Development of the "water smart" South Africa TIMES model: SATIM-W

Modelling the water-energy nexus in South Africa: development of a national water-energy system model with emphasis on the Power Sector.

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Abstract

The South Africa TIMES (SATIM) energy model is a single region national supply and demand representation of energy commodity flows developed by the Energy Research Centre. The model was further adapted to incorporate existing and future marginal costs of regional water supply infrastructure. The resultant South Africa Energy–Water model (SATIM-W), required the single region model to establish water supply regions for areas of interest where potentially new development in the energy supply sector is likely. This required a spatial representation in SATIM-W of technologies and processes such as power plants, refineries and other energy processes as well as coal and shale gas extraction in order to link water consuming activities to specific water supply regions and water delivery schemes. The model further allows concerns of water quality to be investigated by incorporating different water commodities and the associated costs to remediate water with low utility value.

SATIM-W demonstrates the value of incorporating the alternatives and costs of developing new water supply and treatment infrastructure when considering: the impact of water availability in regions of water scarcity; competition for available water resources from other sectors; and augmenting existing supplies with poorer quality water sources to realize a comprehensive framework able to examine the energy-water nexus tradeoffs. It is shown that investment choices in energy supply are indeed influenced by considerations of regional water resources availability and cost.

List of acronyms

AMD	Acid Mine Drainage
CSP	Concentrated Solar Power
CTL	Coal-to-Liquids
DoE	Department of Energy
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
FGD	Flue Gas Desulphurisation
FT	Fischer-Trospch
GTL	Gas-to-Liquids
m^3	Cubic metre
PF	Pulverised Fuel
PJ	PetaJoule
OM	Operations and Maintenance
RES	Reference Energy System
REWS	Reference Energy-Water System
RO	Reverse Osmosis (Desalination)
SATIM-W	South African TIMES Water-Energy model
Tcf	Tera cubic feet
TDS	Total Dissolved Solids
UF	Ultra-Filtration
UWC	Unit Water Cost
WMA	Water Management Area
WSR	Water Supply Region
ZAR	South African Rand (R)

1 Introduction

In common with many developing countries, South Africa faces a convergence of infrastructure deficits that is increasingly strained by a growing population and maintenance shortfalls. The situation is only exacerbated by the rapid urbanisation of the population requiring effective sustainable planning to maximise the utility of limited resources (Adams,1992;CSIR,2010;Davies,2012;Taylor,2012).

The linkage between energy and water has been widely publicised and the term water-energy nexus has found widespread common currency. Water and energy are strongly linked through their supply chains and due to the similarity of the nature of water and energy supply, the commodities can be analysed by similar methodologies. Modelling in particular, offers the potential to provide useful support to decision makers and planners of infrastructure looking to ensure security of supply. Recognize this critical connection the World Bank has embarked on a Thirsty Energy[1] initiative, sponsoring modelling teams in South Africa and China to spearhead this groundbreaking work.

Attempts to integrate energy and water in planning have a relatively long history in South Africa, mostly arising from water security concerns. The country's first foray into dry-cooling for coal thermal power plants occurred in the late 1960s with two indirect dry-cooled units added to the Grootvlei power plant to investigate dry-cooling as an alternative to wet-cooled systems (Lennon,2011). As a result, to date, approximately 30% of existing coal thermal power plants are of dry-cooled design with the commissioning of the new Medupi and Kusile powerplants increasing the dry-cooled portfolio to almost half the stock. In addition to the actual volumes of water available, attention has increasingly been directed to the quality of water available which impacts its utility value. The Council for Scientific and Industrial Research (CSIR) has stated that:

'*the biggest threat to sustainable water supply in South Africa is not a lack of storage but the contamination of available water resources through pollution*' (CSIR,2010).

Degraded water sources have a direct detrimental effect not only on aquatic ecosystems, but have a far wider impact on the environment and economy as more energy-intensive, predominantly electricity dependent, treatment is required to remediate raw water for productive use. This has the effect of both increasing energy consumption for water utilisation and its subsequent cost. Electricity derived from mined coal further accelerates the pollution-treatment cycle most notably from the contamination of water sources from acidic leachate - commonly referred to as Acid Mine Drainage (AMD) - from mined coal fields with concomitant long term economic and environmental ramifications.

The expansion of water services infrastructure to meet growing demand in a future of increasing environmental and energy constraints requires the consideration of alternative water supply and treatment options as the capacity of the present system is reached. A framework for integrated water-energy analysis as presented in this document is to be implemented as the South Africa TIMES Energy-Water (SATIM-W) model, providing a tool that offers insight into the trade-offs that exist when accounting for the linkages between water and energy systems as part of cost-effective sustainable planning.

[1] http://www.worldbank.org/en/topic/sustainabledevelopment/brief/water-energy-nexus

1.1 The South African TIMES model (SATIM) and its current representation of water

In its current form, SATIM is a single region national representation of energy commodity flows, energy transformation technologies and the incurred costs. For example, the extraction, transmission and distribution of gas and coal their transformation to electricity, the transmission and distribution of that electricity and the use of that electricity by end-use technologies to supply energy services are represented by technologies linked by commodities and characterised by associated efficiencies, costs, plant life and other techno-economic parameters.. Technologies are further organised by sector (e.g. the Power Sector) and type (e.g. large existing coal plants).

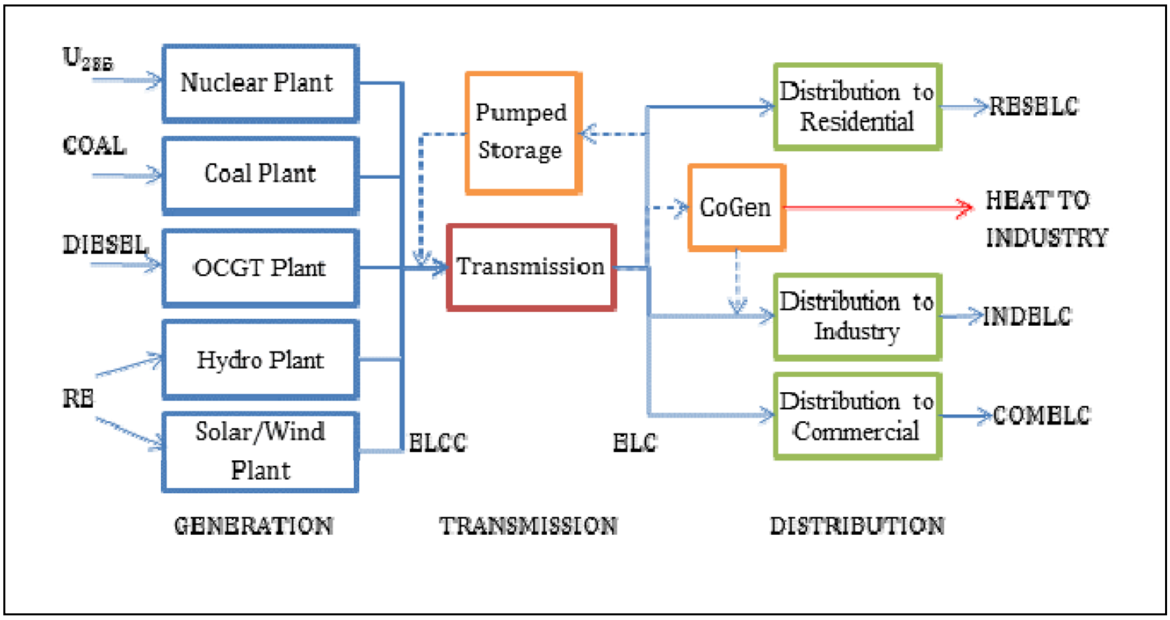

Figure 1 Simplified representation of the power sector in SATIM.

Currently SATIM is configured for two modes of representing the national energy system. In a simplified representation, electricity supply, referred to as the Power Sector, is modelled with an aggregated national demand for electricity. In the more detailed full sector configuration, attention is paid to the growth in demand for electricity and other commodities at the subsector level as is shown schematically in (e.g. electricity demand by the Pulp and Paper sub-sector in Industry). Referring to Figure 1, the Power Sector is divided into three main sections: Generation; Transmission; and Distribution. Electricity is dispatched via a central transmission system that in turn links to distribution nodes for each sector. In the Power Sector configuration, distribution costs and losses are also aggregated. The cost of transmission is therefore uniform for the system while that of distribution can be sector dependent.

In SATIM commodity supply is described by the Supply Sector and includes technologies and processes such as, imports, crude oil refineries and indigenous resource extractive such as coal mining.

The modelling of water consumption and of its transformation within SATIM had received little attention. At present only water consumption by the Power Sector is represented by including the water use intensity of power plants. The implementation did not consider regional disparities in water supply and costs and does not include auxiliary water usage by non-electricity generation technologies such as coal mining. In SATIM water is currently modelled as an accounting flow from the system similar to emissions such as CO_2. The existing representation of a wet-cooled power station is shown in Figure 2. The activity consumes low grade thermal coal (PWRCLE) and produces electricity at the plant gate (ELCC) requiring transmission. The figure depicts the consumptive water flow from the system (PWRWAT) and the environmental levy (PWRENV). The levy, currently set at ZAR 2c/kWh, applies to non-renewable energy sources and contributes to the national Demand Side Management programme.

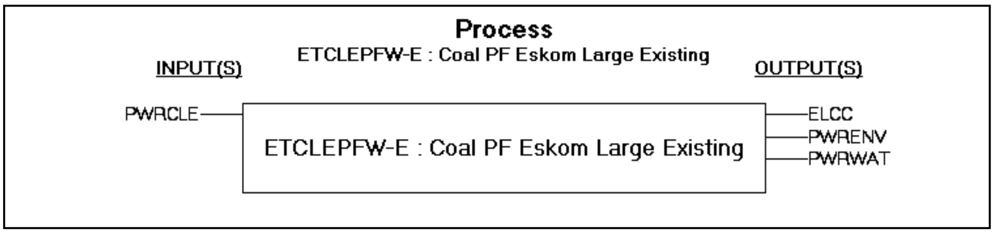

Figure 2: SATIM representation of an existing wet-cooled power plant.

Incorporating a regional cost and quality for water allows the model to examine potential trade-offs within the Power Sector by fully accounting for the cost of electricity generation associated with water consumption arising from:

- Fuel extraction and processing (e.g. coal-washing);
- The consumption and treatment of water for the cooling and steam circuits in thermal plants;
- The possible 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 like flue gas desulphurisation (FGD) that require water.

2 Scope and Objectives

The focus of this study is that of the energy supply sector and referred to as Phase 1. It is envisioned that Phase 2 of the research presented here will be extended to a full sector representation incorporating non-energy sectors. In Phase 1, the following specific objectives were defined to incorporate a regional incremental water supply cost in SATIM to be referred as SATIM-W:

- Allocate major energy supply technologies to different water supply regions such as power plants, oil refineries, coal-to-Liquids (CTL) and gas-to-Liquids (GTL) plants, coal mines and shale gas fields;
- Represent coal-washing and shale gas extraction water use impacts;
- Assess the requirements of Flue Gas De-sulphurisation (FGD) on water consumption as additional water supply infrastructure is required in the country's water scarce but coal-rich northern region for new power plants. Thus also allow the model, as an alternative, to opt for once-through seawater cooled coal-power plants with sea-water based FGD in the vicinity of the country's main coal export terminal;

- Add wet-cooling technologies to new coal and solar thermal technologies available to trade-off the investment cost and increased efficiency of energy supply against the investment cost increased water supply;
- After checking efficiencies of dry and wet cooled existing plants introduce values for new plants; and
- Include regional water commodities that represent water supplies of varying quality. Sub-quality water supplies may then require further treatment in order to have productive use.

SATIM-W represents these activities so that the model is responsive to the regional cost and availability of water.

3 Spatial Characterisation of Water Supply in SA and its Representation in SATIM-W

At present South Africa's water resources management is overseen by the Department of Water Affairs (DWA). Water Management Areas (WMA) are administrative water resources regions established by the Department to decentralise administration of water resources at the catchment level. The boundaries of WMAs do not necessarily align with provincial borders or catchment basins as is illustrated in Figure 3. At present, 19 WMA exist although it has been proposed that these be consolidated into 9 WMA. The Upper Vaal would then be combined with the Middle and Lower into the Vaal WMA, for example.

