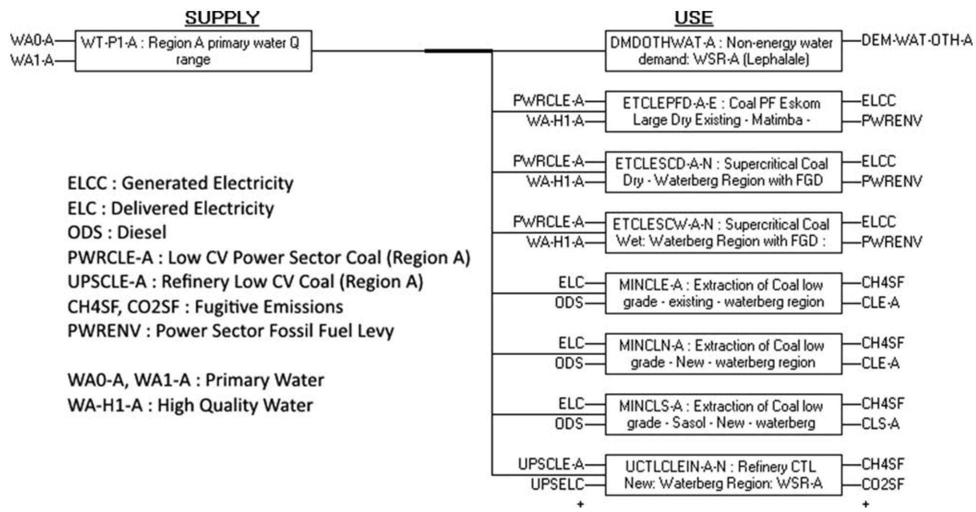


Figure 10. Water supply to regional technologies and processes in water supply region A.

highlight the main drivers of investment uncertainty in the context integrated energy supply planning in South Africa.

MODEL RESULTS AND DISCUSSION

Energy demand is driven by the technology rich full sector SATIM model based on economic forecasts and commodity price forecasts [35]. The SATIM-W model is applied and the reference scenario is contrasting with the case of not costing the water supply chain Figure 13. The most discernible observation is that while coal based electricity supply dominates the planning horizon, the preference for (closed-cycle) wet-cooling is replaced with a choice for dry-cooling.

The consumptive water intensity of coal plants decrease over time from 1.4 l/kWh to 0.4 l/kWh when water is costed compared to an increase 1.7 l/kWh in the non-costed case. The observed rise in water intensity in the period 2025 is due to the increased utilization of the existing wet-cooled power plants as a result of electricity supply constraints in the near term with no new generation available.

The increase in the average water intensity of electricity supply during the period 2045–2050 is because of the model preference for wet-cooling for CSP which is further elaborated in the discussion below. The choice between CSP and further exploitation of indigenous coal resources is seen to represent the heart of water-energy planning as investment decisions in limited water supply resources ultimately affect regional energy sector development.

Excluding the Waterberg (Region A), demand for water from the non-energy sectors is the main driver of new water supply infrastructure (Figure 14). The comparative demands of the energy supply sectors are especially dwarfed by the demand for water in the Orange River (Region D) and Upper Vaal (Region C) regions, largely because of agricultural activity in the Orange River and the expected growth in domestic and industrial demand in the Upper Vaal.

The Olifants (Region B) is the sole region to experience a decline in water demand because the existing wet-cooled power plants are predominately located in that region, and their retirement is responsible for the reduction in demand. Agricultural demand dominates in the region, accounting for approximately 50% of the total water requirement, while domestic and industrial demand use 30% of the total. A small

Table 3. Water consumption factors for key model processes and technologies per unit of energy production (mm^3/PJ).

Process/technology	Primary	Boiler feed
Coal PF Eskom Wet (cooled) Existing	0.610	0.027
Coal PF Eskom Dry (cooled) Existing	0.015	0.018
Wet-FGD process (retrofit)	0.056	
Supercritical Coal Dry New (FGD)	0.081	0.006
Supercritical Coal Wet New (FGD)	0.611	0.006
Combined Cycle Gas Turbine Dry (Wet NOx control)	0.005	0.002
Open Cycle Gas Turbine Dry (Wet NOx control)	0.006	0.000
Solar Parabolic Trough 0 storage Dry	0.075	0.006
Solar Parabolic Trough 3 storage Dry	0.077	0.006
Solar Parabolic Trough 6 storage Dry	0.078	0.006
Solar Parabolic Trough 9 storage Dry	0.079	0.006
Solar Parabolic Trough 0 storage Wet	0.812	0.006
Solar Parabolic Trough 03 hrs storage Wet	0.824	0.006
Solar Parabolic Trough 06 hrs storage Wet	0.838	0.006
Solar Parabolic Trough 09 hrs storage Wet	0.849	0.006
Solar Central Receiver 03 hrs storage Dry	0.080	0.006
Solar Central Receiver 06 hrs storage Dry	0.077	0.006
Solar Central Receiver 09 hrs storage Dry	0.077	0.006
Solar Central Receiver 12 hrs storage Dry	0.075	0.006
Solar Central Receiver 03 hrs storage Wet	0.593	0.006
Solar Central Receiver 06 hrs storage Wet	0.577	0.006
Solar Central Receiver 09 hrs storage Wet	0.573	0.006
Solar Central Receiver 12 hrs storage Wet	0.562	0.006
Solar-PV	~0 (negligible)	n/a
Wind	~0 (negligible)	n/a
Coal Supply (includes washing) Region-A (opencast)*	0.013	n/a
Coal Supply (includes washing) Region-B (mixed)*	0.010	
Shale-gas extraction	0.017	n/a
Crude-oil refinery	0.002	0.002
Refinery CTL	0.035	0.108
Refinery CTL FGD retrofit (Semi-Dry)	0.052	

*Assumes an average calorific value of 21 mJ/kg.

