Annex X:

Cost-Effectiveness Payback Period Transformer Model for PCB Study

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The model described below documents the inputs and the calculation methodology followed by the Excel spreadsheet developed in order to estimate the necessary investment and the benefits for upgrading the distribution and transmission transformers in service that may contain hazardous levels of PCBs in the cooling fluid.

One of the challenges in the phase-out of PCB equipment is the cost associated with the replacement of the existing contaminated transformers and switchgear. The reason for this spreadsheet is to evaluate and quantify the economic benefits to the removal of PCBs and the upgrading of this infrastructure. This spreadsheet looks at the cost of replacing contaminated equipment by quantifying the value of the energy savings that will come from replacing a pre-1990, PCB-contaminated transformer with more energy-efficient models that incorporates modern (efficient) core steel and manufacturing techniques that reduce transformer losses. This is important because the purchase price of a transformer is just a fraction of the total cost of ownership of a transformer - the running cost, or the electricity that is lost in the transformer, is far greater.

To illustrate this point, we compare the purchase price and running cost of a 200 kVA three-phase transformer in Eswatini. Two designs are considered – one which is the standard, inefficient model (left) and one which has a reasonably good level of efficiency (right). The pie charts show the purchase price in blue and the running costs in orange. The overall diameter of each pie chart corresponds to the cost incurred by the utility.

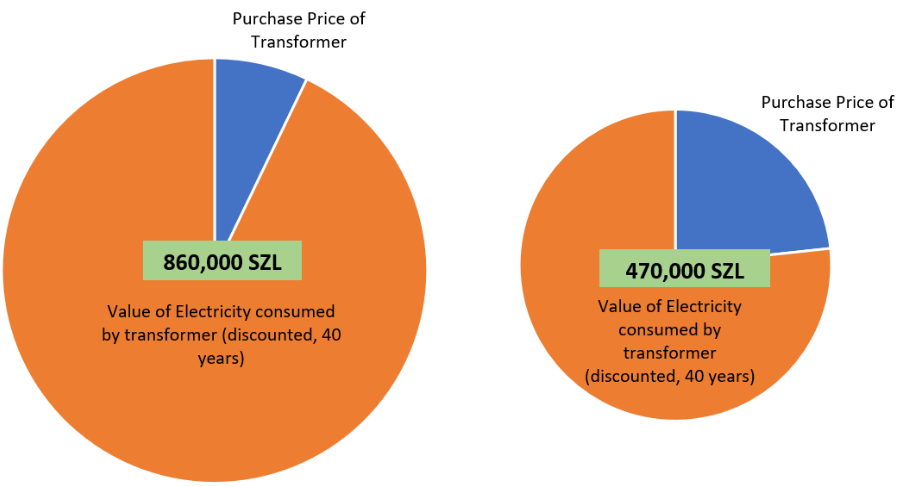

Figure 1. Comparison of purchase price (blue) and running cost (orange) over 40 years of an inefficient and efficient 200 kVA three-phase transformer in Eswatini

For the low efficiency model, the purchase price corresponds to approximately 7% of the total cost of ownership for a given rating, and electricity losses make up the balance of 93%. Over the 40 year analysis period, the cost to the utility for that inefficient design is 860,000 SZL. The efficient design has a total ownership cost of 470,000 SZL, taking into account purchase price and running cost (at the same average (RMS) load). For this efficient design, the purchase price is a higher proportion of the total ownership cost – around 23% of 470,000 SZL. This example demonstrates that energy-efficient transformers may cost a little more at the time of purchase, but they have significantly lower running costs – thus the total cost incurred by the electric utility when supplying electricity is significantly lower.

This document is broken into three parts – inputs, calculation methodology and outputs. For each of these, screen captures are included in order to enable the users to clearly navigate the spreadsheet tool.

The excel file with the spreadsheet can be downloaded separately:

Part 1. Inputs

Like all modelling exercises, the quality of the inputs directly correlates to the quality of the outputs. For this version of the model, all of the inputs needed to run the model are given on one Excel tab. The numbers or options that are adjustable are highlighted in bright yellow. Please note that the spreadsheet itself is 'protected' to avoid accidental damage to the links or formulas on the page. However, if the user wants to unlock the page for editing, then they simply need to select "Review" from the main menu and click on the icon marked "Unprotect Sheet" – no password is needed.