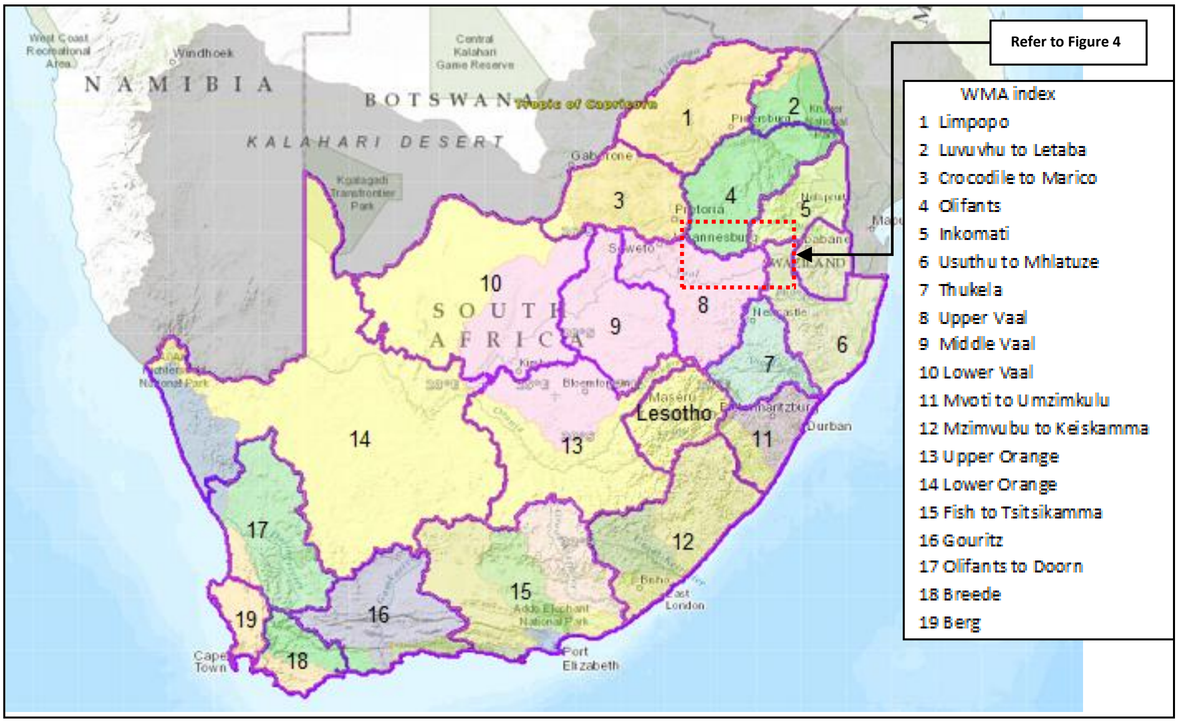

Figure 3: Existing 19 WMA contrasted with catchment basins (shaded). (South Africa. DWA,2012)

In contrast, water supply infrastructure is highly localised and distinct from WMA representing the civil engineering undertaken to implement water supply systems that cater for multiple users across economic sectors. The supply systems are typically comprised of multiple projects that may span WMA. Schemes are discrete projects, for example an inter-basin transfer, for providing additional water to a water supply system. This is illustrated in Figure 4 where the water supply system for the bulk of the country's coal fired power stations is depicted. The figure highlights the actual pipeline infrastructure and interbasin transfers and that are required by the water supply schemes. The term 'Water Supply Region' (WSR) is therefore used in this study to refer to a region of interest that is supplied with water from an integrated water supply network.

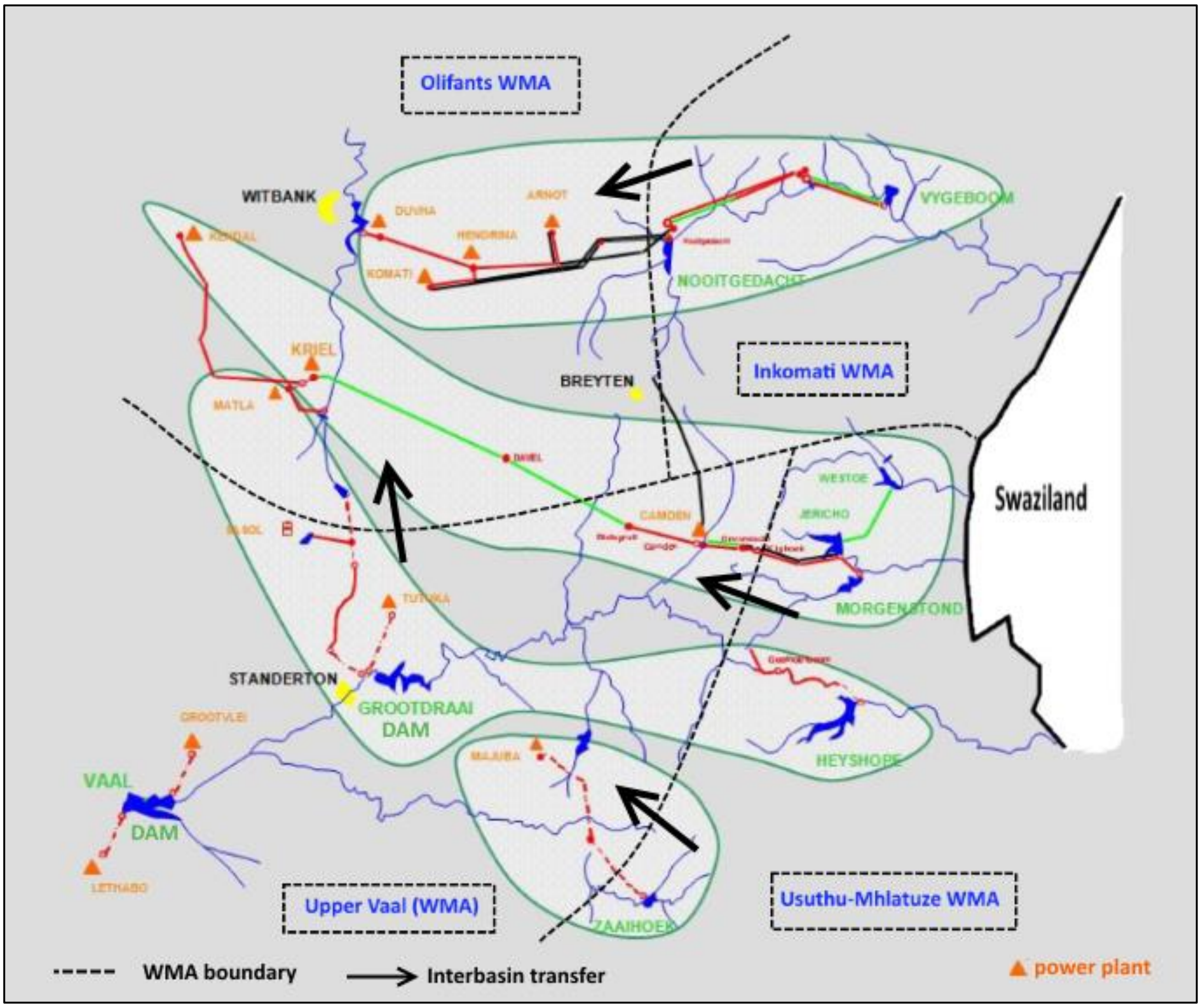

Figure 4 The water supply system for the majority of the existing coal-based power plants in South Africa. Individual supply schemes are highlighted in green borders.

Thus a WSR is serviced by an integrated water supply network or system which may span WMAs and is composed of multiple schemes each of which contributes to the total supply system. Figure 4, for example, depicts the Vaal River Eastern Subsystem (VRES) which is a subsystem of the Integrated Vaal River system. This system at present supplies water to users in the Upper Vaal and Olifants WMA. In future it may also transfer water north to the Limpopo WMA. A further example of the distinction between WMA and WSR is that shale gas mining and Concentrated Solar Power (CSP) generation may occur in the same WMA but incur different water costs because they will likely be supplied by different schemes.

4 Incorporating the Marginal Cost Curves for Water Supply in SATIM-W

In a previous study (referred to as Task 1 in this document), regions of interest for current and future energy supply sector development and where competition for water resources are likely to be experienced with further growth were defined. The marginal cost of supply and delivery of water was then estimated for these Water Supply Regions (WSR).

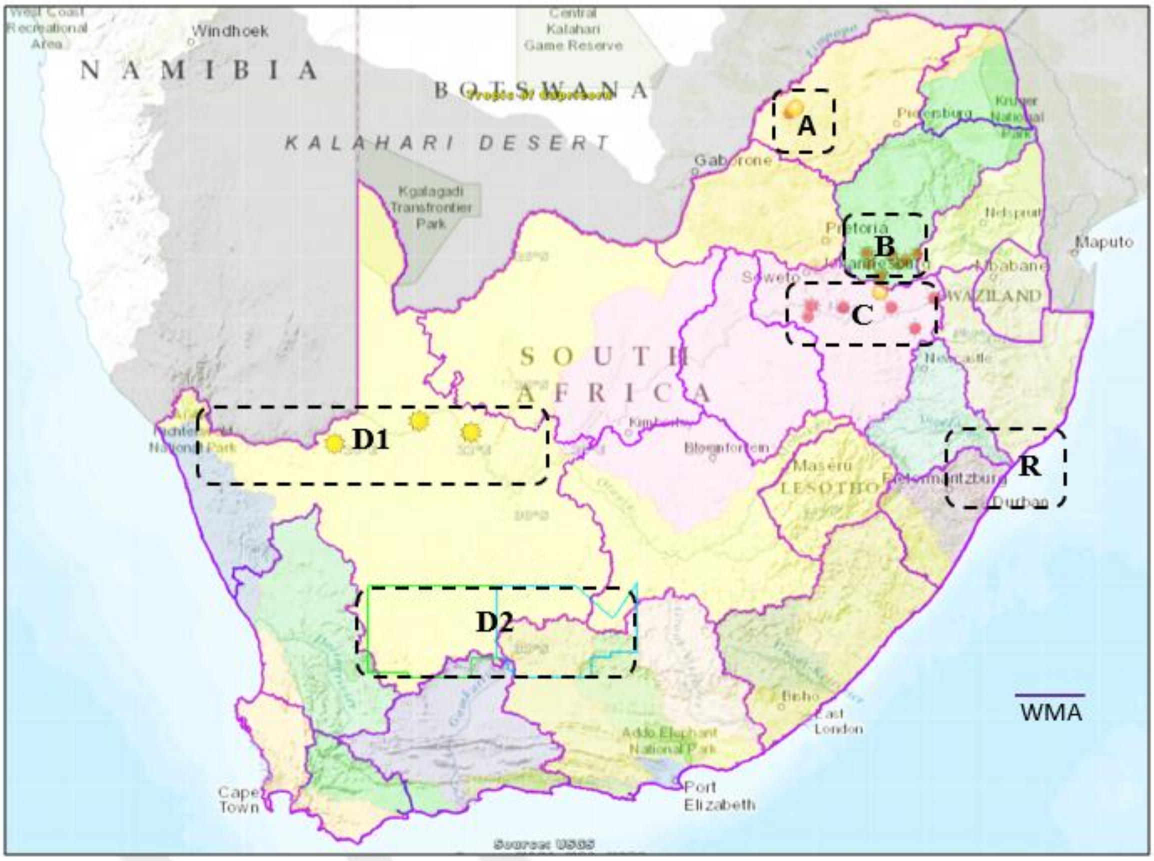

Figure 5: Water supply regions of interest proposed for SATIM-W with the associated WMA.

Figure 5 displays the WSR previously identified and their spatial relationship to the WMA. In the figure, WSRs are differentiated from WMA by the cost of supply and delivery to a particular region within a WMA.

Region 'R,' which is assumed to be in the vicinity of the Richard's Bay Coal Export Terminal (RBT), has been included as a likely site for the option of coastal coal-fired thermal power stations. In this scenario the WMA in which such activity occurs is not considered for water supply as it is assumed that the bulk of process water withdrawn would be seawater. The RBT is the country's primary coal export corridor and is therefore deemed the most plausible location. Table 1 lists the technologies and activities represented in SATIM-W WMAs for Task 1 WSR.

Table 1: Technologies represented in SATIM-W for Phase 1 implementation by water supply system.