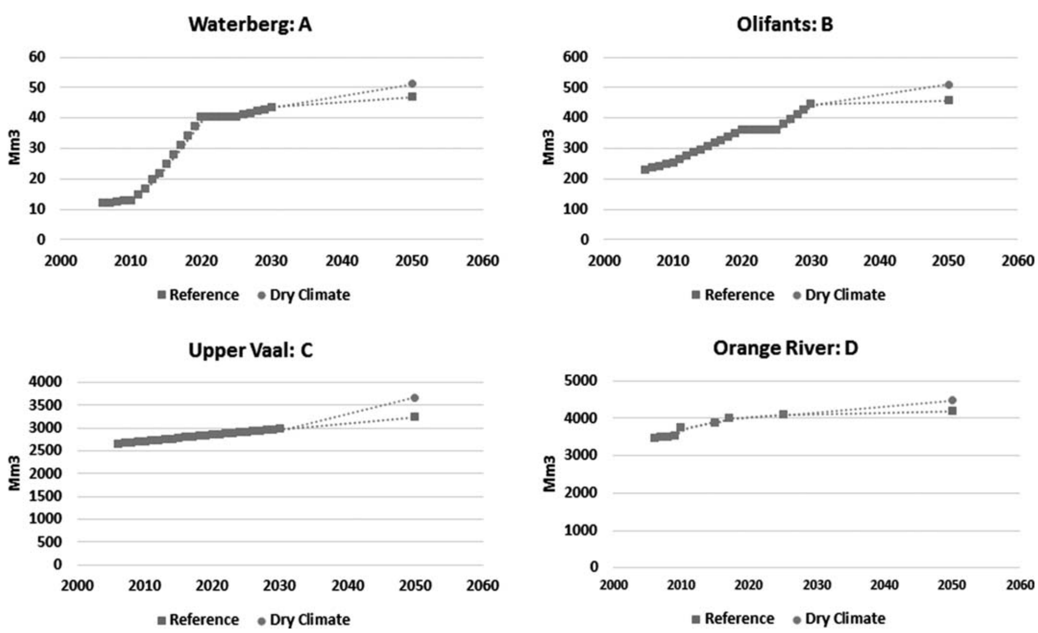


Figure 11. (a-d) Regional water demands for the aggregated non-energy sectors (reference and dry climate scenarios).

Table 4. Change in the average annual water demand and supply by region in 2050 [48,49].

WMA	SATIM-W WSR	DRY climate scenario	
		Water supply	Water demand
Waterberg	A	−2.0%	+8.9%
Olifants	B	−0.5%	+11.4%
Upper Vaal	C	+0.4%	+13.0%
Orange	D	+2.8%	+6.7%

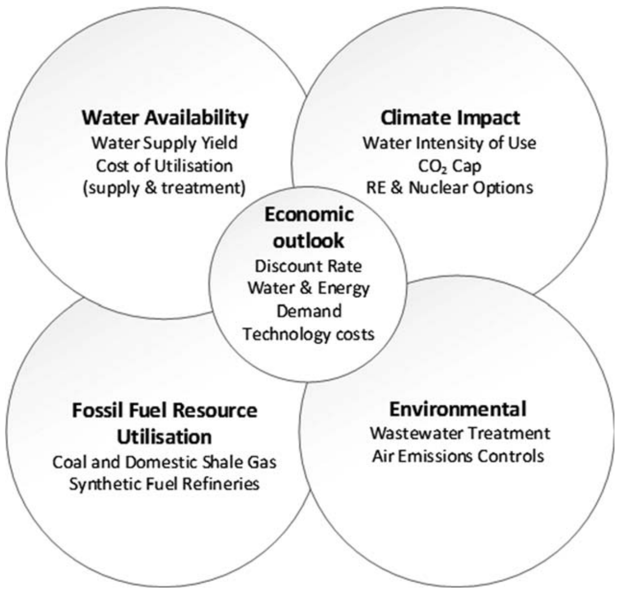


Figure 12. Scenarios themes exploring the water-energy nexus.

portion of the decline in water demand from the energy supply sector is because of the retirement of the existing CTL facility, and a migration of coal mining to the Waterberg from the period 2030–2035 as less-economic coal deposits are abandoned in the Olifants and Upper Vaal in favor of new expansion in the Waterberg region.

In contrast, more than 80% of future water supply to the Waterberg is attributed to the energy supply sector. Power generation directly accounts for 40% of this total. New CTL plants in the region would consume close to 20% of the water supply, while coal mines, assumed to practice wet-beneficiation, would total 25%. A sharp escalation in water demand in the Waterberg is experienced because of continued demand for coal and the preference for new coal plants to be built in this region. The magnitude of water demand is curtailed, as previously discussed, by the preference for dry-cooled coal power plants. This reduces the total water supply requirements for the region to a potential maximum of 260 mm3/year by 2050.

The contrast between the Waterberg and other regions in the annual investment expenditure required for bulk water supply is shown in the left portion of Figure 15. The regional expenditure for water supply infrastructure to reconcile projected demand is concentrated in the Waterberg. The right portion of Figure 15 provides a breakdown of the water conveyance infrastructure required in the Waterberg for water transfers to this arid and water scarce region. The additional supply options are facilitated by the interconnected regional system.

The lack of natural causeways in the vicinity of the Waterberg requires substantial investment in supply pipelines for inter-regional water transfers. This is evident in the relative sizes of the Phase-1 and Phase-2 supply schemes (Figure 15). The "Phase-2" supply schemes refer to multiple pipelines commissioned to meet local demand, whereas "Phase-1" relates to the investment in local pipeline infrastructure to fully utilize the existing local supply system. The additional investment required to establish the supply options, such as the transfer of return flows from the City of Johannesburg

Table 5. Summary of Scenarios Applied to the Model.

Scenario	Description
Reference (Water Costed) [50]	The reference scenario assumes a continuation of status quo planning with a planning horizon until the year 2050. It includes the cost of developing the necessary water supply infrastructure from source to consumer. Indigenous shale gas extraction is not pursued.
Shale gas [8]	Shale-gas extraction occurs in the Orange River region. A total of 40 Tcf of gas is estimated to be economically recoverable.
Dry climate [48]	Regional water supplies and the non-energy water demands in the Reference scenario are adjusted to reflect the possible effects of future climate change, affecting the unit water supply cost of regional schemes (Table C-1).
WaterQ [31]	Water quality of transfers from Regions B and C to Region A is lower than local supplies, requiring additional treatment costs for demineralized application (e.g. make-up water for boilers).
Environmental compliance [53–58]	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
CO_2 Cum Cap 14GT [9,18,50]	The imposition of "Peak-Plateau-Decline" INDC emission pathway, a carbon budget limiting cumulative national GHG emissions to 14 Gt by 2050.

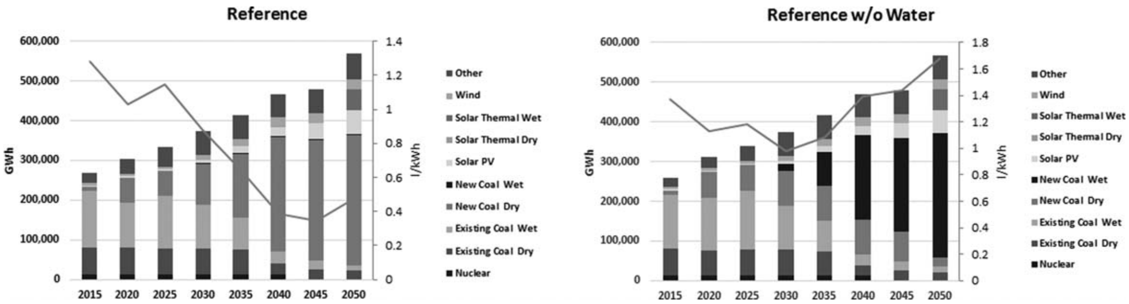


Figure 13. The average consumptive water intensity for national electricity supply.

