Application of stochastic programming to electricity generation planning in South Africa

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Abstract

A two-stage stochastic programming model is used to solve the electricity generation planning problem in South Africa for the period 2013 to 2050, in an attempt to minimise expected cost. Costs considered are capital and running costs. Unknown future electricity demand is the source of uncertainty represented by four scenarios with equal probabilities. The results show that the main contributors for new capacity are coal, wind, hydro and gas/diesel. The minimum costs obtained by solving the two-stage stochastic programming models range from R2 201 billion to R3 094 billion.

1 Introduction

According to Sen & Zhou [34] stochastic programming (SP) deals with a class of optimisation models and algorithms in which some of the data may be subjected to significant uncertainty. The authors suggest that SP models are appropriate when data evolves over time and decisions need to be made prior to observing the entire data stream. This is also the case in this work since electricity generation expansion plans are made in advance and amidst uncertain future electricity demand. The approach followed in this paper is based on SP, which was introduced by Dantzig [9].

In this paper, a two-stage stochastic programming (TSSP) model for electricity generation expansion planning in South Africa, is proposed. Advantages of adopting SP are discussed

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by Higle [22] and Bisschop [6], and a general form of a linear TSSP problem is given by Shapiro *et al.* [32] as seen in equations (1) to (4):

$$\min \quad c^T x + E_\xi[q^T(\omega)y(\omega)], \tag{1}$$

$$\text{s.t.} \quad Ax = b, \tag{2}$$

$$T(\omega)x + W(\omega)y(\omega) = h(\omega), \tag{3}$$

$$x, y(\omega) \geq 0. \tag{4}$$

Where:

- x is a decision vector whose values are to be calculated in stage one;
- c, A, and b are known matrices corresponding to x, with sizes $n_1 \times 1$, $m_1 \times n_1$ and $m_1 \times 1$, respectively;
- $\xi = \xi(\omega)$ which emphasises that ξ is a random vector;
- $y(\omega)$ is the second stage decision variable whose values are to be calculated in stage two;
- $W(\omega)$, $q(\omega)$, $h(\omega)$ and $T(\omega)$ are matrices corresponding to $y(\omega)$ with sizes $m_2 \times n_2$, $n_2 \times 1$, $m_2 \times 1$ and $m_2 \times n_1$, respectively. For a given realisation of ω, the matrices $q(\omega)$, $h(\omega)$ and $T(\omega)$ become known;
- $\xi^T(\omega) = (q^T(\omega), h^T(\omega), T_1(\omega), \cdots, T_{m_2}(\omega))$; and
- E_ξ represents the mathematical expectation with respect to ξ.

In this work, stage one of the proposed TSSP model determines the investment costs for new capacity that will meet unknown future electricity demand. Stage two allocates available capacity to the future electricity demand. The objective is to minimise investment costs with uncertainty in future electricity demand. TSSP is adopted because the methodology:

- is appropriate when electricity demand unfolds over time and decisions need to be made prior to knowing what the entire electricity demand will be, and
- differentiates between what is known and what remains uncertain when decisions are made.

The paper is organised as follows, the application of SP in electricity generation planning is discussed in Section 2. A brief discussion about scenarios is provided in Section 3. The data used in the study is explained in Section 4 and the methodology followed is presented in Section 5. The results obtained are presented in Section 6 and the conclusion is in Section 7. Following the conclusion are Appendices A to J. Appendix A provides more details on existing capacity. Details for committed capacity are in Appendix B. Assumed capacity decommissioning schedules are in Appendices C to E. Input data for potential new technologies is in Appendices F to J.

2 Stochastic programming in electricity generation capacity planning

The WWF South Africa (WWFSA) [66] proposed an increase in renewable generation capacity into the South African system, from between 6% and 9% as suggested by [37],

to between 11% and 19% by 2030. The model used by WWFSA [66] was deterministic for system performance but probabilistic for cost analysis. The WWFSA results showed that the annual renewable energy production in the South African system can be as high as 25% in 2030, if the proposed increase is implemented. According to Birge & Louveaux [5] one of the shortcomings of a deterministic model is that it can only use one scenario at a time. SP models have the capability of solving all the scenarios simultaneously and provide an optimal solution [5]. Hence, an SP model is used in this paper.

TSSP was used by Albornoz *et al.* [2] in Chile over a ten year planning horizon. Even though the Chile electricity industry is privately owned, it is regulated. The uncertainty considered by the authors was the future availability of the thermal power plants which were in operation. Albornoz *et al.* concluded that the TSSP results were realistic and of a better quality compared to the deterministic approach. The TSSP discussed in this paper is implemented in the South African electricity industry, which is largely state owned unlike the Chile case but also regulated.

Birge & Louveaux [5] discussed multi stage SP models which was later reduced to two-stage programming models. Birge & Louveaux's discussion was based on the TSSP model, where electricity demand and costs of various power plants to meet future electricity demand were sources of uncertainty. Bisschop [6] applied TSPP with the aim of determining new power plant design capacities that will meet an increased electricity demand. Bisschop's objective function was minimising daily costs consisting of a fraction of capital costs for building new design capacity, operating cost associated with the allocation decision, and the cost of importing electricity.

The model by Bisschop is similar to the Birge & Louveaux [5] two-stage example, except that the total investment cost was not constrained to a budget and the existing capacity was considered, whereas Birge & Louveaux did not do so.

In this work, TSSP is applied to the South African electricity generation expansion planning problem for the period 2013 to 2050. The objective was to determine new capacities that will meet electricity demand at minimum cost. The TSSP is implemented for a regulated electricity industry, where existing capacity was considered but without a budget constraint.

3   Scenario analysis

According to Milligan *et al.* [28] scenario analysis is the most common representation of uncertainty in stochastic power systems research and this is also the approach used in this study.

Lindgren & Bandholding [27] defined scenario planning as a combination of scenario analysis and strategic planning. Amer *et al.* [1] used scenario, scenario planning and scenario analysis interchangeable. According to Schoemaker [33], "scenario planning stands out for its ability to capture a whole range of possibility in rich details", when compared to other managerial tools for strategic planning. According to Lindgren & Bandholding [27] there is more than one definition of scenarios. However, these authors define scenarios

as a vivid descriptions of a plausible future [27]. According to Lindgren & Bandholding scenario planning is not a well defined field.

There is no optimal number of scenarios according to Ameer *et al.* [1], however the most recommended range is from 3 to 6. The following four generic scenarios were defined by Zahradnickova & Vacik [67]:

- Optimistic scenario
- Basic scenario
- Pessimistic scenario
- Realistic scenario

There are both qualitative and quantitative scenarios [27]. The Forest of Broceliande [44] website defined qualitative scenarios as possible futures in the form of narrative text or story lines. Quantitative scenarios provide tables and figures incorporating numerical data [44]. The scenarios used in this study are quantitative. Although there is no one scenario development technique, generic steps for scenario development is proposed, see [1] for detail.

According to the South African Department of Energy [38] the IRP in the South African context is the national electricity long term plan which directs the expansion of electricity supply over a given period. In the South African Integrated Resources Plan (IRP) 2010-2030 update report [37] (IRP2010 update), scenarios were defined as a particular set of assumptions and set of future circumstances, providing a mechanism to observe the outcomes from these circumstances. The demand scenarios used in this study were taken from the IRP2010 update and details about these scenarios are shown in Figure 1.
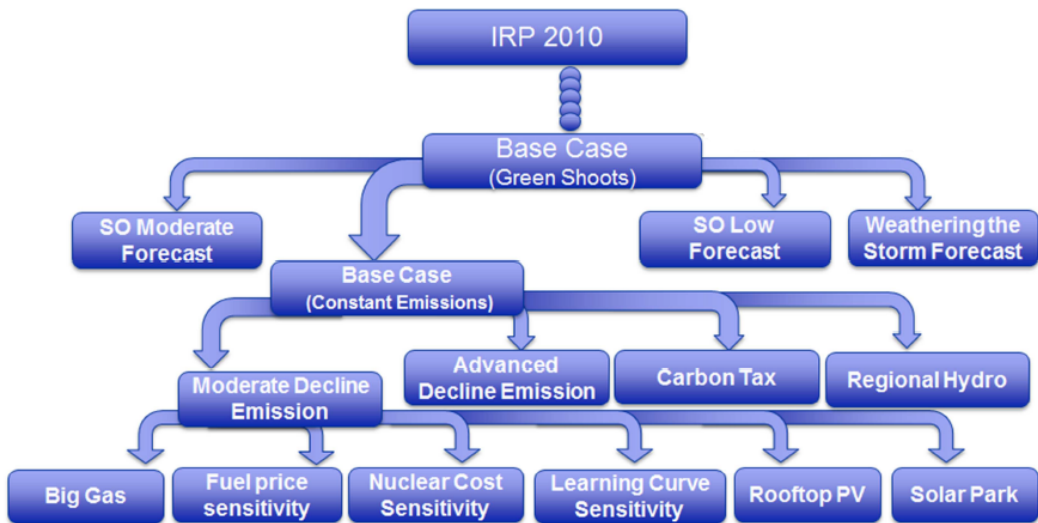

Figure 1: *All scenarios considered in the IRP 2010–2013 report [37].*

4   Data

The data used in this study was taken from the IRP2010 update report [37] since it contained demand scenarios which showed that there was uncertainty about the future demand. The IRP2010 update report also contained more detailed data about the potential technologies when compared to previously published IRP reports. The availability of this complete data made the application of the TSSP possible. The planning period used in the IRP2010 update report was 2013 to 2050, which was also used in this study. In the research work carried out the following data was used:

- The national electricity forecasted demand data. There were four demand scenarios and are presented in Figure 2 in Section 4.1.
- The national existing capacity which was meeting the demand in 2013. Details of this data are in Appendix A.
- The capacity that was committed by the minister of energy based on the IRP 2010-2030 (IRP2010) report [36] and the capacity committed by the public electricity utility in South Africa before the IRP2010 report. Details of this data are in Appendix B.
- A decommissioning schedule for the existing and committed capacity. Appendices C to E contain more details about this data.
- Potential technologies for meeting the forecasted demand together with the existing and committed capacity. The data used for the potential technologies is detailed in Appendices F to J.