WSR	WMA	Region	Activity
A	Limpopo	Lephalale	• Open-cast coal mining • Coal thermal power plants with FGD option • Coal-to-Liquids refineries
B	Olifants	Mpumalanga, Witbank	• Open-cast & underground coal mining • Coal thermal power plants with FGD option. • Coal-to-Liquids refineries
C	Upper Vaal	Mpumalanga, Secunda	• Open-cast & underground coal mining • Coal thermal power plants with FDG option • Inland gas thermal power plants • Inland Gas-to-Liquids refineries
D1	Lower Orange	Northern Cape, Upington	• Concentrated Solar Thermal Power Plants (CSP)
D2	Lower/Upper Orange	Northern Cape, Karoo	• Shale gas mining • Gas thermal power plants • Inland gas-to-liquids refineries
R	n/a	Richards Bay Coal Export Terminal	• Coastal open-cycle coal power plants with seawater cooling and seawater FGD option

In SATIM-W the cooling systems for thermal power plants may be either closed-cycle wet-cooled or direct dry-cooled. The model is free to choose the cooling type, except for open-cycle wet-cooled plants which are restricted to the coastal region, as part of determining the least-cost energy-water integrated system.

5 Representing the Regional Future Costs of Water in SATIM-W

In order to capture the impact of the cost of extraction, transmission and distribution of water in the model, it is necessary to spatially disaggregate the technologies and processes that utilise water to reflect the differing cost of water supply options in different locations.

In the previous incarnation of SATIM power plants were represented in aggregate by technology type (e.g. PF Coal, Nuclear, CCGT, etc.), capacity and vintage (i.e. new or existing). Coal power plants which currently comprise the larger share of generation capacity in the country are categorised as listed in Table 2 along with the representative raw water use intensity. Since the power plants are aggregated, the water use intensities are also aggregated by means of a weighted (by capacity) average.

Table 2: The representation of coal power plants in SATIM with average water use intensities.

Plant Category	Net Capacity (MW)[1]	Weighted raw water consumption (l/MWh)[2]
Existing small (*Eskom*)	5400	2481
Existing IPP small (*Municipal*)	450	2565[3]
Existing large wet-cooled (*Eskom*)	21150	1992
Existing large dry-cooled (*Eskom*)	9390	128
New supercritical dry-cooled (*Eskom*)	4334	229

[1] As of the year 2014; [2](Downes,2011) [3]Value taken from Eskom's Camden plant which is typical of the design and vintage of these plants

Table 3 lists the current and commissioned stock of Eskom's coal power plants according to the water supply region defined in Task 1 along with their water use intensities, capacity and SATIM category as in Table 2 .

Table 3: The individual Eskom coal plants as aggregated in SATIM and by water supply region.

Plant	SATIM Category	Net Capacity	Cooling Type	Raw water use (l/kWh)	Boiler water use (l/kWh)	WSR	Climatic Zone[4]
Matimba	Large Dry Existing	3690	Direct Dry (ACC)	0.12	0.02	A	Hot interior
Medupi	Supercritical New	4334	Direct Dry (ACC)	0.12[3]	0.02[3]	A	Hot interior
Kendal	Large Dry Existing	3840	Indirect-dry	0.12	0.07	B	Cold interior
Duvha	Large Existing	3450	Wet closed cycle	2.2	0.062	B	Cold interior
Kriel	Large Existing	2850	Wet closed cycle	2.38	0.12	B	Cold interior
Matla	Large Existing	3450	Wet closed cycle	2.04	0.077	B	Cold interior
Arnot	Large Existing	2232	Wet closed cycle	2.22	0.157	B	Cold interior
Hendrina	Small Existing	1865	Wet closed cycle	2.61	0.231	B	Cold interior
Komati	Small Existing	906	Wet closed cycle	2.49	0.105	B	Cold interior
Kusile	Supercritical New	4267	Direct Dry (ACC)	0.12[3]	0.02[3]	B	Cold interior
Camden	Small existing	1440	Wet closed cycle	2.31	0.078	B	Cold interior

Plant	SATIM Category	Net Capacity	Cooling Type	Raw water use (l/kWh)	Boiler water use (l/kWh)	WSR	Climatic Zone[4]
Majuba Wet[1]	Large Existing	1980	3 units: Wet cooled	1.86	0.076	C	Cold interior
Majuba Dry	Large Dry Existing	1840	3 units: Direct Dry (ACC)	0.12	0.02	C	Cold interior
Lethabo	Large Existing	3558	Wet closed cycle	1.86	0.076	C	Cold interior
Tutuka	Large Existing	3510	Wet closed cycle	2.06	0.097	B	Cold interior
Grootvlei[2]	Small Existing	1130	Wet/Dry	1.71	0.18	C	Cold interior

[1] From Lethabo. Similar wet cooled system apparent; [2] 4 units: wet closed cycle; and 2 units: indirect dry system with spray condenser and dry cooling tower (implemented during initial experimentation with dry-cooling during ca.1960s) ; [3]Estimated from Matimba; [4]According to the South African National Standard 204 (2008)

It is evident from Table 3 that the current SATIM implementation cannot capture the heterogeneous spatial distribution of plants by water supply region and cooling design. Therefore in order to examine the water-energy relationship for the energy supply sector, SATIM-W requires the power plant categories to be further divided by incorporating additional attributes for the water supply region and cooling design. The additional attributes are incorporated as follows:

- The **cooling design** is attributed by the raw water usage factor for the plant.
- The **WSR** is attributed by mapping regional water commodities to associated regional technologies as indicated in Table 1, as opposed to a single water commodity as currently modelled in SATIM.

An example of changes required to naming conventions in SATIM-W: the case for an existing large PF coal power plant.

The current designation for a large existing coal power plant is given as: **ETCLEPF-E**. The water requirements as described earlier are incorporated in the TIMES model for the appropriate plant type. The concatenated codes that describe the technology are as follows: 'ET' = Electricity generation Technology; 'CLE' = Low Calorific value coal; 'PF' = Pulverised Fuel. The hyphenated '-E' refers to existing technologies where 'N' would refer to new.

In SATIM-W the above technology is further described with the cooling-design and regional identifier. Thus, for the example, the adjusted technology name becomes ETCLEPF[i]-[j]-E where i and j identifies the cooling design and region respectively. Thus for Region C, the technology code is adjusted to **ETCLEPFW-C-E** where the code 'W' identifies the cooling design as closed-cycled wet-cooled. The technology code **ETCLESCO-R-N** would describe a new coal-fired plant that is: supercritical; cooled via open-cycle wet-cooled design and located in Region R.

6 Costing Water in SATIM-W

In SATIM-W, the consumption of water is included as an additional consumption commodity defined as an ancillary or feedstock commodity for a process - similar to the requirement for coking coal in the Iron and Steel subsector or the requirement for feedstock natural gas for the Fischer- Tropsch process for synthetic fuel production.

In this study, the cost of water to a consumer can be considered to have three components: the supply; delivery (transmission and distribution) and treatment required for its application. The treatment of effluent for discharge is not considered although this does not as yet apply to power plants due to the current practice of zero liquid effluent discharge. The necessary treatment and cost incurred further relates to the water quality of the supply system. A scheme for each supply system may have distinctive attributes for each component and it may therefore be necessary to separate the relevant costs. Where applicable however the supply and delivery components are combined for simplicity. This is valid where both components are common to all users of a given supply system. Utilising the results from Task 1, the marginal cost of water delivered per scheme for a given regional supply system is implemented as:

Scheme Marginal Supply Cost = Capital $_{\text{(Scheme + Delivery)}}$ + Fixed_OM (%Capital) $_{\text{(Scheme + Delivery)}}$ + Var_OM$_1$ (Energy cost of conveyance (endogenous)) $_{\text{(Scheme + Delivery)}}$ + Fixed_OM$_2$ (Administrative charges)

The capital, fixed OM and variable OM components are as provided in Task 1 and give the base cost of implementing a scheme and its delivery.

The energy cost of conveyance is proportional to the energy intensity of a particular scheme's supply mechanism as highlighted in Figure 6 which is reproduced from Task 1. The figure contrasts the sensitivity of scheme options such as desalination and regional transfers to electricity costs as compared to schemes that largely exploit gravity.

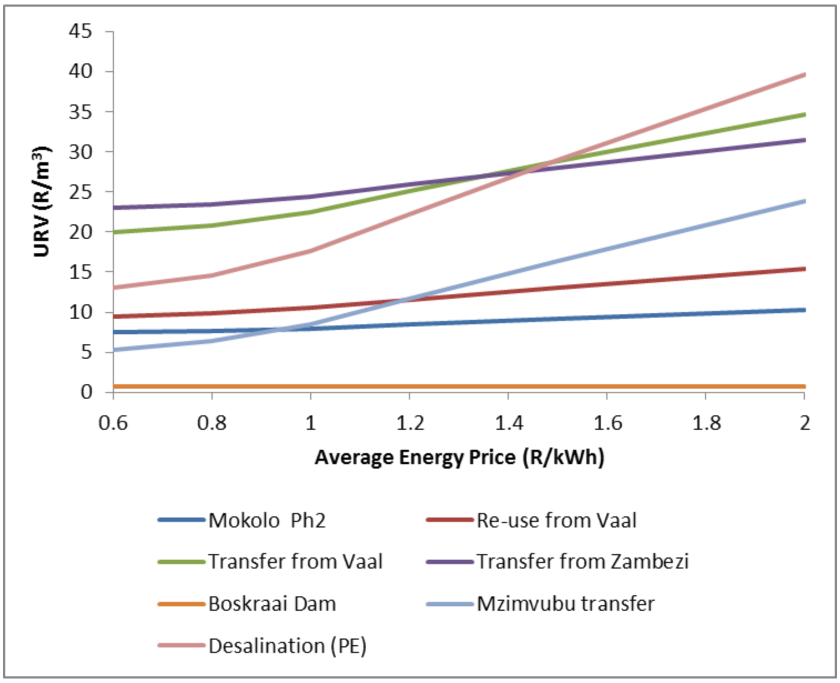

Figure 6: Sensitivity of future water supply scheme costs to changes in the energy price.

Electricity prices are determined endogenously in SATIM and therefore the energy cost attributed to a scheme is better expressed in terms of the energy intensity of water supply (i.e. kWh/m^3). Thus in SATIM-W schemes requiring electricity, whether for conveyance, or production as in desalination, are represented as requiring additional electricity demands. For shale gas water supply the option of water delivery via road freight requires the substitution of electricity demand for diesel consumption as a technology input commodity.

Investment and OM costs for power plants assumed in national energy system models already include the necessary water treatment infrastructure associated with the prevailing water quality of the current supply system (Goyns,2013). Therefore to represent the potential additional costs for the treatment of water incurred due to deterioration in regional water quality with the introduction of new schemes, it is proposed that only the relative change in regional water quality is modelled. This will account for the existing cost structure and allows for the additional cost of water treatment to be included for a change in water quality relative to the Reference case.

Water treatment in the model is interpreted as the additional cost for the transformation of bulk water for process use. Where applicable this would include:

- Primary treatment - clarification via coagulation and flocculation, where consumption would include the makeup water for cooling towers in wet-cooled power stations and coal washing at coal mines, and
- Secondary treatment - production of demineralised water, primarily for boiler recharge or make-up volumes.

Additional treatment costs would include effluent management where applicable. As an end-use consideration, this is further outlined in the sections discussing the processes or activities modelled in SATIM-W. This includes, for example, water management for coal and shale gas mining which are discussed in Sections 8 and 9.

The cost of treatment for bulk water can be represented in two ways as shown below, where
Scheme Marginal Treatment Cost equals:

Var_OM (R/m^3) (simplified form) or:

Capital + Fixed_OM (as %Capital) + Var_OM (kWh/m^3)

The two distinct water treatment types refer to two water commodities that are required by consumers:

- Basic quality or Primary treated water, and
- High Quality (HQ) demineralised water for boiler feed water make-up.

In SATIM-W, for the Power Sector, primary water would then refer to the cooling water requirements while HQ water refers to the boiler circuit water.

Primary treated water has a relatively low energy intensity of production at ~ 6 kWh/1000 m^3 (Ras,2011) such that a standard simplified cost of ZAR 2/m^3 can be applied in the model. The energy intensity of desalination by reverse osmosis (RO) for demineralised water production is higher (2 to 3 kWh/m^3) and depends on the Total Dissolved Solids (TDS) range of feed water (e.g. low or high salinity brackish waters). Therefore to reflect the impact of lesser quality water and energy prices on the cost of HQ water it was decided to model the two water types separately.