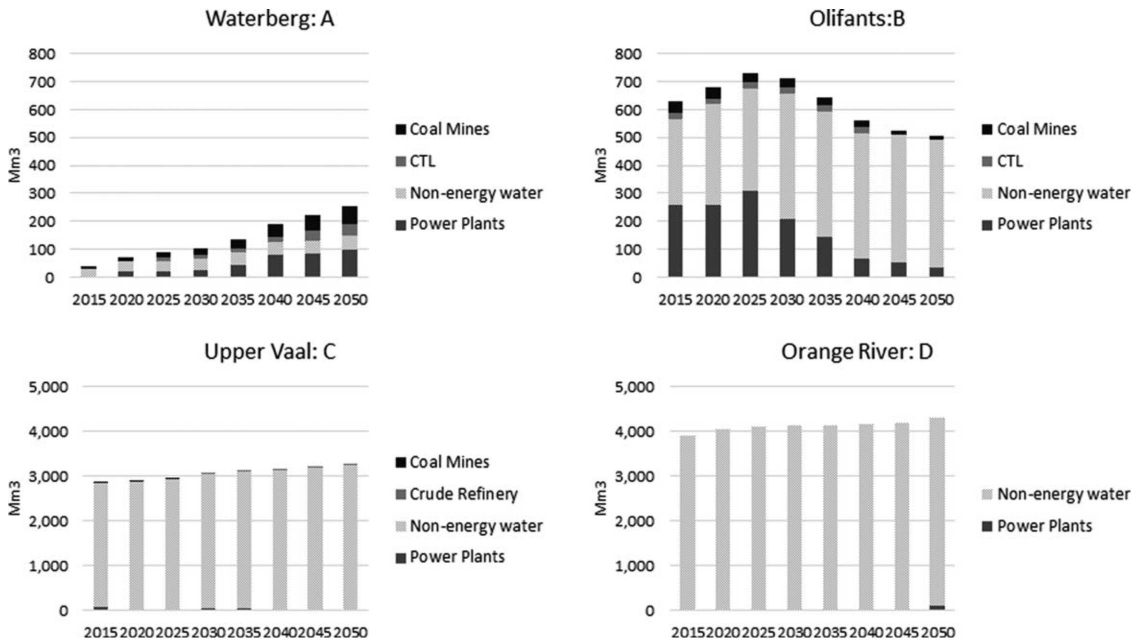


Figure 14. Regional water demands by supply sector – reference case (billions of litres: mm^3).

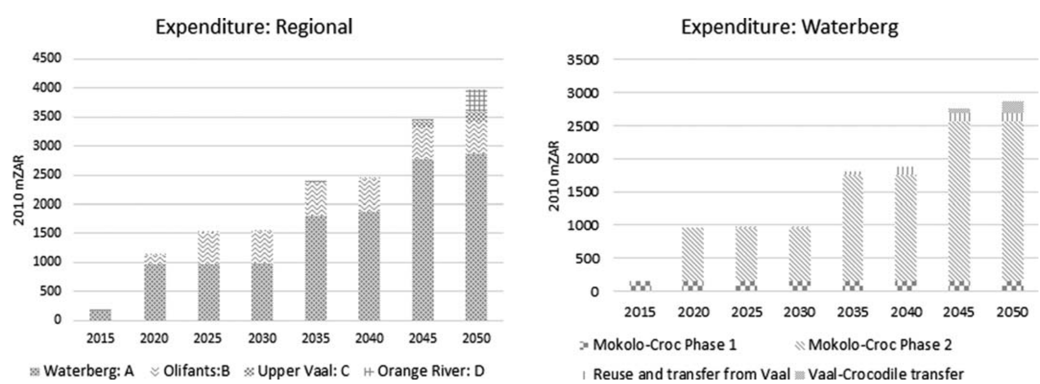


Figure 15. Annual investment in water supply infrastructure (millions of Rands 2010).

(i.e., reuse and transfer from Vaal), represent a much smaller expenditure.

This series of investments in water supply infrastructure will lead to a future of increased water supply costs. The Waterberg is the region where the cost of water can be expected to escalate dramatically should further growth in coal supply proceed unabated. Figures 16 and 17 show the annualized average unit cost of water supply in each region with the concordant lump sum investments in supply infrastructure respectively. For the Waterberg region, the peaks observed for the average water supply cost are due to the lump sum investment in pipelines for water transfers to the region. The peaks in the supply cost are observed as the newly commissioned water supply infrastructure is initially

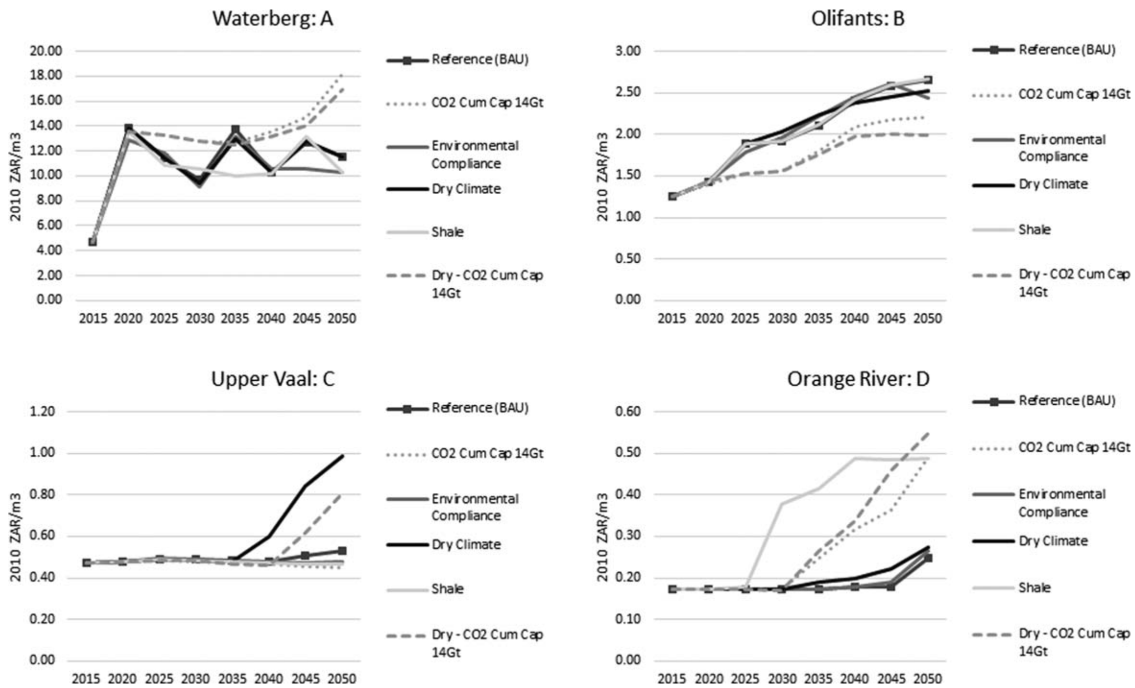


Figure 16. Projected regional average cost of water supply by scenario.