4.1   Data for demand scenarios

The demand data was obtained from the IRP 2010-2030 update report [37]. The random variable, $\xi = S1, S2, S3, S4$ takes the values of the following demand scenarios with equal probability of 25%:

- Weathering the storm is represented by S1,
- System Operator (SO) Low Forecast by S2,
- Base Case Forecast by S3, and
- SO Moderate Forecast 4 by S4.

The demand data for the respective scenarios is displayed in Figure 2. The names given to the above scenarios are similar to the generic scenario names given by Zahradnickova & Vacik [67] in Section 3. The only difference is on weathering the storm forecast and the realistic scenario. Other scenarios in Figure 1 were not considered because they were all based on the same demand scenario. The demand data for the respective scenarios are shown in Figure 2.

As it can be seen in Figure 2, S1 has the lowest demand forecast compared to other scenarios from the middle to the end of the investigation period. Similarly, S4 has the highest demand forecast compared to the other scenarios within the same period. The underlying reason for these differences was due to the economic outlook of each scenario which is shown in Table 1. The actual South African average annual gross domestic
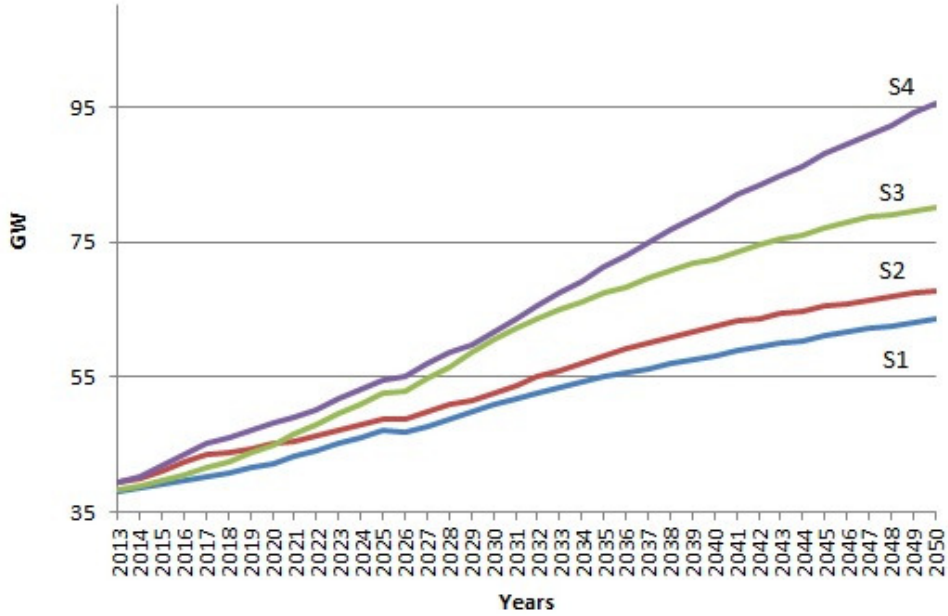
Figure 2: *Demand scenarios whose data was obtained from [37].*

Scenario	Average annual electricity demand from 2013 to 2030 (%)	Average annual electricity demand from 2031 to 2050 (%)	Assumed average annual GDP growth to 2030 (%)
S1	1.8	1.3	5.4
S2	1.9	1.5	5.4
S3	2.7	1.9	4.5
S4	2.8	2.4	2.9

Table 1: *Scenarios economic outlook [37].*

product (GDP) growth rate from 2013 to 2018 was 1.4% [43]. This suggests that at the end of 2018 all the scenarios in Table 1 had an optimistic outlook because their assumed respective average annual GDP growth for this period ranged from 2.9% to 5.4%, which is way above the real average annual GDP growth of 1.4%.

4.2   Data on existing and potential new capacity

To meet the national electricity demand scenarios discussed in Section 4.1, both existing and potential new capacity were considered. Existing capacity included in this research consisted of Eskom fleet, non-Eskom fleet and committed power plants over the period, 2013 to 2050 (see appendices A and B). The sources of energy considered were coal, gas/diesel, hydro, nuclear, solar, wind, and other sources.

The total existing capacity in 2013 was 48 220 megawatt (MW) (see appendix A). During the investigation the existing capacity was increased by the capacity that was committed by the South African public electricity utility before IRP 2010 [36] and the committed capacity from the 2011 ministerial determinations [37]. The committed capacities are presented in Appendix B. The existing capacity was decreased by the capacity of power plants which were expected to be decommissioned during the investigation period. The actual assumed decommissioning dates and the corresponding capacities are in Appendices C to E. Appendices F to J give more details of the new potential technologies, their respective capacities and the corresponding costs.

The same fuel-based annual capacity factors are used throughout the investigation period for both existing and new power plants [42]. This is because the forecasted capacity factors are not available. The assumption made about constant capacity factors might over estimate and sometimes under estimate the actual energy per period produced by the model in Section 5.

Capacity factors for renewable sources were obtained from Calitz *et al.* [7], since this was the only local source with recent renewable capacity factors. Capacity factor data for other power plants was obtained from the South African public electricity utility. Due to the confidentiality nature of the utility's data, only the renewable sources' capacity factors are presented in Table 2 [7].

Energy source	Average capacity factor (%)
Solar photo voltaic (PV)	26
Wind	35
Concentrated solar power (CSP)	31

Table 2: *Average capacity factor [7].*

5 Methodology

The TSSP model discussed in this section follows from the discussion in Section 2. The TSSP model implemented here applies SP to the electricity capacity expansion planning problem in South Africa. The two-stage SP model minimises

- The total annual capital cost for new capacity in the first stage.
- The running costs for new capacity in the second stage. The running costs consist of fuel costs, fixed operating and maintenance (O&M) costs, variable O&M costs, and cost of unserved energy.

The total annual capital cost belongs to the first stage because the decision to expand capacity is taken at this stage. At the time of making this decision the demand growth or decline in the period under consideration is unknown. This is only realised in the second stage. The running costs are allocated to the second stage because they vary according to the energy produced to meet demand.

5.1   Mathematical model

The following considerations were taken into account in the proposed model formulation:

- The objective function in this study minimises annual costs which spans over several years, 2013 to 2050.
- Both existing and new capacity are adjusted by capacity factors due to inefficiency of electricity generating technology.
- The existing capacity is not available throughout the entire planning horizon since some of it is decommissioned.
- The running costs are made up of fuel, fixed and variable maintenance, and the cost of unserved energy.

Equation (5) to equation (15) are only for new technologies. Equations for existing power plants are provided by equation (16) to equation (21), later in this section.

$$\min \qquad \sum_{t,p}[capc_p^t x_p^t + E_\xi \boldsymbol{v}^t], \qquad (5)$$

$$\text{s.t.} \qquad \sum_k \boldsymbol{y}_{pk}^t \le e_p^t capf_p^t \quad \forall (t,p), \qquad (6)$$

$$\beta \boldsymbol{z}_k^t + \boldsymbol{du}_k^t \sum_p \boldsymbol{y}_{pk}^t = \boldsymbol{r}_k^t \quad \forall (t,k), \qquad (7)$$

$$\boldsymbol{r}_k^t = \begin{cases} (\boldsymbol{d}_k^t)\boldsymbol{du}_k^t \text{ if } k=1 \\ (\boldsymbol{d}_k^t - \boldsymbol{d}_{k-1}^t)\boldsymbol{du}_k^t \text{ if } k=2 \end{cases}, \qquad (8)$$

$$x_p^t \ge x_p^{t-1} \quad \forall(t,p), \qquad (9)$$

$$e_p^t = x_p^t - x_p^{t-1} \quad \forall(t,p), \qquad (10)$$

$$\sum_k \left(cue^t \boldsymbol{z}_k^t + \boldsymbol{du}_k^t \sum_p (fom_p^t + vom_p^t + f_p^t)\boldsymbol{y}_{pk}^t \right) = \boldsymbol{v}^t \quad \forall \ (t), \qquad (11)$$

$$x_p^t \ge 0 \quad \forall \ (t,p), \qquad (12)$$

$$\boldsymbol{y}_{pk}^t \ge 0 \quad \forall \ (t,p,k), \qquad (13)$$

$$\boldsymbol{v}^t \ge 0 \quad \forall \ (t), \qquad (14)$$

$$e_p^t \ge 0 \quad \forall \ (t,p), \qquad (15)$$

Where:

- Indices:

  - p is technology type.
  - k is demand category; base (k=1) or peak (k=2).
  - t is year, from 2013 ($t = 1$) to 2050 ($t = n$).