Is should be noted that existing and commissioned plants have a mix of Ion-Exchange (IX) and RO technologies for demineralised water production. For example, according to Eskom data the new Medupi plant located in the Limpopo WMA relies on Ultra-Filtration and Reverse Osmosis (UF-RO) with Electro-Deionisation (EDI) for final polishing. The new Kusile plant located in the Olifants WMA relies on IX. The energy intensity and usage of feedstock chemicals for IX exhibits a wider variation than the UF-RO process for changes in TDS which as highlighted in the Eskom Medupi Water Treatment Plant (WTP) analysis (Eskom,2008).

Reference Energy-Water System (REWS) diagrams for each water supply region identified in Task 1 are detailed below depicting the regional energy technologies and activities listed in Table 1. Descriptions are colour coded in green and TIMES process and commodity names are in black. The supply system for region D differs from the generic format due to the different modes of delivery. This effectively creates sub-regional water supply systems owing to the combination of delivery modes and water sources (i.e. surface and ground water).

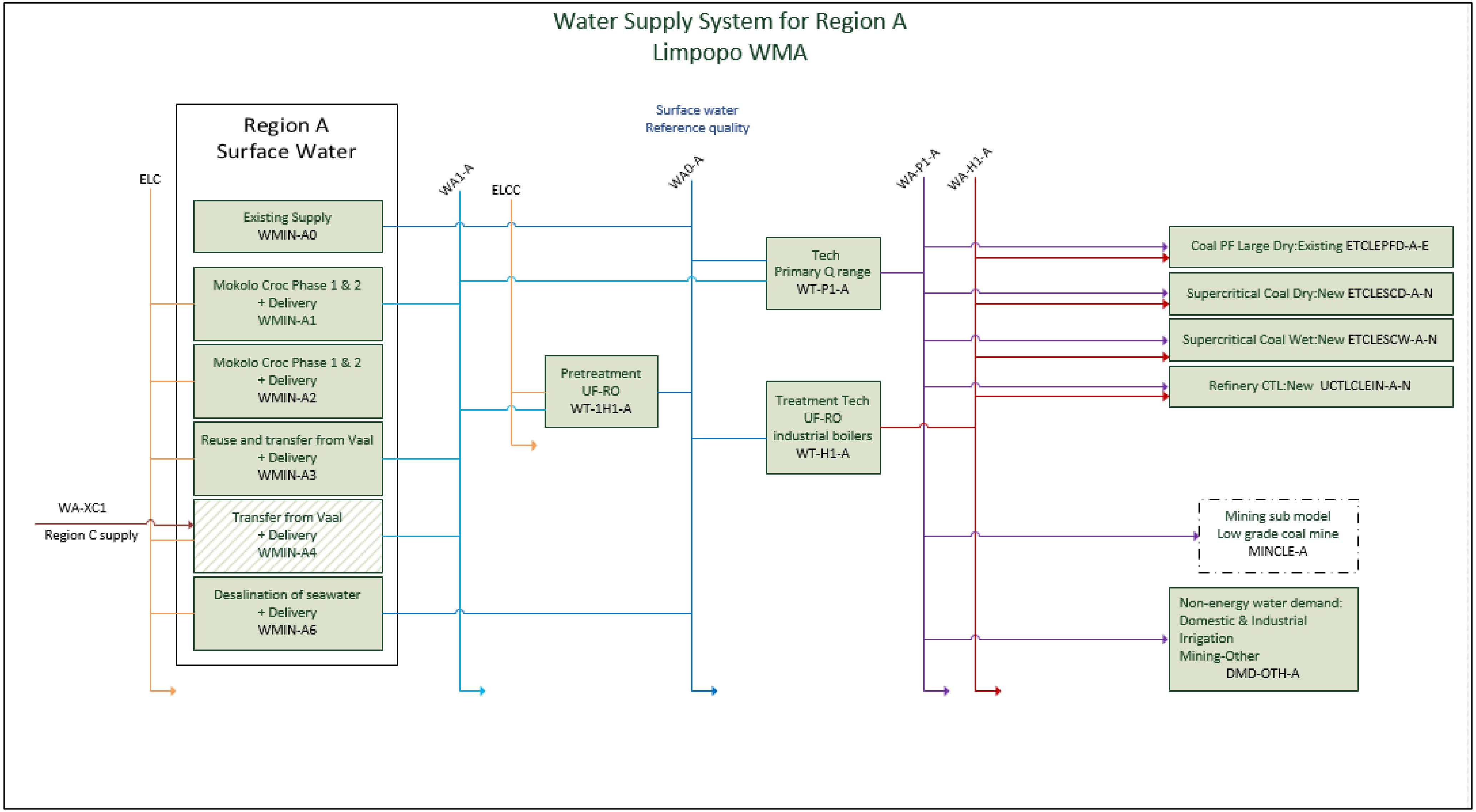

Figure 7 The SATIM-W water supply system for Region A.

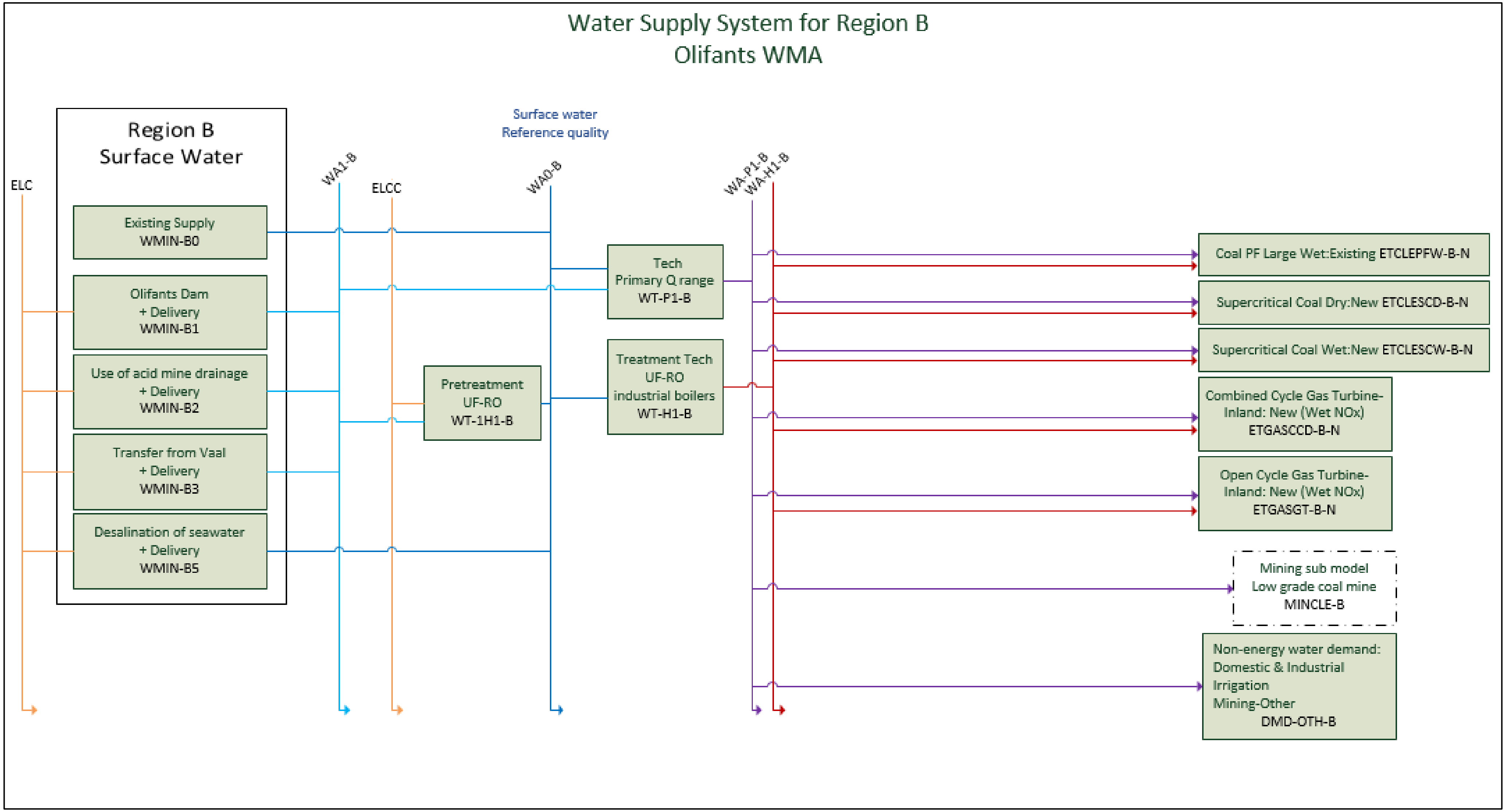

Figure 8 The SATIM-W water supply system for Region B.

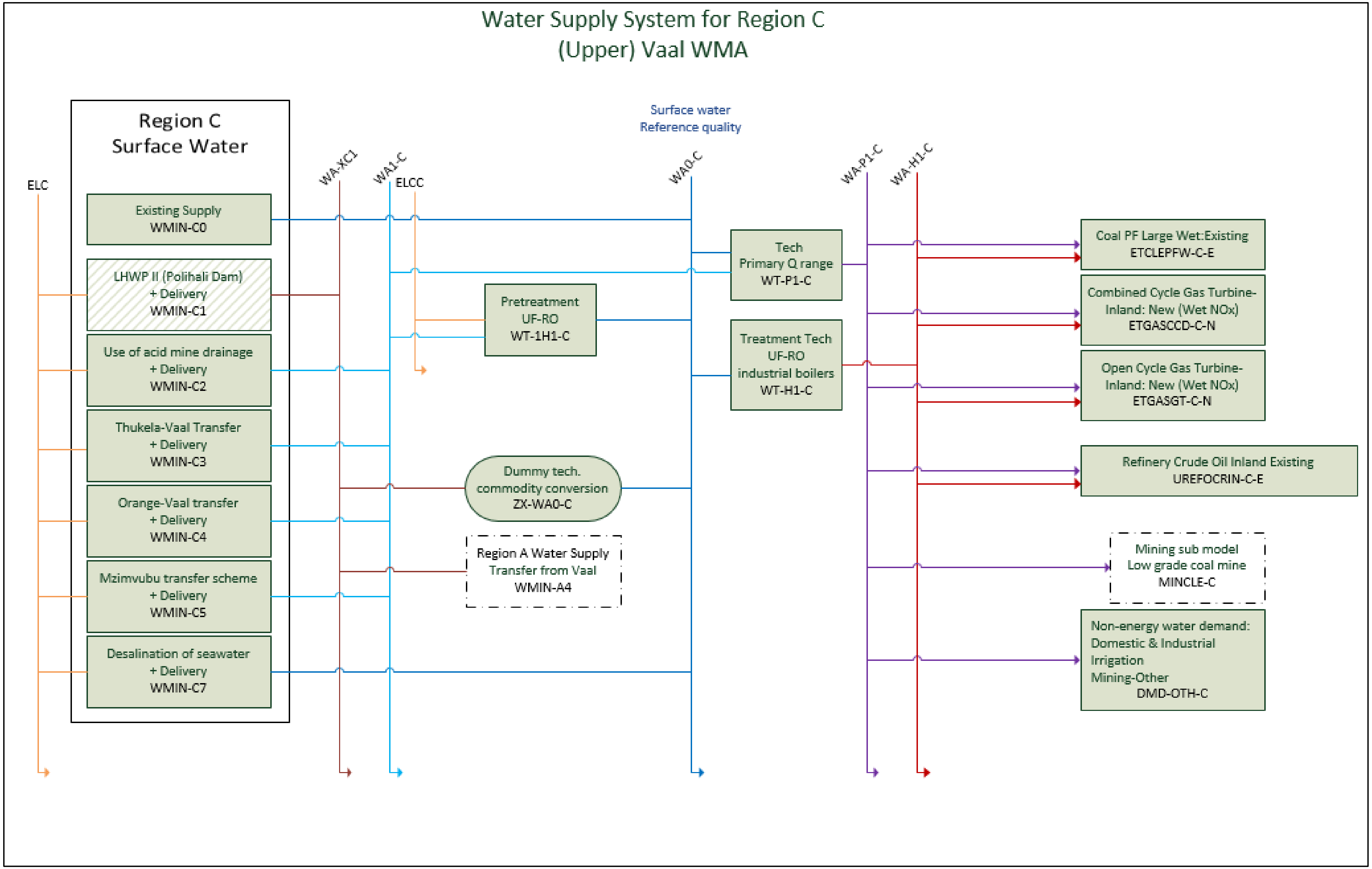

Figure 9 The SATIM-W water supply system for Region C.