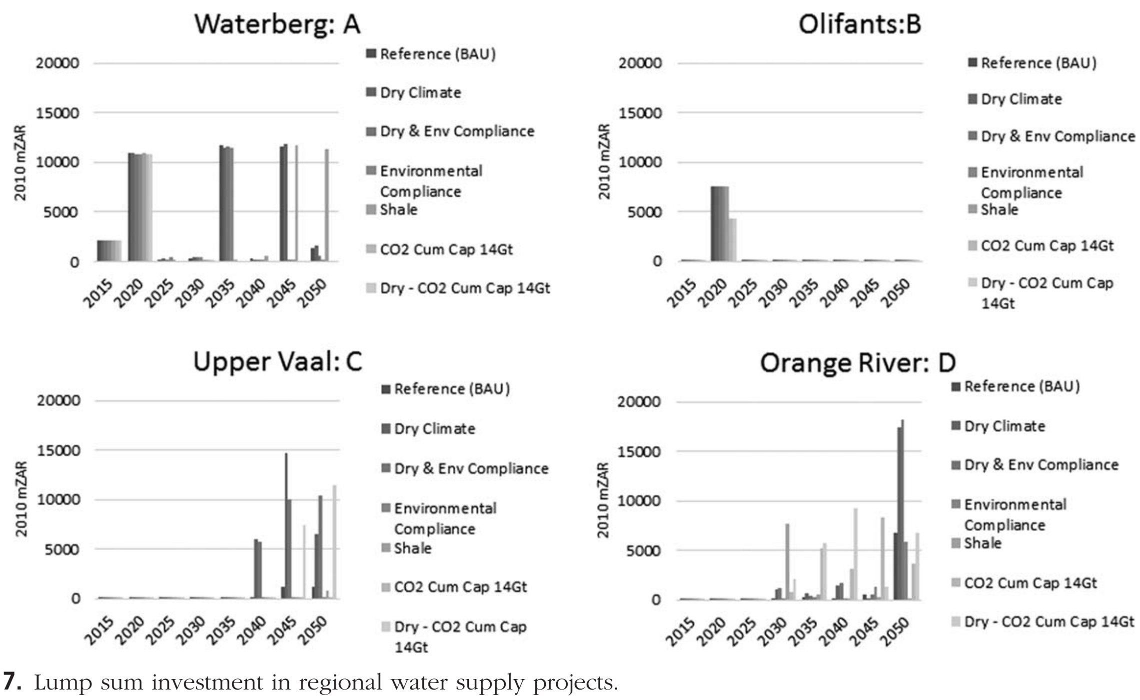


Figure 17. Lump sum investment in regional water supply projects.

underutilized, or operated at a low supply capacity. The unit water supply cost decreases with an increase in water volumes transferred until the existing supply capacity is reached, necessitating new investment for continued exploitation of coal in the Waterberg.

In contrast, the average supply cost for the other regions is not expected to experience a similar escalation. Non-energy demand is responsible for the rise in water supply cost to the Olifants. The resultant expenditure is because of additional water transfers from the Vaal River system with interim usage of treated acid mine drainage near 2020. The option of an additional dam in the Olifants is avoided. The average cost of water in the Olifants effectively doubles over the period from a base cost of R1.3/m^3. The base cost is derived from the existing weighted average tariff to power plants (weighted by generation), which regionally ranges from 50c to R4/m^3. The weighting is required as in this analysis power plants are not individually modeled, but represented by regional categories.

The Orange River region, with regard to water supply, is essentially an agricultural region. Due to the incremental demand for water in this region, the supply cost increases by

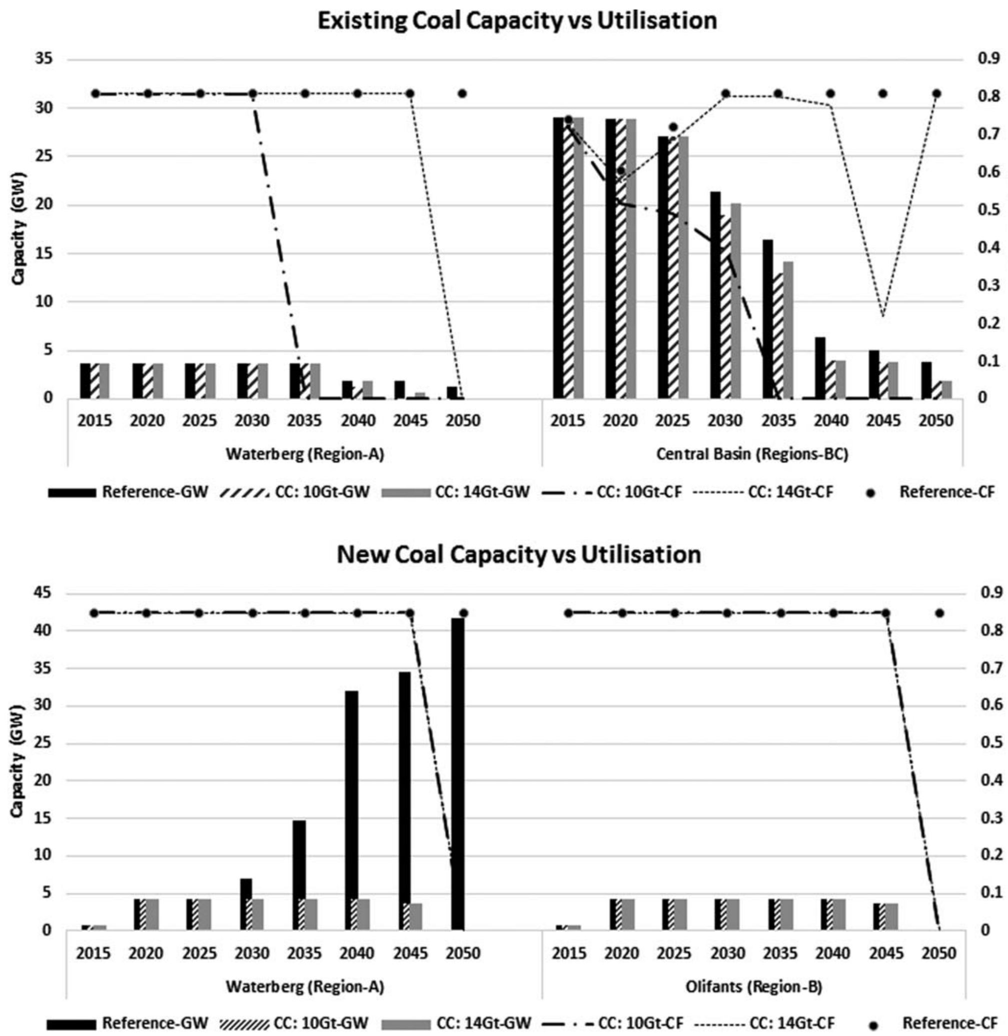


Figure 18. Capacity and utilization of coal power plants: Reference with carbon cap scenarios.

approximately 40% through to 2050, from a base of 17c/m^3 to 25c/m^3. The increase occurs from 2045 and is due to the increase in demand for wet-cooled CSP in this region.