- Parameters:

  - β is a binary parameter which is equal to 0 or 1.
  - e_p^t is the existing capacity for technology p at time t [gigawatt (GW)].

- $capc_p^t$ is annual capital cost for technology p at time t [Rand per kilowatt (R/kW)].
- $capf_p^t$ is annual capacity factor for technology p at time t .
- fom_p^t is fixed operation and maintenance cost for technology p at time t [R/kW] per year.
- vom_p^t is variable operation and maintenance cost for technology p at time t [Rand per megawatt hour (R/MWh)].
- f_p^t is fuel cost of technology p at time t [Rand per gigajoule (R/GJ)].
- cue^t is the cost of unserved energy for all demand category at time t [R/kWh].
- $\boldsymbol{d}_k^t$ is instantaneous electricity demand for k at time t GW.
- $\boldsymbol{du}_k^t$ is duration of demand for category k and at time t; duration for base is 24 hours per day and 6 hours for peak.
- $\boldsymbol{r}_k^t$ is the required electricity for k at time t [gigawatt hour (GWh)].

- Variables:

  - x_p^t is new design capacity of technology p at time t [GW]. This decision was taken just before time t, for the capacity to be available at time t.
  - $capf_p^t$ is based on fuel type [63]. Same capacity factor is used for all technologies and power plants that use the same fuel type. In this study the capacity factor based on fuel type is the quotient of all power plants that generated electricity using a particular fuel type in 2012 and the power plants availability capacity during the same period [63]. Power plant's available capacity is influenced by its planned and unplanned maintenance for each time t.
  - $\boldsymbol{y}_{pk}^t$ is allocation of capacity to each demand, k realization GW at time t for technology p. This decision was taken at time t.
  - $\boldsymbol{z}_k^t$ is the unserved capacity for k at time t [GW]. This decision was taken at time t.
  - $\boldsymbol{v}^t$ is the total cost of: unserved cost of unserved energy, fuel, fixed and variable maintenance.

β is equal to 1 when the available capacity is unable to meet electricity demand and equal to 0 when the capacity is able to meet demand. The variables in bold, in this section, are those that depend on the random variable $\xi = S1, S2, S3, S4$. Equation (5) is the objective function which minimises the capital cost for new capacity and operational costs. The running costs $\boldsymbol{v}^t$ as defined at the beginning of section 5 are expanded in equation (11). The constraint in equation (6) ensures that allocated capacity is less than the available capacity in year t, which is the installed capacity multiplied by the capacity factor. Equation (7) ensures that the required electricity is met by the allocated capacity. The year t capacity is linked to year $t-1$ capacity by equation (9). This is to ensure that the capacity allocated in each year, included what was existing in the previous year. The required electricity per demand category was expanded in equation (8). This equation is introduced to differentiate the required electricity that is met by the base load technologies from the peak load technologies as shown in Table 3.

Hydro under base demand category in Table 3 is classified as mid merit energy fuel source in [16]. Solar and wind are classified as non-dispatchables in [16]. The demand forecast

Base	Peak
Coal	Hydro (pumped storage)
Hydro	Gas/Diesel
Nuclear	
Solar	
Wind	

Table 3: *Fuel demand categories.*

used in this study was taken from [37] and was not categorised into mid merit and non-dispatchables. Hence hydro, wind and solar are classified as base. However, wind and solar have low capacity factors as shown in Table 2, which will be able to counteract the base demand category used. Equation (16) to equation (21) are for existing power plants.

$$\sum_k \boldsymbol{y}_{pop,k}^t \le e_{pop}^t capf_{pop}^t \quad \forall (t, pop), \tag{16}$$

$$e_{pop}^t = e_{pop}^{t-1} - dec_{pop}^{t-1} \quad \forall (t, pop), \tag{17}$$

$$\boldsymbol{du}_k^t \sum_{pop} \boldsymbol{y}_{pop,k}^t = \boldsymbol{r}_k^t \quad \forall (t, k), \tag{18}$$

$$\boldsymbol{y}_{pop,k}^t \ge 0 \quad \forall (t, pop, k), \tag{19}$$

$$e_{pop}^t \ge 0 \quad \forall (t, pop), \tag{20}$$

$$dec_{pop}^t \ge 0 \quad \forall (t, pop). \tag{21}$$

Where:

- pop is power plant.
- dec_{pop}^t is the decommissioned capacity for plant type pop at time t, as defined for new capacity.

All the other variables, parameters and indices in equation (16) to equation (21) are as defined for new technologies but used for existing power plants. It should be noted that no running costs were allocated to existing power plants, because existing capacity running costs were expensive compared to new technologies. The existing power plants are used to make sure that the model allocates electricity demand between existing power plants and new technology.

5.2   Cost of unserved energy

The cost of unserved energy (COUE) which emanates from load shedding, was referred to as backstop technology by Birge & Louveaux [5] and import cost by Bisschop [6]. Load shedding is a controlled way of reducing the electricity demand, with the aim of protecting the electricity system from a total blackout [14]. COUE is the opportunity cost to electricity consumers and the economy from electricity supply interruptions [37]. The COUE is represented by cue^t, which is in the first term of equation (11). The COUE is supposed to be higher than other running costs according to Bisschop and Birge & Louveaux.

A COUE of R75 per kWh was used in [37]. This COUE was revised by the National Energy Regulator of South Africa's (NERSA's) consultation paper [29]. The revised COUE of R87.85 per kWh which was taken from appendix A of the NERSA's consultation paper [29], is used in this paper.

5.2.1 Cost of load shedding to electricity consumers

According to the definition of load shedding in Section 5.2, load shedding affects both the electricity consumers and the economy. This section focuses on the cost of the recent past load shedding to the electricity consumers (COUE-1). In the recent past four stages of load shedding were experienced in South Africa. The four stages are presented in Table 4. The data with actual load shedding days and stages that were implemented by

Stage	Maximum capacity (MW)	Description	Average hours per day	Maximum kWh per day
1	1 000	3 times over 8 day period for 4 hours at a time.	1.5	1 500 000
2	2 000	6 times over 8 day period for 4 hours at a time.	3	6 000 000
3	3 000	9 times over 8 day period for 4 hours at a time.	4.5	13 500 000
4	4 000	12 times over 8 day period for 4 hours at a time.	6	24 000 000

Table 4: *Load shedding stages [14].*

the South African public electricity utility in the financial year 1 April 2018 to 31 March 2019 (2018/19) is in Appendix K. The information in Appendix K was used to calculate the actual number of days where a load shedding stage was implemented.

Stages	Actual kWh	COUE-1 (R)	COUE-1 (R/kWh)
1	9 000 000	790 650 000	527.10
2	72 000 000	6 325 200 000	1 054.20
3	27 000 000	2 371 950 000	175.70
4	168 000 000	14 758 800 000	614.95

Table 5: *Cost of load shedding to electricity consumers.*

The actual number of days were multiplied with the corresponding maximum kWh per day from Table 4, this product is called actual kWh in Table 5. The actual kWh values were multiplied by the COUE value of 87.85 R/kWh, this product is called COUE-1 (Rand (R)) in Table 5. The quotient in the last column of Table 5 is COUE-1 in R/kWh for each day where corresponding load shedding was implemented. The values in the last column of Table 5 were added to the cost of load shedding to the economy which is discussed in Section 5.2.2 and which were used in the model.

5.2.2 Cost of load shedding to the economy

In Section 5.2 it was discussed that electricity interruptions do not only affect the electricity consumer, but also the economy. This section focuses on the cost of the recent past load shedding to the economy. According to Investec's chief economist, Annabel Bishop, the load shedding that was implemented in the first quarter of 2019 in South Africa could wipe off between 33% and 50% of the gross domestic product (GDP) [55]. Bishop's claim was used to calculate the cost of load shedding to the economy for the period in Appendix K. To be conservative 33% was used.