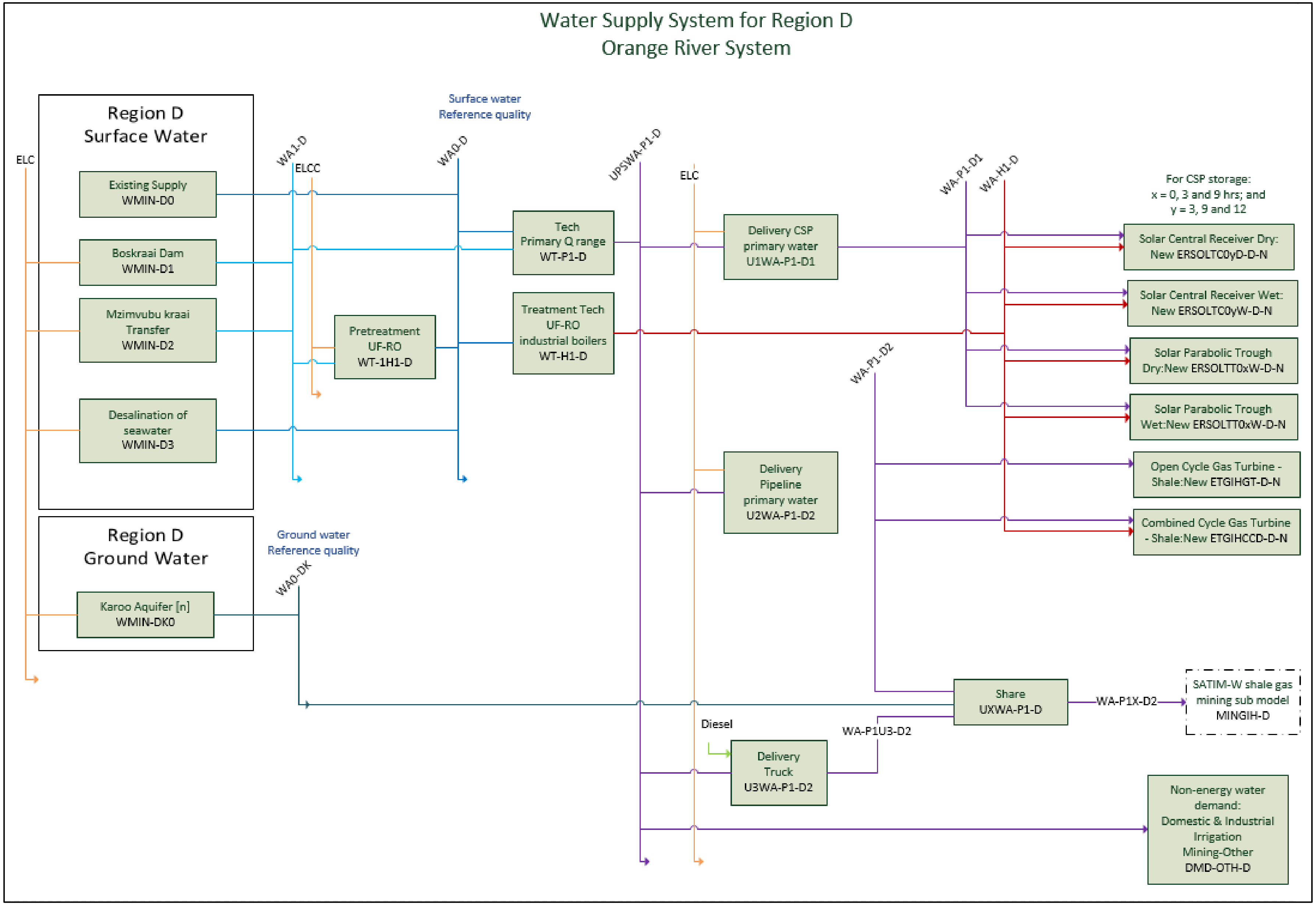

Figure 10 The SATIM-W water supply system for Region D.

7 Parameterisation of Water Supply Technologies

The model parameters for implementing the regional water supply systems in SATIM-W are summarised below in Table 4. For the treatment technologies, the simplified expression is included as an alternative should a levelised cost be preferred for certain cases. This may occur if a treatment cost is relatively small and would apply to primary treatment. As previously discussed Region D requires the delivery component to be separated.

Table 4 SATIM-W parameters characterising a water supply system.

TIMES parameters	Scheme Supply & Delivery	Treatment
Time varying parameters		
NCAP_COST	Capital (ZAR/Mm3)	Capital (ZAR/Mm3/annum)
NCAP_FOM	Fixed OM (ZAR/Mm3/yr)	Fixed OM (ZAR/Mm3/yr)
PRC_ACTFLO	Energy commodity Electricity or Diesel (kWh/m3) or (L/m3)	Energy commodity Electricity (kWh/m3)
ACT_COST[1]	In SATIM-W included as a FOM cost	n/a
ACT_BND	Yield (Mm3)	n/a
Time invariant parameters		
TOP-IN (Commodity input)	Electricity or Diesel	Electricity
TOP-OUT (Commodity output)	W[i]1 (Mm3)	W[i]H1 (Mm3)
Commodity usage :	(simplified alternative for Primary Treatment)	
FLO_COST	n/a	Unit Water Cost (ZAR/Mm3)

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

Note that some schemes have construction lead times. For example, this applies to the case of the use of Acid Mine Drainage as an interim option should the cheaper Vaal–Usutu scheme be unavailable at such a time when the DWA water demand forecast requires additional supply for the Vaal region. The construction lead times are taken from the DWA study of the marginal cost of water for future supply options that informs the analysis of Task 1.

7.1 Water Supply Costs

The net Unit Water Cost (UWC) for an increase in regional water supply (as derived from Task 1) are given in Table 5. The net UWC includes both supply and delivery for Regions A to C. For Region D, the supply and delivery costs are shown for the different modes of supply and delivery. Due to the construction lead times, the marginal costs may not be in ascending order. However it should be noted that in the model the UWC is dynamic as it ultimately depends on a specific scenario of regional commodity demand. This has the impact of deciding which water schemes are required.

Table 5 Summary of regional water supply costs (prices in ZAR 2014).

Region	Regional supply ID	Scheme description	Delivery mode	Net UWC (ZAR/m^3 per annum)	Cumulative supply (Mm^3 per annum)
Lephalale (Limpopo)	WMIN-A1	Mokolo Croc Phase 1	Gravity pipeline from Lephalale	18.11	14
	WMIN-A1	Mokolo Croc Phase 2	Included in net supply cost	30.73	54
	WMIN-A3	Reuse and transfer from Vaal		27.46	180
	WMIN-A4	Transfer from Vaal		14.03	270
	WMIN-A6	Desalination of seawater	Included in net supply cost	33.67	(unlimited)
Upper Olifants	WMIN-B1	Olifants Dam	Pipeline from Olifants Dam	17.54	55
	WMIN-B2	Use of acid mine drainage	Reuse AMD - pipeline from dam in Upper Olifants	8.74	86
	WMIN-B3	Transfer from Vaal River	Import Vaal Dam - pipeline from dam in Upper Olifants	10.43	276
	WMIN-B5	Desalination of seawater	Included in net supply cost	24.47	(unlimited)
Vaal	WMIN-C1	LHWP II (Polihali DAm)	No additional cost	3.76	437
	WMIN-C2	Use of AMD		5.85	475
	WMIN-C3	Thukela-Vaal Transfer		7.47	997
	WMIN-C4	Orange-Vaal transfer		5.95	1514
	WMIN-C5	Mzimvubu transfer scheme		11.26	2145
	WMIN-C7	Desalination of seawater		15.58	(unlimited)
Lower Orange	WMIN-D1U1	Boskraai Dam	CSP pipeline: Included in plant Investment cost	0.61	227
	WMIN-D2U1	Mzimvubu kraai Transfer		6.28	392
	WMIN-D3U1	Desalination of seawater		22.43	(unlimited)
Lower Orange	WMIN-D1U2	Boskraai Dam	Hydraulic fracturing: pipeline	122.59	227
	WMIN-D2U2	Mzimvubu kraai Transfer		128.26	392
	WMIN-D3U2	Desalination of seawater		144.42	(unlimited)
Lower Orange	WMIN-D1U3	Boskraai Dam	Hydraulic fracturing: road transport	113.99	227
	WMIN-D2U3	Mzimvubu kraai Transfer		119.66	392
	WMIN-D3U3	Desalination of seawater		135.81	(unlimited)
Lower Orange	WMIN-DK0	Hydraulic fracturing - groundwater	None applicable	2.27	0.1[#]

[#]Annual supply from aquifer

Note:
- Seawater desalination was chosen as the ultimate scheme supply. The alternate option of a transfer from the Zambesi River was not included due to potential water security concerns.
- The electricity tariff for pumping was adjusted to estimate the industrial tariff at ca. ZAR 50c/kWh.
- Road transport diesel consumption was estimated at 2MJ/tonne-km with a calorific value of diesel given as 35.94 MJ/L and a load factor of 50%.

- The costs for pumping and road transport are estimates and their actual value will depend on the demand for water in the model as electricity and diesel consumption are explicitly modelled as input commodities in terms of kWh/m^3 and $Litres/m^3$ of water delivered (although in TIMES the native units are $PetaJoules/Mm^3$).

7.1.1 Water quality and treatment costs

In the model 'water quality' refers to the TDS of the water supply and the TDS of the regional supply system is taken as the reference water quality. The reference quality can vary by region but plants or mines built or commissioned in a region would have the costs incorporated for regional reference water quality. New schemes that are commissioned to augment regional supply may require pre-treatment by the consumer if the TDS of the scheme is above the operational design of the existing water treatment facilities. It is proposed that this be represented by a pre-treatment technology in SATIM-W which would include investment and operational costs.

Additional schemes are then ranked as equivalent to the reference scheme or less. The concentration of TDS is supply specific and the sensitivity to the level of TDS is use specific. For example, the operating pressure of boilers has a direct dependence on feed water quality with low pressure boilers more tolerant to higher TDS concentrations (Lenntech,2014). The method used represents an average discrete marginal cost across uses with an explicit representation of electricity as a driver of cost for the production of high quality water. In this manner a direct account of TDS variation is abstracted by considering a relative departure from the reference.

Table 6 Water parameter and commodity types in SATIM-W.

Water parameter	Commodity type	Description
W[i]0[1]	Scheme supply	Existing Reference Water Quality
W[i]1	Scheme supply	Sub-Reference Water Quality category 1
W[i]H1	System supply	High quality water (demineralised)
W[i]P1	System supply	Primary treated water for general use
W[i]P0	System supply	Raw water supply. Includes agricultural use for example. This is not implemented in Phase 1 as non-energy demands are aggregated

[1]Water supply region 'A' would have WA0 as the reference existing quality for example.

8 Coal Mining

With the exception of the Majuba plant, all coal-fired plants are linked to a coal mine which supplies the plants via a run-of-mine (ROM) design, the majority of which are conveyor systems. As such no distribution cost is incurred for coal supply to the Power Sector in the current aggregated representation as depicted Figure 11. Also shown in the figure are the associated fugitive emissions and additional upstream supply. In SATIM, commodity demand for coal mining activity is captured in the Industrial sub-sector 'Mining' while supply and distribution is implemented in the Supply sector. Work is underway though to fully encapsulated coal mining - both opencast and underground - within the Supply sector.