In the Waterberg, the average supply cost of R4.70/m^3 in 2015 assumes a fully operational Phase-1 implementation. The cost is an approximate 700% increase to the existing local supply tariff of 60c/m^3 (2010 ZAR) for the existing local dry-cooled power plant.

A point of clarification is warranted when comparing the supply cost to the supply tariff, as the cost would not necessarily reflect the actual price paid via the tariff. The water supply tariff is usually structured on a 20 year cost recovery, after which a return-on-assets component is reflected. Furthermore, tariffs differ by consumer category. Agriculture and domestic consumers reliant on the local supply system would be subject to a lower supply tariff. Therefore, the average supply costs in this analysis are indicative of future water tariffs that may be required for timely investment in regional water supply infrastructure.

It is also important to note that currently the water demand from the non-energy sectors are included in aggregate, and modeled without consideration of sectoral water reallocation or demand reduction interventions. A refinement of the model incorporating the disaggregation of water demand from the non-energy sectors may therefore result in deferment of investment in regional water supply infrastructure as water-use efficiency and value-added usage improves.

Table 6. Share of electricity generation of RE and coal in the national supply mix.

	% RE			% Coal		
Scenario	**2015**	**2030**	**2050**	**2015**	**2030**	**2050**
Reference	**6%**	**7%**	**23%**	**83%**	**76%**	**67%**
SATIM	6%	7%	22%	85%	76%	68%
Shale	6%	4%	8%	83%	66%	51%
Dry climate	6%	7%	24%	83%	76%	65%
Environmental compliance	6%	7%	27%	83%	76%	61%
Dry & Env. compliance	6%	7%	27%	83%	76%	60%
CO2 Cum Cap 14GT	6%	13%	68%	82%	70%	7%

However, since investment in the Waterberg is dominated by the requirement for the conveyance infrastructure and water demand is primarily for energy supply, it is doubtful whether such further consideration would significantly affect investment requirements in this region.

Carbon Cap scenarios produce the highest water costs in the region of new coal-intensive energy supply (Waterberg) as commissioned water supply infrastructure is potentially underutilized reflecting higher unit supply costs as no new coal power plants are commissioned in these scenarios (Figure 16). The vulnerability of economically stranded water-energy infrastructure is also highlighted as stricter carbon mitigation policies (e.g. a 10 Gt Carbon Budget) would require additional coal capacity to remain unused thus demonstrating the benefit of integrated water-energy supply planning (Figure 18) [52].

Existing coal power plants remain operational over their technical life for the 14 Gt scenario as shown in the figure despite the highly variable utilization from 2040 onwards. Of note, the retirement of existing wet-cooled plants provision new dry-cooled plants with adequate water supply (Figures 14 and 18). As previously discussed, the increasing trend in the average cost of water in the Olifants region is because of the increasing demand for water from the non-energy sectors, and this remains true across all scenarios.

The observed increase in the supply cost of water in the Orange River region under Carbon Cap is because of a shift towards CSP investment away from coal as evidenced in Table 6 which displays the generation share of electricity for RE and Coal in the national supply mix. Similarly, in the Orange River shale gas extraction region would also see an increase in local water supply costs as continued investment in the shale gas energy sector would necessitate a regional water supply pipeline assuming a restriction on local groundwater usage (Figure 19).

Shale gas extraction and exploitation would also defer investment in new coal and renewable energy options.

The Environmental Compliance scenario primarily requires the retrofit of SO_2 (FGD) to existing coal plants and existing and new CTL refineries as well. New coal plants are required to have FGD incorporated.

Environmental compliance in this context has minimal impact on energy supply investment with the curtailment of new coal investment late in the planning period in the Waterberg (Figure 20) in the order of 6 GW. The Dry Climate scenario actually sees an increase in new plant build in this region as competing demand for water in the neighboring Olifants region by the non-energy sector results in the early

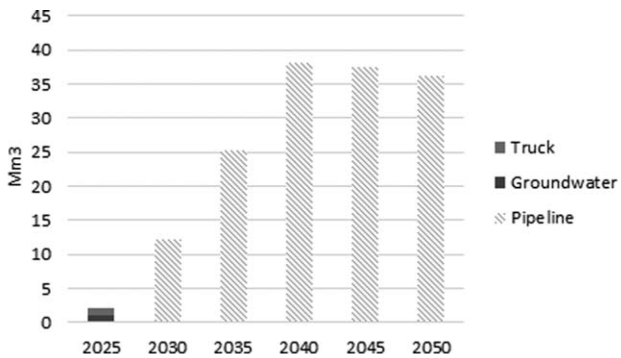


Figure 19. Mode of water delivery for shale gas extraction.

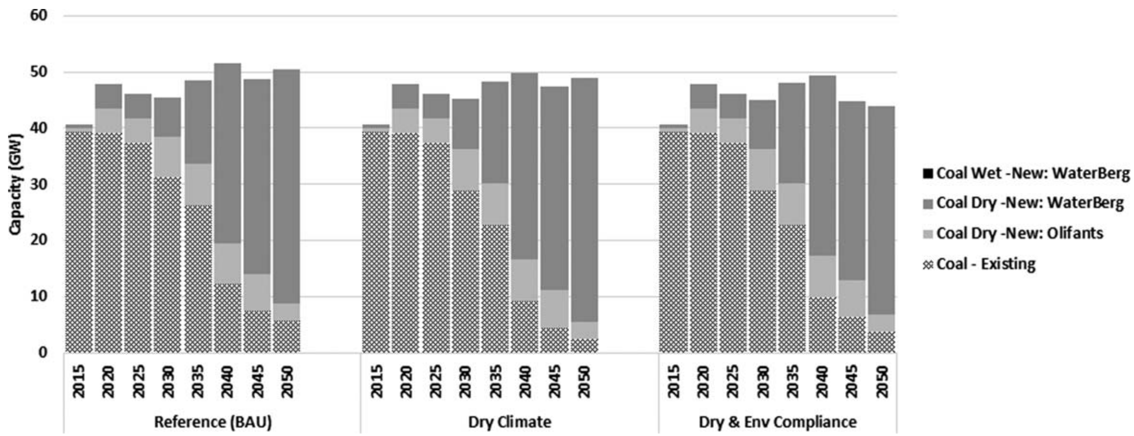


Figure 20. Capacity of coal power plants under a dry climate and with stricter environmental operating conditions.