For the load shedding period under consideration, corresponding quarterly GDP in Rand (R) was taken from the Statistics South Africa GDP report for the fourth quarter of 2018 [43]. The monthly GDP (R) was estimated by interpolating quarterly GDP using cubic splines function in Matlab [8]. Monthly GDP for December 2018 was also used for February and March 2019, because GDP for the first quarter of 2019 is not published yet. The daily GDP (R) was derived by dividing the monthly GDP by the number of days in each month. The economic cost (R) for each day of load shedding was derived by multiplying the daily GDP by 33%. Then the economic cost (R) was added for all the days where the same loading shedding stage was implemented, the results are in the second column of Table 6.

Stage	33% of daily GDP (R)	COUE-2 (R/kWh)
1	51 282 677 742	205 131
2	102 774 112 673	205 548
3	18 631 564 286	2 760
4	50 527 873 497	14 737

Table 6: *Cost of load shedding to the economy.*

The values in the second column of Table 6 were divided by the corresponding maximum kWh per day in Table 4. The quotient was multiplied by the number of days for each loading stage. The results are in the last column of Table 6, COUE-2 (R/kWh) for each day where corresponding load shedding stage was implemented. The COUE-2 (R/kWh) was added to the COUE-1 (R/kWh) in Table 5. The results are shown in Table 7. These values were used in the model and the results are presented in Table 8.

Case	COUE-3 (R/kWh)
A	2 935.93
B	15 352.25
C	205 657.81
D	206 602.43

Table 7: *Cost of load shedding to electricity consumers and the economy.*

However, it should be noted that the COUE -3 (R/kWh) in Table 7 cannot be used for other load shedding periods, because:

- the COUE -3 (R/kWh) values were derived from load shedding stages that implemented during the load period under consideration,

- GDP values used change from period to period, and
- the economist's view might also be different for load shedding which might be implemented in the future.

However, if a higher percent of GDP was used, say greater than 33% but less or equal to 50%, this percent of GDP would have resulted in higher values of COUE -3 (R/kWh).

6 Results and discussion

In this section, results for new capacity capital costs and corresponding running costs are presented. The new capacity and its corresponding CO_2 emissions are also presented.

6.1 Costs for new capacity

In this study, Advanced Interactive Multidimensional Modelling System (AIMMS) software was used in the modelling process. Solutions were computed by employing the commercial solver CPLEX 12.6. The determined costs are for the new capacity only as shown by the first term of the objective function in equation (5). Table 8 shows the capital costs, running costs and total cost, when a COUE values derived in Section 5.2 were used. The costs in Table 8 are for each element of ξ = S1, S2, S3, S4, provided as part of the solution.

Rand (billion)	S1	S2	S3	S4	Solution
		Case A			
Capital Costs	1 532.61	1 532.61	1 532.61	1532.61	
Running costs excluding COUE	0.37	0.49	0.79	1.17	
COUE costs	0.00	0.00	724.26	1 949.24	
Total	1 532.98	1 533.10	2 257.66	3 483.01	**2 201.69**
		Case B			
Capital Costs	2 746.55	2 746.55	2 746.55	2 746.55	
Running costs excluding the COUE	0.37	0.48	0.83	1.31	
COUE costs	0.00	0.00	0.00	764.78	
Total Costs	2 746.92	2 747.04	2 747.39	3512.64	**2 938.50**
		Case C			
Capital Costs	3 094.19	3 094.19	3 094.19	3 094.19	
Running costs excluding the COUE	0.36	0.47	0.81	1.28	
COUE costs	0.00	0.00	0.00	0.00	
Total Costs	3 094.55	3 094.66	3 095.00	3 095.47	**3 094.92**
		Case D			
Capital Costs	3 094.19	3 094.19	3 094.19	3 094.19	
Running costs excluding the COUE	0.36	0.47	0.81	1.28	
COUE costs	0.00	0.00	0.00	0.00	
Total Costs	3 094.55	3 094.66	3 095.00	3 095.47	**3 094.92**

Table 8: *SP total capital costs for new capacity.*

In Table 8 the running costs consist of 0% of the COUE (R) for:

- S1 and S2 in Case A.
- S1, S2 and S3 in Case B.
- All scenarios in Case C and D.

Table 8 shows that the capital costs are the same for all the elements of ξ in each case. This is the case because the capital costs are the first stage optimal results. For all the cases the running costs for S1 are the lowest compared to other scenarios, this was also expected because of the low electricity demand for S1. The results in Table 8 show that the solution to the objective function *i.e.* equation (5) is increasing from R2 201.69 billion in Case A to R3 094.92 in Cases C and D. The increase in objective function value is due to the increasing capital costs which is a result of high demand. However, one should bare in mind that the optimistic demand scenarios with equal probabilities and constant capacity factors were used when determining the results in Table 8.

The COUE results in Table 8 show that initially the model did not add new capacity, instead the COUE was used, hence COUE values are greater than zero for S3 and S4 in Case A, and S4 in Case B.

The results in Table 8 show that the COUE (R) decreased with increasing value of COUE (R/kWh). However, the COUE (R) did not decrease further for Case D. Table 8 also shows that any COUE (R/kWh) greater than Case C's will produce the same results as Case C. This was observed in Case D results. Results similar to C would have been obtained if the COUE -3 (R/kWh) values were derived from a GDP percent higher than 33%.

6.2 New capacity for SP model

In this section the new capacity corresponding to the capital costs discussed in Section 6.1 is presented. The model increased capacity because of more demand than the existing capacity. Existing capacity kept on decreasing even after the installation of committed capacity as shown in Appendix B, due to decommissioned power plants as shown in Appendices C to E.

Table 9, Table 10 and Table 11 show new capacity according to the technologies, x_p^t, based on sources of energy. As an example, the second column of Table 9 is the sum of x_p^t from technology p which use coal energy source as shown in Appendix F. The corresponding years, t, are in the first column.

It can be seen in Table 9 that new capacity started in 2026 with hydro energy sources. The hydro capacity was increased in 2031, where the wind energy capacity also started. The coal energy source capacity started in 2036 and then gas/diesel energy source capacity started in 2042. The total capacity for Case A kept increasing until 2045 and remained constant till the end of the period.

Unlike in Table 9, Table 10 shows that:

- new capacity started in 2021, with both gas/diesel and hydro energy sources;
- wind energy source came a year earlier.

Year	Coal	Gas/Diesel	Wind	Hydro	Total
2026	0.00	0.00	0.00	1.36	1.36
2027	0.00	0.00	0.00	1.36	1.36
2028	0.00	0.00	0.00	1.36	1.36
2029	0.00	0.00	0.00	1.36	1.36
2030	0.00	0.00	0.00	1.36	1.36
2031	0.00	0.00	12.14	3.53	15.68
2032	0.00	0.00	12.14	3.84	15.98
2033	0.00	0.00	12.14	7.68	19.82
2034	0.00	0.00	12.14	7.68	19.82
2035	0.00	0.00	12.14	7.68	19.82
2036	9.91	0.00	19.20	7.68	36.79
2037	21.43	0.00	19.20	7.68	48.31
2038	24.12	0.00	19.20	7.68	51.00
2039	28.20	0.00	19.20	7.68	55.08
2040	34.58	0.00	19.20	7.68	61.46
2041	37.16	0.00	19.20	7.68	64.04
2042	37.16	0.52	19.20	7.68	64.56
2043	37.16	5.31	19.20	7.68	69.36
2044	37.16	5.31	19.20	7.68	69.36
2045	37.16	5.56	19.20	7.68	69.61
2046	37.16	5.56	19.20	7.68	69.61
2047	37.16	5.56	19.20	7.68	69.61
2048	37.16	5.56	19.20	7.68	69.61
2049	37.16	5.56	19.20	7.68	69.61
2050	37.16	5.56	19.20	7.68	69.61

Table 9: *Case A: SP new capacity per technology (GW).*

The annual capacity allocation, y_{pk}^t and $y_{pop,k}^t$, results are shown in Figure 3 for Case A. For Case A, y_{pk}^t is based on the new capacity in Table 9, however $y_{pop,k}^t$ is based on existing power plants and committed capacity in Appendix A and Appendix B, respectively. Most of the existing capacity is decommissioned during the investigation period as shown in Appendix C to Appendix E.

Figure 3 shows the total capacity allocated to the demand categories k, for each year, t. The total capacity allocation is guided by the forecasted demand scenarios in Figure 2 for all the four scenarios. Case B, C and D will also show results similar to Figure 3.

Comparing Table 11 to Table 9 and Table 10:

- Similar to Table 9, hydro energy source capacity was installed first by the model. However, this capacity featured as early as 2014.
- The wind energy source capacity came next, but much earlier than in Cases A and B.
- Similar to Cases A and B, coal energy capacity featured in 2036.
- Unlike in Cases A and B, nuclear energy source capacity came after coal.
- Similar to Case A gas/diesel energy source capacity came last, but much later when compared to Case A.