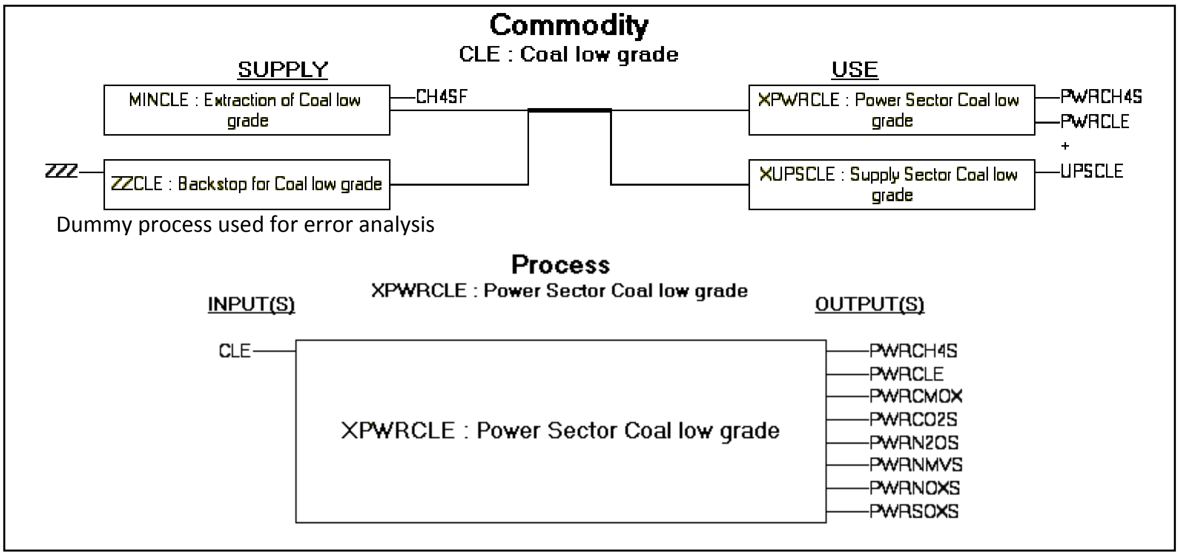

Figure 11 Coal supply to the power sector as implemented in SATIM.

SATIM-W conforms to the current SATIM representation of coal commodities. Three calorific grades of coal are defined, namely: High; Low and Discard. All current power generation technologies utilise the low grade coal. For low grade coal a weighted average calorific value of 21 MJ/kg is obtained from an average of the current coal mine thermal coal production.

8.1 Coal mining sub-model REWS diagram

The REWS diagram for the implementation of coal mining in SATIM-W as proposed above is introduced in Figure 12.

The water needs for coal mining is taken to be of basic quality. As with power plants, coal mines are disaggregated by regional water supply systems. Coal for delivery to power plants is via regional distribution. Region A represents the relatively undeveloped Waterberg deposits in the north while regions B and C together represent the Central Basin where the existing power plants predominate (refer to Figure 4). The distribution technologies are coloured-coded in the REWS to show similar costs.

Also included is the rail link to the Richards Bay Export Terminal (RBT). A coastal-build scenario in the vicinity of the RBT is selected as the most likely locale given the existing high capacity transport infrastructure. As the cost for transport to RBT from either B or C is similar only transport from either region is necessary n the model. In the RES, region C is chosen.

As shown in the REWS diagram and selected for SATIM-W is the inclusion of the cost of a water treatment facility for discharge mine water.

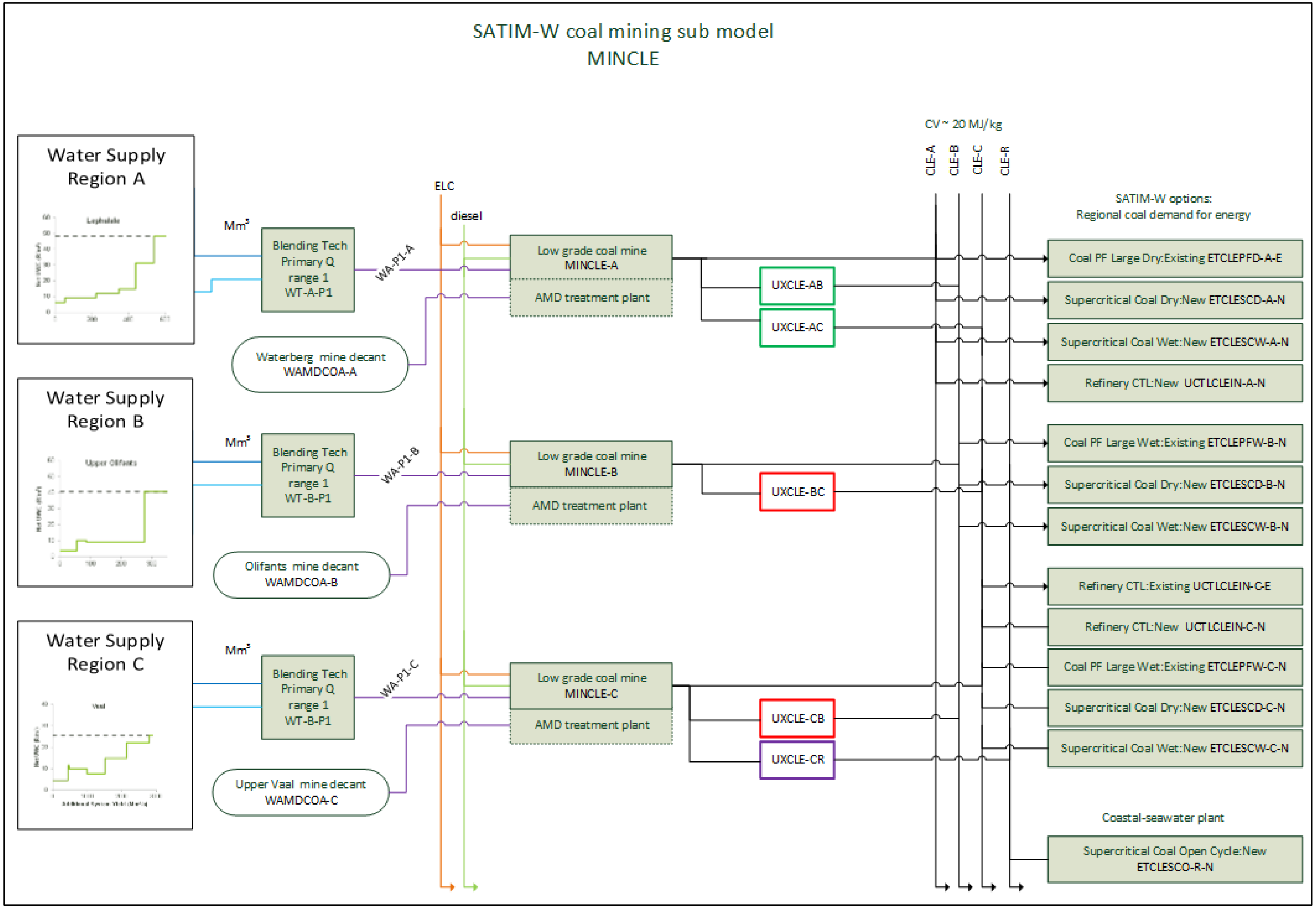

Figure 12: The implementation of coal mining (MINCLE) linked to regional water supply systems in SATIM-W.

9 Shale Gas Mining

The Power sector has been identified as a potential strategic consumer of shale gas should mining proceed. With regard to existing and future generation technologies in SATIM-W, Open-Cycle Gas Turbine (OCGT) and Combined-Cycle Gas Turbine plants (CCGT) can utilise gas. SATIM-W distinguishes several gas commodities. For example the model includes the inland import of regional gas from Mozambique and coastal imported LNG. This analysis focuses rather on the potential exploitation of indigenous shale-gas in the energy sector in the context of a possible water-energy trade-off.

The SATIM-W implementation of shale gas is based on the recent Energy Research Centre (ERC) study of gas utilisation in South Africa. The sub-model Power Sector RES diagram for shale gas mining (MINGIH) is displayed below in Figure 13, while Figure 14 depicts shale gas distribution with the other gas commodities in the model. The RES diagrams depict the two forms of shale gas utilisation in the model: 1) in the vicinity of extraction; and 2) inland where the majority of coal fired plants are located. Generation collocated with shale gas mining only incurs distribution costs while inland generation incurs both transmission and distribution costs. The figure depicts the fugitive emissions associated with extraction (MINGIH) and distribution (XPWRGIH) as well as the existing 2c/kWh fossil fuel levy (PWRENV). Also shown are the OCGT and CCGT gas plant technologies. Figure 14 also displays the distribution of gas to non-energy sectors as the national gas utilisation study assessed the full sector potential for gas demand and supply. In Phase 1, the SATIM-W implementation restricts shale gas utilisation to the Power Sector.

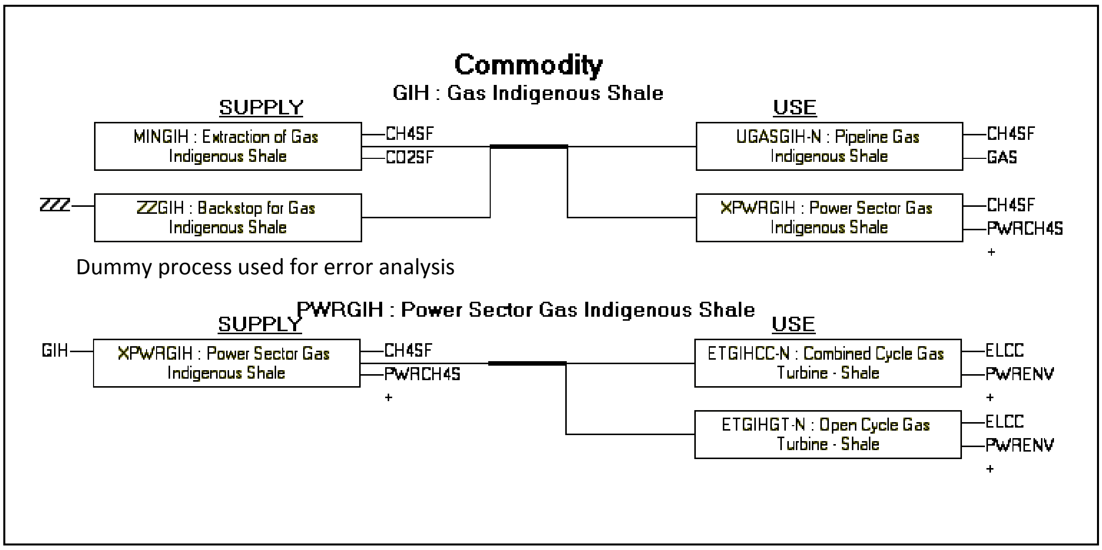

Figure 13: Shale gas extraction and collocated generation in SATIM.

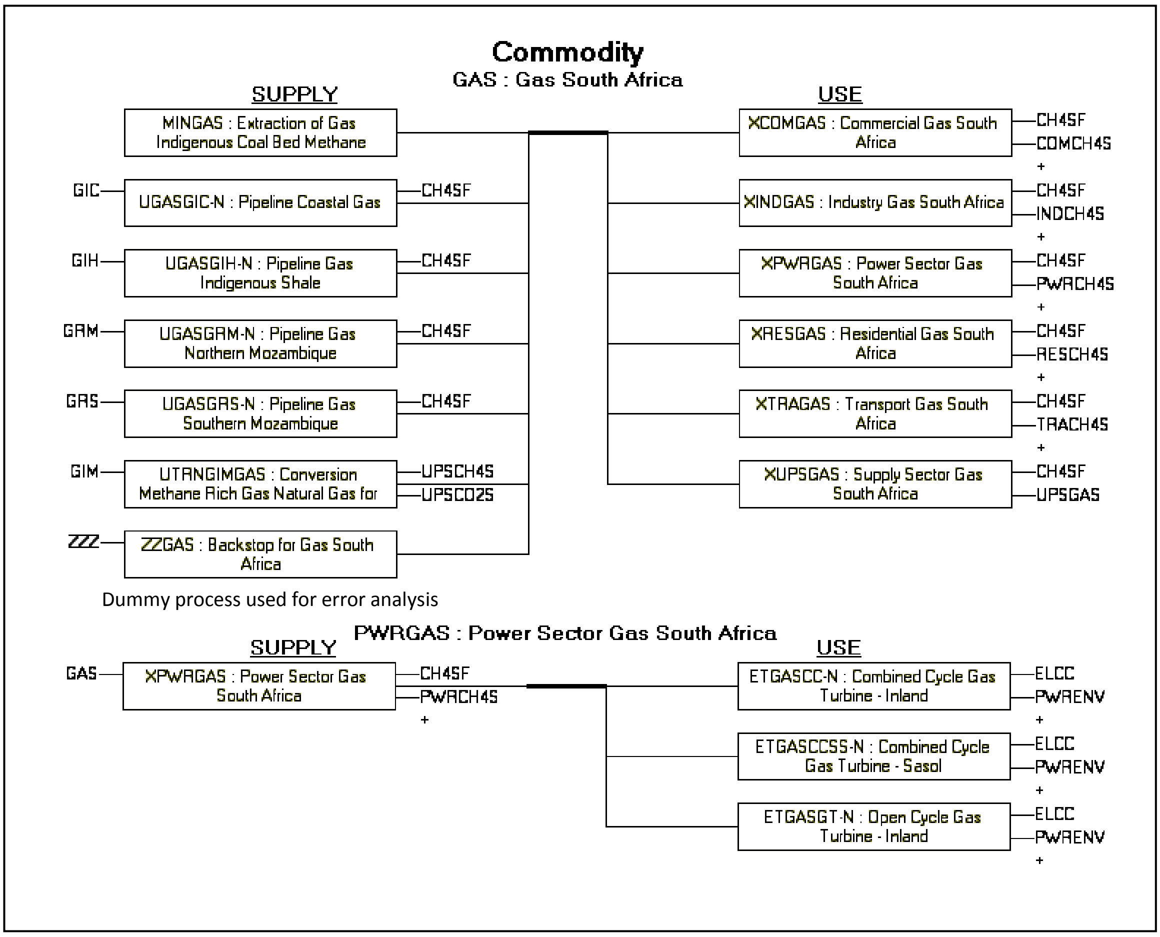

Figure 14: Shale gas extraction inland generation by the Power sector in SATIM.