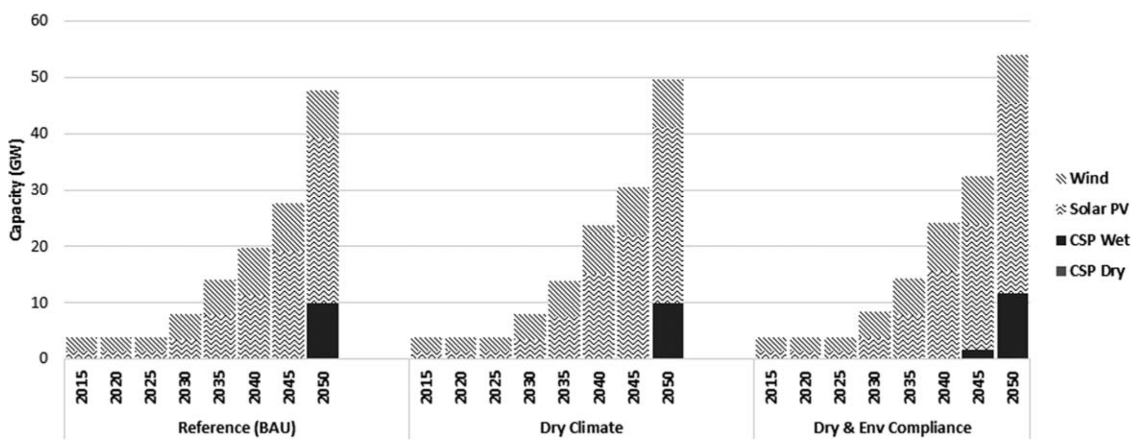


Figure 21. Capacity of RE power plants under a dry climate and with stricter environmental operating conditions.

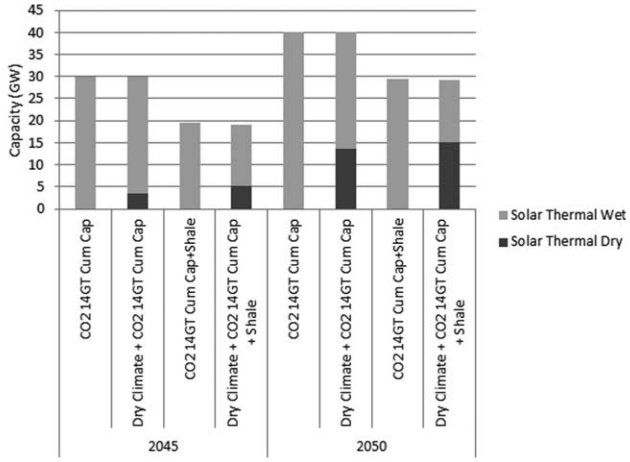


Figure 22. Installed capacity of solar thermal power plants (CSP) by cooling method.

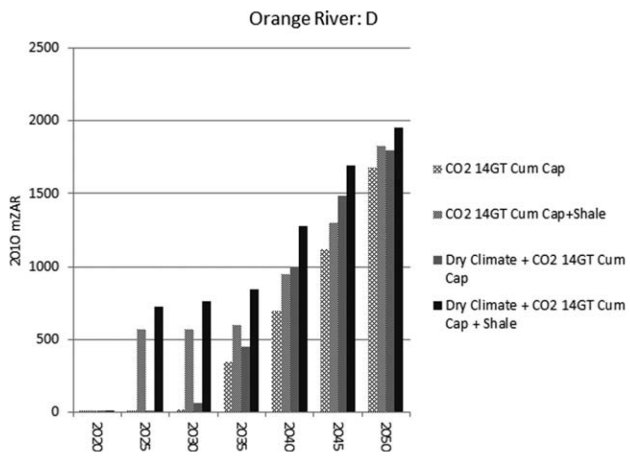


Figure 23. Annualized investment in water infrastructure (2010 mZAR).

retirement of ~ 3 GW of existing coal power plants. This capacity is replaced in the Waterberg.

For new coal power plants, dry-cooling rather than wet-cooling is opted for in the coal supply regions where the cost of water and is highest. Unlike new plants which are dry cooled, the existing plants are water-intensive wet-cooled and therefore we note a decrease in water supply cost in the Olifants for the Dry Climate scenario.

With the exception of commissioned dry-cooled CSP, closed-cycle wet-cooled CSP is preferred in the Orange River (Figure 21). With lower investments costs and higher generation efficiencies for wet-cooled CSP plants, the lower cost of water in this region compared to the Waterberg is insufficient to motivate for dry-cooled options. Furthermore an increase in Solar-PV capacity (~ 5 GW) in the Dry Climate with Environmental Compliance scenario also occurs.

However when considering the Dry climate and Carbon Cap scenarios, the additional water supply required to support continued growth in CSP results in a preference for a mix of dry-cooled and wet-cooled CSP (Figures 22 and 23).

CONCLUSIONS

In South Africa, given the tandem existing supply constraints for both water and energy, the value of the model, as demonstrated, is the ability to factor regional disparities of cost and availability of water supply infrastructure into a least cost expansion of an energy supply system.

Infrastructure projects typically have lengthy commissioning periods and the model highlights the dependency on key water supply projects by potential new energy supply projects. Specifically the model suggests that:

- The Waterberg (Region A) is the key water-energy region of concern in South Africa
- Energy supply choices influenced by water cost and quality
- The integrated water supply network is climate resilient
- The risk for stranded water supply infrastructure exists
- Dry cooling for power plants is an optimal hedge against uncertainties in demand for energy and water, climate change and policy choices

It is noted though that further work is required to include an endogenous representation of the non-energy sector demands for water and the potential for reallocation of supply from different sectors. However the previous discussion has demonstrated the value and flexibility of a strategic energy planning tool that incorporates water supply as an integral model component. Complementary water resources modelling which informs water supply planning provides the foundation for a tool which economically allocates water resources to regions of energy supply and therefore improves policy choices that aim to sustainably management both water and energy resources.

Furthermore, a national-level energy systems optimization model that considers regional disparities of water supply and demand is adaptable to other countries. A water-integrated energy sector planning tool that optimizes energy supply by considering, for example, whether to:

- Expand coal supply for energy under stricter environmental operating conditions that account for the treatment of liquid effluent from coal mines and the inclusion of water-consuming flue-gas desulphurization;
- Invest in additional water treatment plants to address poor regional water quality;
- Invest in dry or wet-cooled generation; or
- Transport washed coal to coastal regions utilising existing and/or new rail export infrastructure where cheaper and more efficient open-cycle seawater cooled powerplants (with SO_2 scrubbing) can be exploited.