Wind and hydro are the only renewable energy sources the model selected for all cases. The objective function of the model used in this paper minimises costs. As a result the

Year	Coal	Gas/Diesel	Wind	Hydro	Total
2021	0.00	2.27	0.00	2.18	4.45
2022	0.00	2.27	0.00	2.18	4.45
2023	0.00	2.27	0.00	2.18	4.45
2024	0.00	2.27	0.00	2.18	4.45
2025	0.00	2.27	0.00	2.18	4.45
2026	0.00	2.27	0.00	2.18	4.45
2027	0.00	2.27	0.00	2.18	4.45
2028	0.00	2.27	0.00	2.18	4.45
2029	0.00	2.27	0.00	2.18	4.45
2030	0.00	2.27	12.14	2.18	16.59
2031	0.00	2.27	12.14	3.12	17.54
2032	0.00	2.27	12.14	3.43	17.84
2033	0.00	2.27	12.14	7.68	22.09
2034	0.00	2.27	12.14	7.68	22.09
2035	0.00	2.27	12.14	7.68	22.09
2036	21.43	2.27	19.20	7.68	50.58
2037	32.95	2.27	19.20	7.68	62.10
2038	34.58	2.27	19.20	7.68	63.73
2039	34.58	2.27	19.20	7.68	63.73
2040	34.58	2.27	19.20	7.68	63.73
2041	36.09	2.27	19.20	7.68	65.24
2042	37.78	2.27	19.20	7.68	66.93
2043	39.79	5.56	19.20	7.68	72.23
2044	43.45	5.56	19.20	7.68	75.89
2045	46.76	5.56	19.20	7.68	79.20
2046	64.13	5.56	19.20	7.68	96.58
2047	64.13	5.56	19.20	7.68	96.58
2048	64.13	5.56	19.20	7.68	96.58
2049	64.13	5.56	19.20	7.68	96.58
2050	64.13	5.56	19.20	7.68	96.58

Table 10: *Case B: SP new capacity per technology (GW).*

model did not select technologies that use renewable energy with high costs. The costs for renewable energy sources' technologies are in Appendices H, I and J. It can be observed that wind technology was cheaper when compared to solar technologies. Also wind had a higher capacity factor compared to solar renewable energy source as shown in Table 2.

Case C and D also had capacity from nuclear energy source. Nuclear energy source in Appendix G has expensive capital costs but lower fixed costs and a higher capacity factor when compared to solar energy sources in Appendices H and I.

The data used in this study was collected before 2013, when solar technologies were still expensive. However, the solar PV prices have fallen by 80% between 2009 and 2017 [13]. The model was not adjusted with new data for PV prices because there was no latest comprehensive data as shown in appendices at the time of writing this paper. Unlike the PV technology there were no actual price decrease statistics for CSP technology in literature. This is possibly the case since according to the International Energy Agency (IEA), only 6 countries worldwide had installed the CSP technology by 2017. However, IEA expected the CSP technology uptake to increase from 2018 to 2023.

Year	Coal	Nuclear	Gas/Diesel	Wind	Hydro	Total
2014	0.00	0.00	0.00	0.00	2.59	2.59
2015	0.00	0.00	0.00	0.00	2.59	2.59
2016	0.00	0.00	0.00	0.00	2.59	2.59
2017	0.00	0.00	0.00	0.00	2.59	2.59
2018	0.00	0.00	0.00	0.00	2.59	2.59
2019	0.00	0.00	0.00	0.00	2.59	2.59
2020	0.00	0.00	0.00	0.00	2.59	2.59
2021	0.00	0.00	0.00	0.00	3.53	3.53
2022	0.00	0.00	0.00	0.00	3.53	3.53
2023	0.00	0.00	0.00	0.00	3.53	3.53
2024	0.00	0.00	0.00	19.20	3.53	22.73
2025	0.00	0.00	0.00	19.20	3.53	22.73
2026	0.00	0.00	0.00	19.20	3.53	22.73
2027	0.00	0.00	0.00	19.20	3.53	22.73
2028	0.00	0.00	0.00	19.20	3.53	22.73
2029	0.00	0.00	0.00	19.20	3.53	22.73
2030	0.00	0.00	0.00	19.20	3.53	22.73
2031	0.00	0.00	0.00	19.20	3.53	22.73
2032	0.00	0.00	0.00	19.20	3.84	23.04
2033	0.00	0.00	0.00	19.20	3.84	23.04
2034	0.00	0.00	0.00	19.20	3.84	23.04
2035	0.00	0.00	0.00	19.20	3.84	23.04
2036	9.91	0.00	0.00	19.20	7.68	36.79
2037	21.43	0.00	0.00	19.20	7.68	48.31
2038	24.12	0.00	0.00	19.20	7.68	51.00
2039	27.46	0.72	0.00	19.20	7.68	55.05
2040	34.58	1.76	0.00	19.20	7.68	63.22
2041	34.58	1.76	0.00	19.20	7.68	63.22
2042	35.95	1.76	0.00	19.20	7.68	64.59
2043	37.96	1.76	0.00	19.20	7.68	66.60
2044	49.03	1.76	0.00	19.20	7.68	77.67
2045	60.55	1.76	0.00	19.20	7.68	89.19
2046	60.55	1.76	0.00	19.20	7.68	89.19
2047	69.16	1.76	0.00	19.20	7.68	97.80
2048	69.16	1.76	0.00	19.20	7.68	97.80
2049	69.16	1.76	3.29	19.20	7.68	101.10
2050	69.16	1.76	5.56	19.20	7.68	103.37

Table 11: *Case C & D: SP new capacity per technology (GW).*

Table 12 shows the energy sources' percentage allocation for 2013 and for the new and existing capacity (total capacity) as at 2050 for each case. The total capacity is dominated by coal for all cases. However, this is clean coal since the underlying coal technologies have carbon capture and storage (CCS) and flue gas desulphurisation (FGD) [23].

It can be observed in Table 12 that from 2013 to 2050 there is a capacity shift from coal, nuclear and other for all cases. The shifted capacity moved to wind and hydro in Case A. However in Cases B, C and D, the new capacity for coal increased from 59% to 68%. The wind allocation decreased with increasing coal allocation for Cases B, C and D. In Cases C and D, nuclear's allocation increased when compared to Cases A and B.
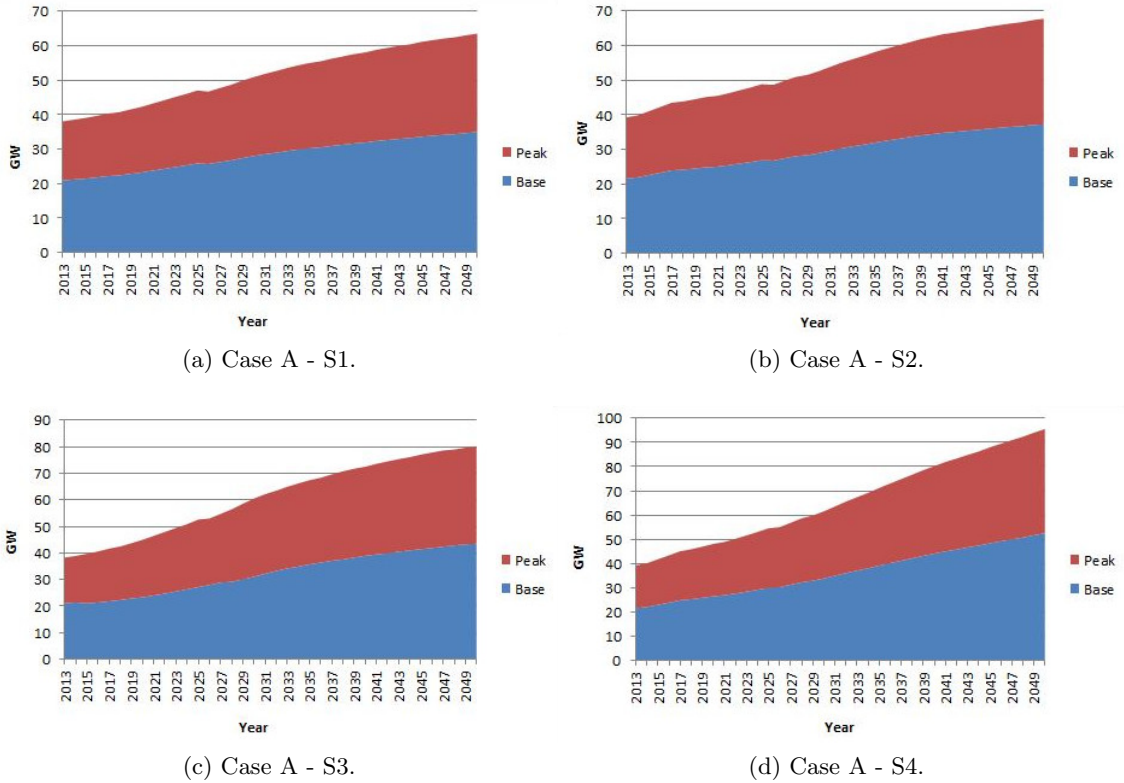
(a) Case A - S1.

(b) Case A - S2.

(c) Case A - S3.

(d) Case A - S4.