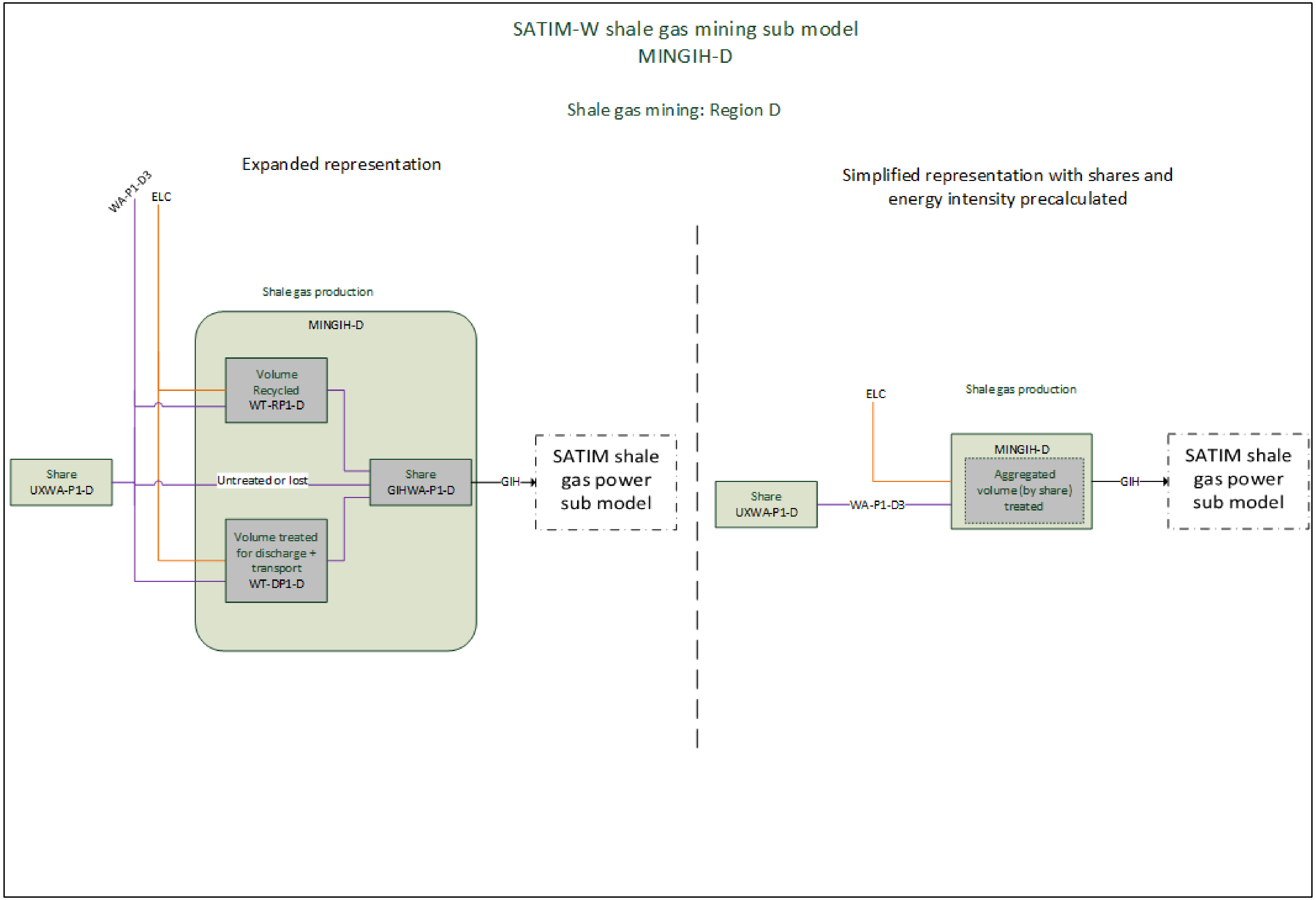

Figure 15: The implementation of shale gas mining (MINGIH).

10 Scenarios for Phase 1: energy supply sector analysis (*draft*)

The five themes that encompass the water-energy modelling framework are illustrated in Figure 16.

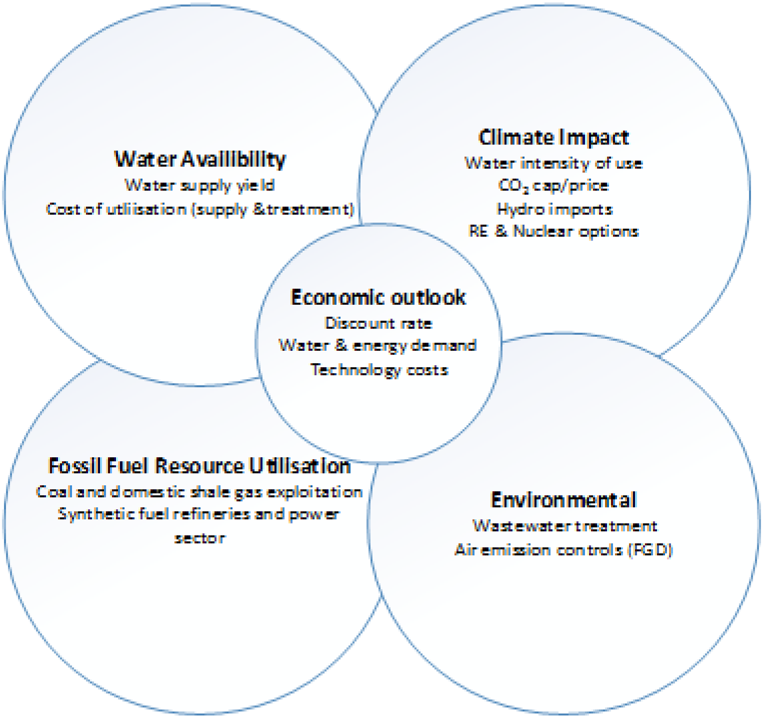

Figure 16: The scenario themes adopted for the model results

These themes explore the interaction of the various factors that would influence planning decisions in the energy supply sector from a water and energy perspective.

The various external interacting factors or elements which are considered to impact the uncertainty of the model outcomes are listed in Table 7. Table 8 lists potential policy options which are candidates for assessment using SATIM-W.

Of these scenario elements, draft scenario cases are created. Certain elements are combined to give a composite scenario variable. For example, the Environmental Compliance variable encapsulates options that would be implemented if environmental regulations were enforced. These include air emissions standards and wastewater treatment. The scenario parameters are further described below.

Table 7: External factors that impact modelling outcomes.

External Factors	Dependencies
Electricity demand	• GDP • Population • Income • Household electrification • Electricity use intensity (Transport- EV's, etc)
Regional water demand	• GDP • Population • Income • Water-use intensity (Climate: cooling water demand, CTL growth)
Regional water yield and cost	• Construction time and capital expenditure • Climate
Regional water quality	• Population • Sectorial water management (e.g. Industry, Mining, Agriculture, Residential)
Gas supply and cost	• Recoverable reserves, water availability and cost (supply and treatment) • Decommissioning cost
Coal supply and cost	• Recoverable reserves, water availability and cost (supply and treatment) • Decommissioning cost

Table 8: Policy options that impact modelling outcomes.

Policy Options	Dependencies
Hydro import capacity	• Climate • Cost
CO2 cap	
CO2 tax	
Air emissions (FGD) FGD to existing plant with >10 yrs life remaining (extension of retrofitted plant life)	• Legislation • Cost • Plant retirement
Waste water treatment (mining) Treatment of liquid effluent suitable for environmental discharge.	Mining Sector growth?
Dry-cooling retrofits For existing >10 yrs life remaining (extension of retrofitted plant life)	• Plant retirement profile • Cost

10.1 Scenario variables

Water and electricity demand: The impact of economic growth on both water and energy demand is considered. At this stage existing sectorial water-use intensities are projected with economic growth forecasts. In Phase 2 further consideration will be given to sectorial demand. The residential sector, for example, accounts for nearly a third of national water demand according to the National Water Resources Strategy 2 (2012) and may act as a stressor on the supply regime considering the migration to formal housing from the informal sector which at present is serviced via standpipes that inherently curtail demand.

The cost of water: The cost of water as provided by the cost curves obtained in Task 1 is incorporated to analyse the impact of pricing water on the generation portfolio compared to the case where the cost of water is not considered. An increase in cost would consider the impact of investment cost uncertainty for future supply schemes.

Climate change: The uncertainty of the yield of a water supply scheme as well as a likely increase in water-use intensity from consumers if a region is projected to experience a decrease in precipitation and elevated temperatures. This may apply to the Agricultural, Residential and Power sectors (i.e. impact on cooling water approach for wet-cooled plant).

A "No-Hydro" import case accounts for a decline in hydro-electricity imports due to regional climate change. The analysis from Task 1 (Section 4.4) summarises two climate change scenarios: Wet; and Dry. The results are reproduced in Table 29. The potential change in supply and demand for these scenarios are applied to the reference case.

Table 9: Change in the average annual water demand and supply for future energy production.

WMA		Water Supply		Annual Demands	
	SATIM-W WSR	Wet	Dry	Wet	Dry
1 Limpopo	A	9.5%	-2.0%	2.8%	8.9%
4 Olifants	B	7.1%	-0.5%	4.4%	11.4%
6 Usutu to Mhlatuze		6.4%	4.0%	3.3%	8.8%
8 Upper Vaal	C	1.5%	0.4%	4.5%	13.0%
14 Lower Orange	D	4.9%	2.8%	3.8%	6.7%

CO_2 cap or price: The final results of the ERC National Gas Utilisation study (currently underway) should better inform our decision as to which presents the more interesting option.

- The application of a CO2 cap of 275 Mt/a for the Power Sector (Phase1) or a 14 Gt cap by 2050 for a full sector analysis (Phase 2).

- The application of a CO2 tax. Based on the analysis of the current ERC National Gas Utilisation Study, two price regimes of R100/t and R300/t are considered.

Environmental compliance: Considers regulatory compliance in the power and extractive sectors for effluent discharge. This comprises:

- Retrofitting of FGD controls to existing candidate coal plants, where wet (limestone) FGD and seawater FGD is considered, and
- Investment in waste water treatment infrastructure for mining activity.

Shale gas mining: The development of an indigenous unconventional gas supply and its impact on:

- Water allocation/supply, and
- Investment in gas-fired power plants.

A high water cost is considered with this option due the limited existing supply in the region of interest for shale gas extraction.

The cost of low carbon technologies: The uncertainty of investment costs for energy supply alternatives to coal based generation.

Increased water treatment costs due to poorer raw water quality: The additional cost of water treatment relative to the reference water quality cost.

Improved water-use efficiency (Phase 2): A decoupling of water demand from economic growth as the economy/country becomes water-use efficient. For example, municipalities actively pursue and maintain water conservation and water demand management reducing residential demand. Industrial water-use intensities decline where applicable as zero-liquid-discharge practice is adopted.

10.2 Scenarios

The scenario variables identified are combined to form scenarios (or cases). These scenarios form the basis for the interrogation of the water-energy model developed to highlight possible trade-offs for future investment in the Energy sector. Table 10 summarises the scenarios formulated for the modelling in Phase 1. Table 11 lists the scenarios and the scenario variables for the defined model runs.