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NOMENCLATURE

2010 mZAR	Millions of 2010 Rands
AMD	Acid mine drainage
CF	Capacity factor
CSP	Concentrated solar (thermal) power
CTL	Coal-to-liquid fuels
INDC	Intended nationally determined contributions
FGD	Flue gas desulphurization
GW	Giga watts
m^3	Cubic meter (1000 litres)
Mm^3	Mega cubic-metre (1 billion litres)
RE	Renewable energy
RES	Reference energy system
REWS	Reference energy water system
Region-A	Waterberg
Region-B	(Upper) Olifants
Region-C	Vaal

Region-D	(Upper) Orange
SATIM	South Africa TIMES (model)
SATIM-W	South Africa TIMES Water (model)
TIMES	The Integrated MARKAL-EFOM System
WSR	Water supply region
WMA	Water management area

REFERENCES

1. DWA (2013), National Water Resource Strategy: Water for an Equitable and Sustainable Future, June 2013, Pretoria, South African Department of Water Affairs. Available Online: **https://www.dwa.gov.za/nwrs/LinkClick.aspx?fileticket=CIwWyptzLRk%3D&tabid=91&mid=496**
2. International Energy Association (2014), Energy Balance for South Africa [Online], Available: **http://www.iea.org/Sankey/#?c=South** Africa&s=Balance, Paris.
3. STATSSA (2017), Poverty Trends in South Africa: An examination of absolute poverty between 2006 and 2015, Pretoria, Statistics South Africa
4. DWA (2008), *Water for Growth and Development in South Africa: Version 6*, Pretoria, Department of Water Affairs
5. Jordaan, H. & Grove, B. (2012), An *economic analysis of the contribution of water use to value chains in agriculture, Report No. 1779/1/12,* Pretoria, Water Research Commission.
6. WRC (2014), *Parched prospects: The emerging water crisis in South Africa*, The Water Wheel, December 2014, Pretoria, Water Research Commission.
7. Von Bormann, T. & Gulati, M. (2014), *The Food Energy Water Nexus: Understanding South Africa's most urgent sustainability challenge*. WWF-SA, South Africa.
8. NPC (2012), *National Development Plan 2030, Our Future - Make it Work (Executive Summary)*, National Planning Commission, Department in The Presidency, Pretoria: Government Printer, Available Online: **http://www.gov.za/issues/national-development-plan-2030**
9. DEA (2015), *Discussion Document South Africa's Intended Nationally Determined Contribution (INDC)*, August 2015, Pretoria, South African Department of Environmental Affairs. Available Online: **https://www.environment.gov.za/sites/default/files/docs/sanational_determinedcontribution.pdf**
10. DEA (2013), *National Environmental Management Air Quality Act 39 of 2004 - Regulations and Notices - Government Notice R893*. Pretoria: Government Printer
11. Grenon, M. & Lapillonne, B. (1976), *The WELLM Approach to Energy Strategies and Options,* Vienna: International Institute for Applied Systems Analysis (IIASA), RR-76-19.
12. Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, R.S.J., & Yumkella, K.K. (2011). *Considering the energy, water and food nexus: Towards an integrated modelling approach*, Energy Policy, 39, 7896–7906. pp
13. Marsh, D. (2008) *The water-energy nexus: a comprehensive analysis in the context of New South Wales*, Phd, Australia, Sydney University of Technology.
14. Friedrich, E., Pillay, S., & Buckley, C.A. (2009). *Carbon footprint analysis for increasing water supply and sanitation in South Africa: a case study*, Journal of Cleaner Production, 17, 1–12.
15. Colvin, C., Burns, A., Schachtschneider, K., Maherry, A., Charmier, J., & de Wit, M. (2011). *Coal and Water Futures in South Africa The case for protecting headwaters in the Enkangala grasslands*, South Africa, World Wildlife Fund-South Africa (WWF-SA).
16. Xu, X., Gao, J., Cao, G., Yurii, Y., Tatiana, E., & Rovenskaya, E. (2015). *Structure Model of China Coal* Production and Water Challenging, 34th International Energy Workshop, Abu Dhabi, U.A.E.
17. Goga, S. & Pegram, G. (2014). *Water, energy and food: A review of integrated planning in South Africa, Understanding the Food Energy Water Nexus*, South Africa, World Wildlife Fund-South Africa (WWF-SA).
18. DOE (2013), *Integrated Resource Plan for Electricity (IRP) 2010 – 2030 Update Report 2013*, 21 November 2013, Pretoria, South African Department of Energy (No longer publically available – copy available on request).
19. DOE (2013), *Draft 2012 Integrated Energy Planning Report - Executive Summary (For Public Consultation),* June 2013, Pretoria, South African Department of Energy.
20. DWA (2010), *Assessment of the ultimate potential and future marginal cost of water resources in South Africa*, DWA Report No. P RSA 000/00/125610. Department of Water Affairs, Pretoria, South Africa, September 2010.
21. DWAF (2010) Integrated Water Resource Planning for South Africa: A Situation Analysis, Report Number: P RSA 000/00/12910, Department of Water Affairs & Forestry, Pretoria, South Africa.
22. Wright, J., Bischof-Niemz, T., Calitz, J., Mushwana, C., van Heerden, R. & Senatla, M. (2017). *Formal comments on the Integrated Resource Plan (IRP) Update Assumptions, Base Case and Observations 2016*, April 2017, Pretoria, The Council of Scientific and Industrial Research (CSIR).
23. Aurecon (2014), *Modelling the Water Energy Nexus in South Africa Task 1 Report: Development of Regional Marginal Water Supply Cost Curves*, Document prepared by: James Cullis and Nicholas Walker, Aurecon South Africa (Pty) LTD, 22 September 2014 Available online: **http://energydata.uct.ac.za/dataset/water-energy-nexus-reports**
24. Golder Associates (2010), *Environmental Impact Assessment for the Anglo American thermal coal proposed expansion of the eMalahleni mine water reclamation scheme*, South Africa: Golder Associates.
25. Golder Associates (2012) *Conceptual Study - Supply of Reclaimed Mine Water from the Mpumalanga Highveld Coalfields*, South Africa, Golder Associates.
26. Gunther, P. & Mey, W. (2008). *Selection of mine water treatment technologies for the eMalahleni (Witbank) Water Reclamation Project*, *WISA Biennial Conference*. May 2008.
27. Martin, B. & Fisher, T. (2012). *The energy-water nexus: Energy demands on water resources*, South Africa, Environmental Monitoring Group (EMG).
28. Maherry, A., Nel, J., Botha, M. (2012). South Africa's water supply areas: Development of NFEPA High Water Yield Areas and future refinement needs, Pretoria, Council Scientific and Industrial Research, Available online: **http://biodiversityadvisor.sanbi.org/wp-content/uploads/2012/09/06-Development-of-NFEPA-high-water-yield-areas-Maherry.pdf**
29. Energy Research Centre. (2013). *Assumptions and Methodologies in the South African TIMES (SATIM) Energy Model*, [Online], Available: **http://www.erc.uct.ac.za/groups/esap/satim**
30. International Energy Association. (2011). Overview of TIMES Modelling Tool, [Online], Available: **http://www.iea-etsap.org/web/Times.asp**
31. Eskom. (2008). *Water Quality Impacts on Eskom*, Sandton: Eskom
32. Pulles, W., Boer, R. H., & Nel, S. (2001). *A generic water balance for the South African coal mining industry*, Pretoria: Water Research Commission
33. Kgole, M. (2014). *Eskom Power Station Data*, Personal Communication, April 2014.