Figure 3: *Annual capacity allocation for Case A.*

The challenge with the selected renewable energy sources is the intermittent nature of wind and hydro energy sources that are imported from Zambia and Mozambique as shown in appendix J. Hydro is imported since South Africa is one of the driest countries in the world, according to the South African Department of Water and Sanitation [61].

One should bear in mind that the electricity demand is slowing down in South Africa as shown in Figure 4 [12]. The declining electricity demand in South Africa has also been confirmed by the declining electricity sales as shown in Table 13.

If the trends shown by Figure 4 and Table 13 continue till the end of the investigation period and the actual electricity generation capacity expansion was based on more optimistic demand scenarios like S3 and S4, this would result in excessive electricity generation capacity surplus.

6.3 CO$_2$ emissions

The general move from fossil fuels energy sources to renewable sources is driven by the agreement which was taken on the 21st session of the Conference of the Parties (COP21) [62]. According to Eskom's 2017/18 integrated report [15] historical electricity generation accounted for 42% of the nation's CO$_2$ emission. In an effort to make sure that the country abide by the COP21 pledge, government departments have published the following documents:

Energy Source	2013	Case A: 2050 (%)	Case B: 2050 (%)	Cases C & D: 2050 (%)
Coal	76	59	68	68
Wind	0	21	16	15
Hydro	8	14	11	10
Gas/diesel	5	6	5	4
Nuclear	4	0	0	1
Other	7	0	0	0

Table 12:   *2013 vs. 2050 SP total capacity allocation.*
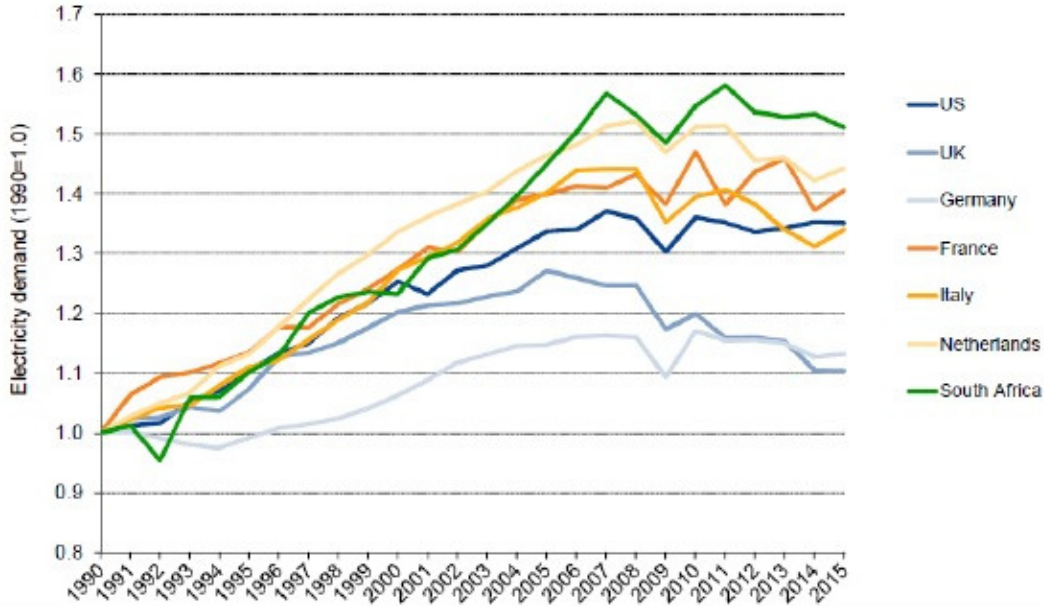
Figure 4:   *Historic electricity demand - SA vs. other countries [12].*

Year	Growth (%)
2012/13	-3.7
2013/14	0.6
2014/15	-0.7
2015/16	-0.8
2016/17	-0.2
2017/18	-0.9

Table 13:   *South African public utility total electricity sales growth[15].*

- Department of Environmental Affairs (DEA) has gazetted a draft National greenhouse gas emission reporting regulations in June 2016 [39].
- DEA has also gazetted a climate change bill in June 2018 [41].
- South African National Treasury has published a carbon tax bill draft for public comments [60].

The CO_2 emissions were determined only for the allocated new capacity. The model did not allocate the new capacity immediately. Hence the CO_2 in Table 14 started later than

2036, where the coal new capacity was introduced. Table 14 shows that S1 emit less CO_2 compared to other scenarios. This is because S1 has less demand when compared to other scenarios. Some of S1 demand was met by renewable energy resources with no emission.

Year	S1	S2	S3	S4
2037	0	15 222	69 565	99 017
2038	0	22 471	78 166	111 572
2039	11 989	36 038	91 747	141 604
2040	25 687	50 872	106 624	210 262
2041	36 909	61 801	120 146	253 242
2042	40 115	64 435	127 034	268,753
2043	44 020	68 246	145 405	290 229
2044	55 641	79 730	194 884	333 707
2045	65 263	89 090	231 931	366 428
2046	132 542	168 451	280 319	404 048
2047	144 664	203 435	314 368	442 539
2048	206 413	256 220	363 117	496 807
2049	231 275	281 593	386 605	530 560
2050	265 612	310 989	414 409	570 594

Table 14: *Case A: Total CO_2 emission per scenario (tonne).*

Year	S1	S2	S3	S4
2037	0	15 222	69 565	99 017
2038	0	22 471	78 166	111 572
2039	11 989	36 038	91 747	141 604
2040	25 687	50 872	106 624	210 262
2041	36 909	61 801	120 146	253 242
2042	40 115	64 435	127 034	267 248
2043	44 020	68 246	145 405	284 804
2044	55 641	79 730	194 884	327 459
2045	65 263	89 090	231 931	362 119
2046	132 542	168 451	276 995	410 868
2047	144 664	203 435	312 873	456 195
2048	206 413	251 141	364 053	514 948
2049	231 275	274 627	389 030	548 701
2050	262 132	304 848	418 618	588 735

Table 15: *Case B: Total CO_2 emission per scenario (tonne).*

For all the cases, CO_2 emissions increase from 2037 to 2050 as shown in Table 14 to Table 16. Furthermore, CO_2 emission also increase from S1 to S4.

However, CO_2 emissions increased from Case A to Case C and D. This is the case even though Table 12 showed that the coal energy source capacity was decreasing from Case A to Case C and D. The increased coal capacity observed for Case A is due to coal technologies with FGD. Appendix F shows that coal technology with FGD have high CO_2 emissions and is cheaper when compared to coal technology with CCS.

South African long term emissions trajectory, "peak, plateau and decline", is for the entire country [40]. However, DEA derived the electricity supply sector "peak, plateau and decline" (PPD), from the country's as shown in Figure 5.

Year	S1	S2	S3	S4
2037	0	15 222	69 565	99 017
2038	0	22 471	78 166	111 572
2039	11 989	36 038	91 747	127 658
2040	25 687	50 872	106 624	175 905
2041	36 909	61 801	120 146	225 246
2042	40 115	64 435	124 741	240 608
2043	44 020	68 246	126 377	258 163
2044	55 641	79 730	160 526	300 819
2045	65 263	89 090	197 573	335 894
2046	132 542	153 698	250 209	384 083
2047	143 719	175 241	286 087	425 250
2048	172 055	224 501	337 612	482 804
2049	203 801	247 986	362 452	523 338
2050	235 492	278 207	391 876	565 714

Table 16: *Cases C and D: Total CO_2 emission per scenario (tonne).*

Comparing the upper limit of Figure 5 in 2050 to Table 14, Table 15 and Table 16 2050's CO_2 emissions, it looks like the scenarios are above the upper limit. However, S1 is close enough for all the cases. One must bear in mind that all the demand scenarios were optimistic about electricity demand, low electricity demand will help with lowering CO_2 emissions.

The CO_2 emissions recorded by the South African electricity public utility [15] in 2012/13 financial year was 227.9 million tons and 205.5 million tons in 2017/18. According to Figure 5 the electricity public utility's emissions as at 2017/18 were between the lower and upper limits. However, as shown in Appendix A, the electricity public utility is not the only supplier of electricity.
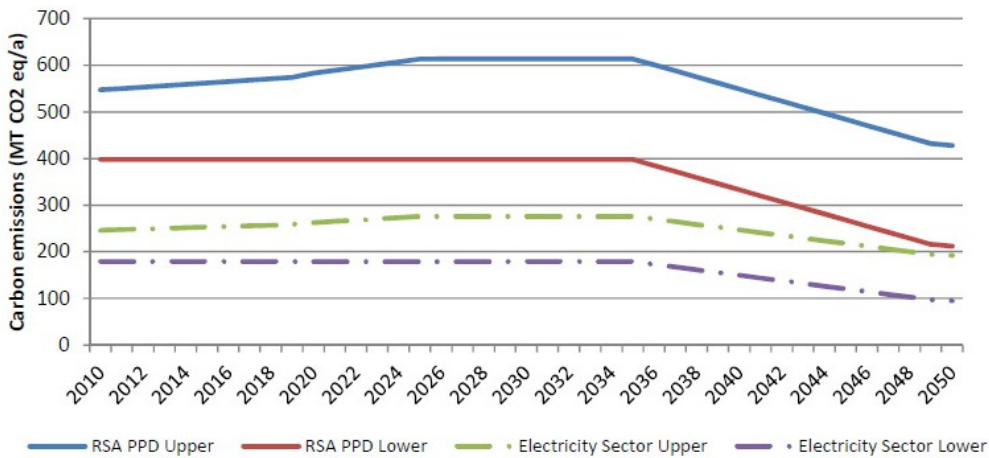

Figure 5: *SA and electricity supply sector PPD [37].*

According to the South African Department of Environmental Affairs (DEA) [40] electricity supply is the largest source of emissions. However, the electricity supplier can limit the emissions by shifting to lower carbon source of energy [40]. The emission results in Table 14, Table 15 and Table 16 show that the new capacity CO_2 emissions in Section 6.2 will be above the upper limit by 2050. This is before including the existing capacity's CO_2 emissions by 2050.