Table 10 Scenario summary

Index	Scenario or Case	Description
1	**Reference (Ref)**	• The SATIM-W Power Sector configuration is run with default assumptions similar to the SATIM configuration with the cost of water not considered and without indigenous shale gas.
2	**Water Supply Cost**: Reference with the cost of water.	• The SATIM-W Power Sector configuration is run with the default assumptions incorporating the cost of water. • The reference case is that of a business as usual demand for energy and water with GDP growth (i.e. water and energy use intensities are constant).
3	**Climate Change**: Water Supply Cost with Climate Change	• Water supply cost curves and water demands adjusted as reflected in Table 9. • The cooling water demand and efficiencies of power plants are adjusted by region if significant. • Includes "No-Hydro" imports. (for drying scenario or both?)
4	**High Economic Growth**: Climate Impact with growth in demand	• Explores the case of increased economic growth and its effect on energy and water demand. • The reference case is that of a business as usual demand for energy and water with GDP growth (i.e. water and energy use intensities are constant).
5	**Local Environmental Best Practice**: High Economic Growth with local environmental best practice	• As with Scenario 4 but with local environmental best practice. • Wet Flue Gas Desulphurisation technology fitted to all new coal power plants, and retrofitted to candidate existing coal power plants. • Coal mining includes waste water treatment.
6	**Shale Gas**: Environmental Compliance with shale gas mining	• Similar to scenario 5 but includes shale gas mining. Shale gas mining includes water treatment as with coal mining.
7	**Increased Water Supply Cost**: Shale Gas with increased investment cost of water supply schemes	• The impact of investment cost uncertainty for future supply schemes.
8	**Low Carbon Technologies Increased Cost**: Increased Water Supply Cost with low carbon technology options	• The sensitivity of the model results to an increase in cost for low carbon options are examined. The options include imported hydropower, renewable energy and nuclear power)

Table 11: The proposed scenario modelling matrix for SATIM-W

Case	Description	CO_2 cap/price	The cost of water	Climate change	Water and electricity demand	Environmental compliance	Shale gas mining	The cost of low carbon technologies (Imported Hydro, RE costs, Nuclear Costs)
1	Reference	NO	NO water Costs	No Impacts	Reference	SATIM base: No	No Shale	SATIM base
1.1	CO2 price/constraint level 1	1	NO water Costs	No Impacts	Reference	SATIM base: No	No Shale	SATIM base
1.2	CO2 price/constraint level 2	2	NO water Costs	No Impacts	Reference	SATIM base: No	No Shale	SATIM base
2	Water Supply Cost	NO	Base	No Impacts	Reference	SATIM base: No	No Shale	SATIM base
2.1	CO2 price/constraint level 1	1	Base	No Impacts	Reference	SATIM base: No	No Shale	SATIM base
2.2	CO2 price/constraint level 2	2	Base	No Impacts	Reference	SATIM base: No	No Shale	SATIM base
3	Climate Change	NO	Base	Climate Impacts	Reference	SATIM base: No	No Shale	SATIM base
3.1	CO2 price/constraint level 1	1	Base	Climate I	Reference	SATIM base: No	No Shale	SATIM base
3.2	CO2 price/constraint level 2	2	Base	Climate I	Reference	SATIM base: No	No Shale	SATIM base
4	High Economic Growth	NO	Base	Climate I	HIGH	SATIM base: No	No Shale	SATIM base
4.1	CO2 price/constraint level 1	1	Base	Climate I	HIGH	SATIM base: No	No Shale	SATIM base
4.2	CO2 price/constraint level 2	2	Base	Climate I	HIGH	SATIM base: No	No Shale	SATIM base
5	Local Environmental Best Practice	NO	Base	Climate I	HIGH	YES	No Shale	SATIM base
5.1	CO2 price/constraint level 1	1	Base	Climate Impacts	HIGH	YES	No Shale	SATIM base
5.2	CO2 price/constraint level 2	2	Base	Climate Impacts	HIGH	YES	No Shale	SATIM base
6	Shale gas	NO	Base	Climate Impacts	HIGH	YES	With Shale	SATIM base
6.1	CO2 price/constraint level 1	1	Base	Climate Impacts	HIGH	YES	With Shale	SATIM base
6.2	CO2 price/constraint level 2	2	Base	Climate Impacts	HIGH	YES	With Shale	SATIM base
7	Increased Water Supply Costs	NO	HIGH	Climate Impacts	HIGH	YES	With Shale	SATIM base
7.1	CO2 price/constraint level 1	1	HIGH	Climate Impacts	HIGH	YES	With Shale	SATIM base
7.2	CO2 price/constraint level 2	2	HIGH	Climate Impacts	HIGH	YES	With Shale	SATIM base
8	Low Carbon Tech. Increased Cost	NO	HIGH	Climate Impacts	HIGH	YES	With Shale	High
8.1	CO2 price/constraint level 1	1	HIGH	Climate Impacts	HIGH	YES	With Shale	High
8.2	CO2 price/constraint level 2	2	HIGH	Climate Impacts	HIGH	YES	With Shale	High
	Reserve Scenario Variables							
	Increased Water treatment costs due to poorer raw water quality							
	Water Demand Management. Reduction in water demand from lower water-use intensities across sectors (Phase 2)							

Comment (Water and electricity demand, Reference): This is the reference demand in the DWA study excluding water for energy. We require GDP assumptions to agree with energy demand projections.

Comment (Climate change, Climate Impacts): Impact on both supply curve and water-use intensity of Power and other sectors. Require Aurecon input if significantly different.

Comment (Water and electricity demand, HIGH): Requires a high demand projection (excl. water for energy) for water with accompanying GDP growth assumption. (This could be done simply by applying the reference sectoral intensities to higher sector growth).

Comment (The cost of water, HIGH): Higher costs - using upper limits of cost estimates/higher discount rates. Require Aurecon input.

11 Preliminary Model Results (*draft / pending*)

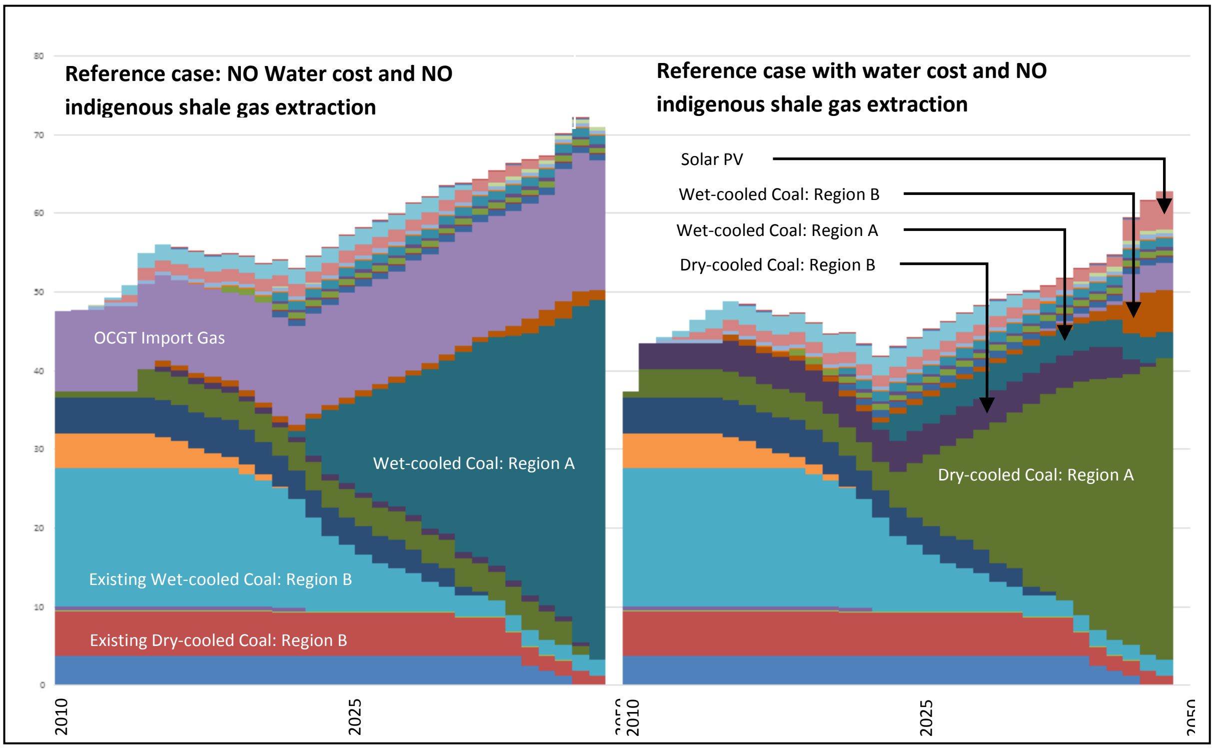

Figure 18 The impact of costing of water in electricity generation investment choice with no new gas field development (scale shown in 10x GW of capacity).

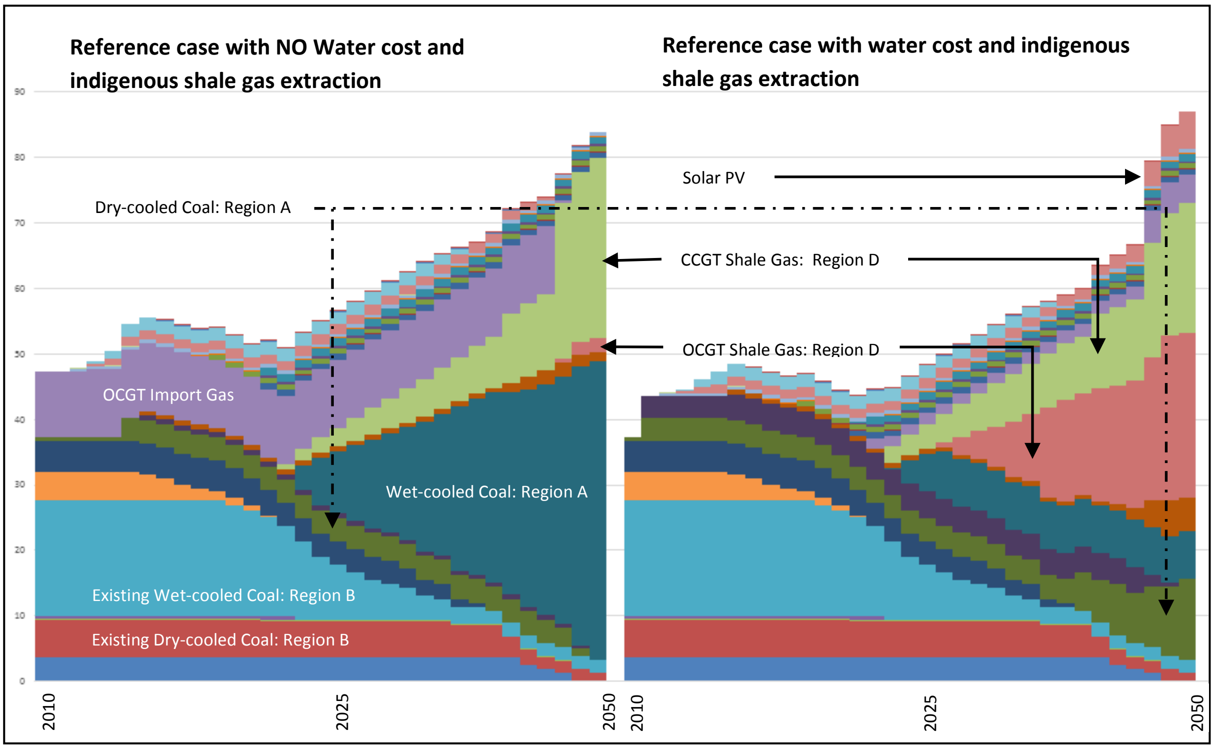

Figure 19 The impact of costing of water in electricity generation investment choice with indigenous shale gas available (scale shown in 10x GW of capacity).

Indicative results of initial model runs are shown in Figure 18 and Figure 19. It is clear that the portfolio of electricity generation plant is influenced by the consideration of future investment costs for water supply infrastructure. In the example figures, when consideration is given to the regional cost of water supply, dry-cooled generation plant is preferred. The choice of Open Cycle Gas Turbines (OCGT) in the Reference Case seems to be abandoned due to competition for water resources in Region C by the oil refineries.

With the emergence of an indigenous shale gas sector in the proximity of the year 2025, gas generation in in context of water availability (as highlighted in Figure 19) is deemed the most cost effective plant choice with the early entrance of Combined Cycled Gas Turbines in the generation portfolio. In this case, shale gas generation largely displaces wet-cooled coal power plants.

The above figure demonstrate the value of incorporating water supply in an energy planning tool such as TIMES.

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