34. Electric Power Research Institute. (2012). *Power Generation Technology Data for Integrated Resource Plan of South Africa*. Palo Alto.
35. Pearce, K. & Whyte, D. (2005). *Water and wastewater management in the oil refining and re-refining industry*. Pretoria: Water Research Commission
36. Ras, C. (2011). *An industrial ecology approach to saltrelated environmental sustainability issues in a large industrial complex*, Cape Town: University of Cape Town.
37. Savannah Environmental. (2013). *Final Scoping Report; Proposed Construction of Phase 2 and Phase 3 of the Upington Solar Thermal Plant, Northern Cape Province*, South Africa: Savannah Environmental.
38. Shaw, G. (2012). *Gas to Liquid Technologies*. Cape Town: PetroSA.
39. Goyns, P. (2013). *Water related costs for power plants*. Personal Communication.
40. SASOL. (2014). *Technical Appendix: Draft Motivation for Exemption from default application of certain Minimum Emissions Standards in terms of Section 59 of NEM:AQA*. Johannesburg: SASOL.
41. Black & Veatch (2012), *Cost and performance data for power generation technologies: prepared for the NREL*. Black & Veatch
42. Zhai, H. & Rubin, E. (2010). *Performance and cost of wet and dry cooling systems for pulverized coal power plants with and without carbon capture and storage*, Energy Policy, 38, 5653.
43. Klett, M.G., Kuehn, N.J., Schoff, R.L., Vaysman, V., White, J.S., & Rutkowski, M.D. (2007). *Power Plant Water Usage and Loss Study*, Department of Energy (USA), National Energy Technology Laboratory.
44. Poullikkas A., Hadjipaschalis I., & Kourtis G. (2013). *A comparative overview of wet and dry cooling systems for Rankine cycle based CSP plants*, Trends in Heat & Mass Transfer, 13, 27.
45. Nicot, J.P., & Scanlon, B.R. (2012). *Water use for shale-gas production in Texas*, USA. Environmental Science & Technology, 46, 3580.
46. Martínez, D.Y., Jiménez-Gutiérrez, A., Linke, P., Gabriel, K.J., Noureldin, M.M.B., & El-Halwagi, M.M. (2014). *Water and energy issues in gas-to-liquid processes: Assessment and integration of different gas-reforming alternatives*, ACS Sustainable Chemistry & ENGINEERING, 2, 216.
47. Ahjum F. (2014). *Development of the "water smart" SATIM-W model. Modelling the water-energy nexus in South Africa: Development of a national water-energy system model with emphasis on the Power Sector*. Task 2: Phase 1. September 2014. South Africa, Energy Research Centre. Available online: **http://energydata.uct.ac.za/dataset/water-energy-nexus-reports**
48. DEA (2014), *The Economics of Adaptation to Future Climates in South Africa. An integrated biophysical and economic analysis*. Report No/6 for the Long Term Adaptation Scenarios Flagship Research Program. Department of Environmental Affairs, Pretoria, South Africa, July 2014
49. Cullis JDS, Stzepek KM, de Jager G, & Chang A (2014) "Water Resources Modelling to Support an Assessment of the Economic Impacts of Climate Change in South Africa" Hydrology and Water Resources Symposium 2014. Perth, Australia 24–27th February 2014
50. Merven, B. & Durbach, I. (2015). *Obtaining long-term forecasts of the key drivers of greenhouse gas emissions in South Africa*, Energy Research Centre, University of Cape Town.
51. Various (2015), *Stakeholder and conference presentations made on the findings of the study*. Available online: **http://energydata.uct.ac.za/dataset/water-energy-nexus-dissemination**
52. Burton, J., Caetano, T., Hughes, A., Merven, B., Ahjum, F., McCall, B. (2016). *The impact of stranding power sector assets in South Africa: using a linked model to understand the economy-wide implications*. Energy Research Centre, University of Cape Town. Cape Town Available online; **http://www.erc.uct.ac.za/sites/default/files/image_tool/images/119/Papers-2016/2016-Burtonetal-Impact_stranding_power_sector_assets.pdf**
53. Singleton, T. (2010). *The decision to install flue gas desulphurisation on Medupi Power station: identification of environmental criteria contributing to the decision making process*. Johannesburg: University of the Witwatersrand
54. Eskom. (2012). *Practical Considerations in the Implementation of Emissions Reduction Solutions at Eskom's Coal Fired Power Plant*, presentation at 4th EU-SA Clean Coal Technologies Working Group Meeting, Emperor's Palace, Kempton Park, RSA, 6 November 2012 accessed from: **http://www.energy.gov.za/files/4thEUSouthAfricaCleanCoalWorkingGroup/Practical%20Considerations%20in%20the%20Implementation%20of%20Emissions%20Reduction%20Solutions%20in%20SA%20Coal%20Fired%20Power%20Plant%20Final.pdf**
55. Eskom. (2014). *Title: Implementation of De-SOx Technologies in an Eskom Context*, Presentation by Candice Stephen, 5 May 2014, accessed from: **http://www.crses.sun.ac.za/files/services/conferences/eppei-conference/session3a/Candice%20Stephen.pdf**
56. Hutton B., Kahan I., Naidu T., & Gunther P. (2009). *Operating and maintenance experience at the eMalahleni water reclamation plant. International Mine Water Conference,* 19 – 23 October, South Africa: International Mine Water Association
57. Johansson L. (2012). *Different aspects to consider selecting FGD type of technology. Power-Gen India & Central Asia*, April 2012, France: Alstom
58. Lebalelo Water User Association. (2012*). Proposed Oliphants river mine water scheme: water supply to middle Oliphants river area*, South Africa: *Lebalelo Water User Association*.