In future work, CO_2 emissions will be constrained in the model such that the new capacity emissions are aligned with DEA's recommendation of limiting emissions.

7 Conclusion

In this study TSSP modelling was applied to the South African electricity generation expansion planning for the first time. The random variable, ξ, was represented by four electricity demand scenarios, S1, S2, S3 and S4. Each demand scenario had 25% probability of occurring. As the actual demand is being realised the scenarios' probabilities can be adjusted to favour the most likely scenario. However, even though four scenarios were considered, the TSSP model incorporated all the scenarios at once. This resulted in optimal total costs ranging from R2 201 billion to R3 094 billion. The total costs from [37] range from R5 800 billion to R8 000 billion. However, these two sets of results are based on similar data up to an extent but assumptions, software and optimization models are not the same.

The costs constituencies as shown in Section 6 simplifies the decision makers' work because the capital costs are the same across all scenarios for each value of COUE (R/kWh) used; what changes per scenario are the running costs.

Results from Case A, S1 are considered to be more applicable, since these results are based on a more conservative demand scenario and have lower costs. Comparing 2013 and 2050 total capacities (existing and new) a decrease from coal, nuclear and other energy sources was observed. This decrease resulted in renewable energy sources' capacity increase. However, technologies that use solar renewable energy source were not selected because of high costs at the time when the data was collected and low capacity factors.

However, Case A's coal technologies emit more CO_2. This can be resolved by constraining the CO_2 emissions in the model.

An increased capacity from renewable energy sources in South Africa's electricity generation mix will contribute towards CO_2 emissions decrease. This will assist the country in fulfilling the COP21 pledge.

8 Acknowledgements

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Appendices

A. Existing capacity [37]

Plant name	Capacity (MW)	Source of energy
Eskom	**42 330**	
Camden	1 520	Coal
Grootvlei	1 080	Coal
Komati	900	Coal
Arnot	2 220	Coal
Hendrina	1 900	Coal
Kriel	2 880	Coal
Duvha	3 480	Coal
Matla	3 480	Coal
Kendal	3 840	Coal
Lethabo	3 540	Coal
Matimba	3 720	Coal
Tutuka	3 540	Coal
Majuba	3 840	Coal
Koeberg	1 860	Nuclear
Gariep	360	Hydro
Vanderkloof	240	Hydro
Colleywobbles	70	Hydro
Drakensberg	1 000	Hydro
Palmiet	400	Hydro
Acacia	180	Gas/ Diesel
Port Rex	180	Gas/ Diesel
Ankerlig	1 350	Gas/ Diesel
Gourikwa	750	Gas/ Diesel
Non-Eskom	**5 890**	
Cahorra Bassa	1 500	Hydro
Aggreko	90	Gas
Pretoria West	90	Coal
Rooiwal	180	Coal
Sasol Infrachem	150	Gas
Sasol SSF	500	Coal
Steenbras	180	Hydro
Co-generation	360	Other
MTPPP	280	Other
DR Peaking	500	Other
Interruptible Load	2 060	Other
TOTAL	**48 220**	

Table 17: *Existing capacity.*

Where:

- SSF is Sasol synthetic fuel
- MTPPP is Eskom's medium term power purchase programme
- DR is demand response
- Hydro is hydroelectric and pumped storage

B.   Committed capacity [37]

The committed capacity was not yet built in 2013 but was already committed.

MW	Coal	Other	Gas	Wind	Other renewable
2010	**380**	**260**	0	0	0
2011	**679**	**130**	0	0	0
2012	**303**	0	0	400	100
2013	**823**	**333**	1020	400	25
2014	**722**	**999**	0	0	100
2015	**1444**	0	0	0	100
2016	**722**	0	0	0	0
2017	**2 168**	0	0	0	0
2018	**723**	0	0	0	0
2019	**1 446**	0	0	0	0
2020	**723**	0	0	0	0

Table 18:   *Committed capacity [37].*

Where:

- The energy sources' capacities in bold are Eskom's commitments pre IRP.
- Other energy sources capacities which are not bold were committed in 2011 ministerial determinations.
- The wind energy source includes 100 MW for Eskom's Sere plant.

C. Assumed decommissioning schedule - 1 [37]

MW Year	Arnot	Camden	Duvha	Grootvlei	Hendrina	Kendal	Komati	Kriel	Lethabo
2013	0	0	0	0	0	0	0	0	0
2014	0	0	0	0	0	0	0	0	0
2015	0	0	0	0	0	0	0	0	0
2016	0	0	0	0	0	0	0	0	0
2017	0	0	0	0	0	0	0	0	0
2018	0	0	0	0	0	0	0	0	0
2019	0	0	0	0	0	0	0	0	0
2020	0	380	0	0	0	0	0	0	0
2021	0	190	0	0	380	0	0	0	0
2022	0	570	0	0	380	0	0	0	0
2023	0	380	0	0	190	0	0	0	0
2024	0	0	0	0	190	0	200	0	0
2025	740	0	0	180	190	0	100	0	0
2026	370	0	0	360	190	0	100	480	0
2027	370	0	0	180	380	60	300	480	0
2028	370	0	0	360	0	0	200	960	0
2029	370	0	0	0	0	0	0	960	0
2030	0	0	1 160	0	0	0	0	0	0
2031	0	0	580	0	0	0	0	0	0
2032	0	0	580	0	0	0	0	0	0
2033	0	0	580	0	0	0	0	0	0
2034	0	0	580	0	0	0	0	0	0
2035	0	0	0	0	0	0	0	0	590
2036	0	0	0	0	0	0	0	0	590
2037	0	0	0	0	0	0	0	0	0
2038	0	0	0	0	0	630	0	0	0
2039	0	0	0	0	0	0	0	0	1 800
2040	0	0	0	0	0	0	0	0	590
2041	0	0	0	0	0	1 890	0	0	590
2042	0	0	0	0	0	630	0	0	0
2043	0	0	0	0	0	630	0	0	0
2044	0	0	0	0	0	0	0	0	0
2045	0	0	0	0	0	0	0	0	0
2046	0	0	0	0	0	0	0	0	0
2047	0	0	0	0	0	0	0	0	0
2048	0	0	0	0	0	0	0	0	0
2049	0	0	0	0	0	0	0	0	0
2050	0	0	0	0	0	0	0	0	0

Table 19: *Assumed decommissioning schedule - 1 [37].*

D.   Assumed decommissioning schedule - 2 [37]

MW Year	Majuba	Matimba	Matla	Tutuka	Pretoria West	Rooiwal	Sasol Infrachem	Sasol SSF	Koeberg
2013	0	0	0	0	0	0	0	0	0
2014	0	0	0	0	0	0	0	0	0
2015	0	0	0	0	0	0	0	0	0
2016	0	0	0	0	90	0	0	0	0
2017	0	0	0	0	0	0	0	0	0
2018	0	0	0	0	0	0	0	0	0
2019	0	0	0	0	0	0	0	0	0
2020	0	0	0	0	0	0	0	0	0
2021	0	0	0	0	0	0	0	0	0
2022	0	0	0	0	0	0	0	0	0
2023	0	60	0	0	0	0	0	0	0
2024	0	0	0	60	0	180	0	0	0
2025	0	0	0	0	0	0	0	500	0
2026	0	0	0	0	0	0	0	0	0
2027	0	0	0	0	0	0	0	0	0
2028	0	0	0	0	0	0	0	0	0
2029	0	0	580	0	0	0	0	0	0
2030	0	0	1 160	0	0	0	0	0	0
2031	0	0	580	0	0	0	0	0	0
2032	0	0	580	0	0	0	0	0	0
2033	0	0	580	0	0	0	0	0	0
2034	0	0	0	0	0	0	0	0	0
2035	0	0	0	580	0	0	0	0	0
2036	0	0	0	1 160	0	0	0	0	0
2037	0	1 220	0	580	0	0	0	0	0
2038	0	610	0	580	0	0	0	0	0
2039	0	610	0	0	0	0	0	0	0
2040	0	610	0	580	0	0	0	0	0
2041	0	610	0	0	0	0	0	0	0
2042	0	0	0	0	0	0	0	0	0
2043	0	0	0	0	0	0	150	0	0
2044	0	0	0	0	0	0	0	0	1 860
2045	0	0	0	0	0	0	0	0	0
2046	610	0	0	0	0	0	0	0	0
2047	610	0	0	0	0	0	0	0	0
2048	610	0	0	0	0	0	0	0	0
2049	670	0	0	0	0	0	0	0	0
2050	670	0	0	0	0	0	0	0	0

Table 20:   *Assumed decommissioning schedule - 2 [37].*

E. Assumed decommissioning schedule - 3 [37]

MW Year	Acacia	Aggreko	Ankerlig	DoE IPP	Gourikwa	Port Rex	Co-generation	MTPPP
2013	0	0	0	0	0	0	0	0
2014	0	90	0	0	0	0	0	0
2015	0	0	0	0	0	0	0	0
2016	0	0	0	0	0	0	0	0
2017	0	0	0	0	0	0	0	0
2018	0	0	0	0	0	0	0	0
2019	0	0	0	0	0	0	0	0
2020	0	0	0	0	0	0	0	0
2021	0	0	0	0	0	0	0	0
2022	0	0	0	0	0	0	0	0
2023	0	0	0	0	0	0	0	0
2024	0	0	0	0	0	0	0	0
2025	0	0	0	0	0	0	0	0
2026	180	0	0	0	0	180	0	0
2027	0	0	0	0	0	0	0	0
2028	0	0	0	0	0	0	0	0
2029	0	0	0	0	0	0	0	0
2030	0	0	0	0	0	0	0	0
2031	0	0	0	0	0	0	0	0
2032	0	0	0	0	0	0	0	0
2033	0	0	0	0	0	0	0	0
2034	0	0	0	0	0	0	0	0
2035	0	0	0	0	0	0	0	0
2036	0	0	0	0	0	0	360	0
2037	0	0	1 350	0	750	0	0	0
2038	0	0	0	0	0	0	0	0
2039	0	0	0	0	0	0	0	0
2040	0	0	0	0	0	0	0	0
2041	0	0	0	0	0	0	0	280
2042	0	0	0	0	0	0	0	0
2043	0	0	0	0	0	0	0	0
2044	0	0	0	0	0	0	0	0
2045	0	0	0	0	0	0	0	0
2046	0	0	0	1 020	0	0	0	0
2047	0	0	0	0	0	0	0	0
2048	0	0	0	0	0	0	0	0
2049	0	0	0	0	0	0	0	0
2050	0	0	0	0	0	0	0	0

Table 21: *Assumed decommissioning schedule - 3 [37].*

F. Coal technologies [37]

Appendix F displays the new technology input data that was used in the model for technologies that use coal as a source of energy. The contents of this appendix were taken from the IRP update report [37].

	PC with FGD	PC with CCS	FBD with FGD	FBD with CCS	IGCC	IGCC with CCS
Rated capacity, net (MW)	4 500 (750x6)	4 500 (750x6)	250	250	1 288 (644x2)	1 288 (644x2)
Adjusted overnight capital cost (R/kW)	25 772	48 789	23 661	44 325	32 340	43 160
Fixed O&M cost (R/kW) per year	552	923	543	902	794	951
Variable O&M cost (R/MWh)	51.2	81.4	110.8	149.1	42.5	65.4
Variable fuel cost (R/GJ)	17.5	17.5	8.75	8.75	17.5	17.5
CO_2 emissions (kg/MWh)	947.3	136.2	978	150	930	120

Table 22: *Coal technologies [37].*

Where:

- PC is pulverised coal
- FGD is flue gas desulphurisation
- CCS is carbon capture and storage
- FBD is fluidised bed combustion
- IGCC is integrated gasification combined cycle
- O&M is operating and maintenance
- kg/MWh is kilogram per megawatt hour

G. Nuclear and gas/diesel technologies [37]

Appendix G displays the new technology input data that was used in the model for technologies that use nuclear and gas/diesel as a source of energy. The contents of this appendix were taken from the IRP update report [37].

	Nuclear single unit	Nuclear fleet	OCGT	CCGT	CCGT with CCS
Rated capacity, net (MW)	1 600	9 600 (1600x6)	115	711	591
Adjusted overnight capital cost (R/kW)	58 036	59 226	4 671	7 089	14 632
Fixed O&M cost (R/kW) per year	532	532	78	163	292
Variable O&M cost (R/MWh)	29.5	29.5	0.2	0.7	0.7
Variable fuel cost (R/GJ)	6.8	6.8	92	92	92
CO_2 emissions (kg/MWh)	0	0	618	388	47

Table 23: *Nuclear and gas/diesel technologies [37].*

Where:

- OCGT is open cycle gas turbines
- CCGT is closed cycle gas turbine

H. Technologies for renewable sources - 1 [37]

Appendix H displays the new technology input data that was used in the model for technologies that use renewable sources of energy. The contents of this appendix were taken from the IRP update report [37].

	Wind	CSP Parabolic trough 3hrs	CSP Parabolic trough 6hrs	CSP Parabolic trough 9hrs
Rated capacity, net (MW)	100 (50x2)	125	125	125
Adjusted overnight capital cost (R/kW)	15 945	44 626	56 381	67 512
Fixed O&M cost (R/kW) per year	310	582	599	616
Variable O&M cost (R/MWh)	0	1.9	2	2
Variable fuel cost (R/GJ)	0	0	0	0
CO_2 emissions (kg/MWh)	0	0	0	0

Table 24: *Technologies for renewable sources - 1 [37].*

Where:

- CSP is Concentrated Solar Power

I.   Technologies for renewable sources - 2 [37]

Appendix I displays the new technology costs input data that were used in the model for technologies that use renewable energy sources. The contents of this appendix were taken from the IRP update report [37].

	CSP Central receiver 3hrs	CSP Central receiver 6hrs	CSP Central receiver 9hrs	PV Crystalline silicon fixed tilt
Rated capacity, net (MW)	125	125	125	10
Adjusted overnight capital cost (R/kW)	41 469	49 513	56 949	29 141
Fixed O&M cost (R/kW) per year	537	555	573	208
Variable O&M cost (R/MWh)	0	0	0	0
Variable fuel cost (R/GJ)	0	0	0	0
CO_2 emissions (kg/MWh)	0	0	0	0

Table 25:   *Technologies for renewable sources - 2 [37].*

J.   Import hydro [37]

Appendix J displays the new technology costs input that were used in the model for technologies that use hydro imports as a source of energy. The contents of this appendix were taken from the IRP update report [37].

	Import hydro (Moz A)	Import hydro (Moz B)	Import hydro (Moz C)	Import hydro (Zam A)	Import hydro (Zam B)	Import hydro (Zam C)
Rated capacity, net (MW)	1 500	850	160	120	250	120
Adjusted overnight capital cost (R/kW)	21 117	9 874	17 414	10 877	7 355	4 900
Fixed O&M cost (R/kW) per year	344	80.2	80.2	80.2	80.2	80.2
Variable O&M cost (R/MWh)	0	0	13.9	13.9	13.9	13.9
Variable fuel cost (R/GJ)	0	0	0	0	0	0
CO_2 emissions (kg/MWh)	0	0	0	0	0	0

Table 26:   *Import hydro [37].*

Where:

- Moz is Mozambique
- Zam is Zambia

K. Load shedding days and stages

Appendix K shows the dates when the South African public electricity utility implemented load shedding, within 1 April 2018 to 31 March 2019 financial year. The stages are the highest load shedding stages implemented on that particular day. That is if the load shedding started at stage 1, then increased to stage 2 and ended in stage 3, stage 3 will be used for that day.

Date	Highest load shedding stage implemented	Source
14/6/2018	stage 1	[17]
15/6/2018	stage 1	[17]
16/6/2018	stage 1	[17]
31/7/2018	stage 1	[17]
18/11/2018	stage 1	[45]
1/12/2018	stage 2	[24]
2/12/2018	stage 2	[11]
3/12/2018	stage 2	[25]
4/12/2018	stage 2	[46]
5/12/2018	stage 2	[47]
6/12/2018	stage 2	[48]
7/12/2018	stage 2	[49]
8/12/2018	stage 1	[26]
10/2/2019	stage 2	[20]
11/2/2019	stage 4	[31]
12/2/2019	stage 3	[30]
13/2/2019	stage 3	[50]
14/2/2019	stage 2	[21]
15/3/2019	stage 2	[18]
16/3/2019	stage 4	[51]
17/3/2019	stage 4	[52]
18/3/2019	stage 4	[56]
19/3/2019	stage 4	[57]
20/3/2019	stage 4	[53]
21/3/2019	stage 4	[58]
22/3/2019	stage 2	[54]
23/3/2019	stage 2	[58]

Table 27: *Load shedding days and stages.*