Figure 2. MS Excel Button for Unprotecting the Worksheet

Input #1. Country, discount rate and electricity price.

Please select the country you are modelling from the drop menu (click on the country name and the down arrow will appear to the right of the cell). The user may select from: Botswana, Eswatini, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Seychelles, Tanzania, Zambia and Zimbabwe. Please enter the discount rate for your electric utility and the value of a kWh of electricity consumed at a transmission or distribution transformer.

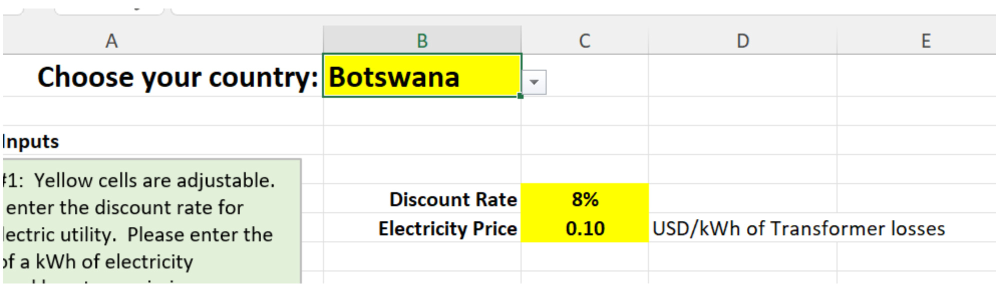

Figure 3. Screen clip from the Modelling Tool that shows the first three user inputs

Input #2. Number of transformers installed before 1990

The number of transformers installed before 1990 in each national network are scaled from the stock and age of transformers in the Mozambique network. If you wish to correct / modify these estimates, please enter new numbers in the yellow shaded cells shown in Figure 4. Note that for each entry there is a representative kVA rating which is meant to capture the number of units between the "Range of kVA ratings" in the range shown for low kVA to high kVA.

Total Number of Transformers installed in your Electricity Network that were installed in or before 1990

Range of kVA ratings Low (kVA)	High (kVA)	Representative Model (kVA)	Moz. estimate for your country (# units)	Your Country Estimate (# units)
30	70	50	3	3
100	160	100	13	13
200	250	250	17	17
300	400	315	31	31
500	650	500	41	41
750	1,000	800	9	9
1,500	2,500	1,500	4	4
3,500	6,300	5,000	2	2
8,000	20,000	10,000	16	16
22,500	55,000	30,000	10	10
100,000	200,000	100,000	2	2
		Total # transformers that are pre-1990:	148	148

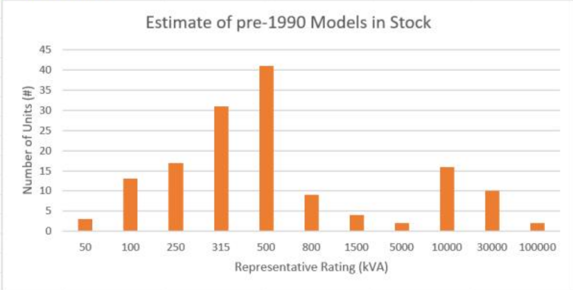

Figure 4. User-inputs for the number of transformers still in service in your network which are pre-1990. These initial estimates are scaled from the Mozambique database.

Input #3. Pre-1990 Models that Need Replacement (PCB contaminated)

These inputs – the results of transformers sampled and tested for a Screening Test, Gas Chromatography Test and Degree of Polymerisation Test - is expected to vary widely across the region. The flow diagram (Figure 5) is included to assist with estimating the number of transformers that are in need of being replaced with new, PCB-free, energy-efficient models. In Figure 6, the yellow cells are where users enter the percentage of transformers that pass (do not contain PCBs > 50 ppm) or fail (do contain PCBs > 50 ppm) for each of the three tests shown. In order to assess the accuracy of these percentages, there is table below the user inputs (see Figure 6) that shows the results (both in absolute numbers of units and percentages) of the percentages you enter at the various kVA ratings.

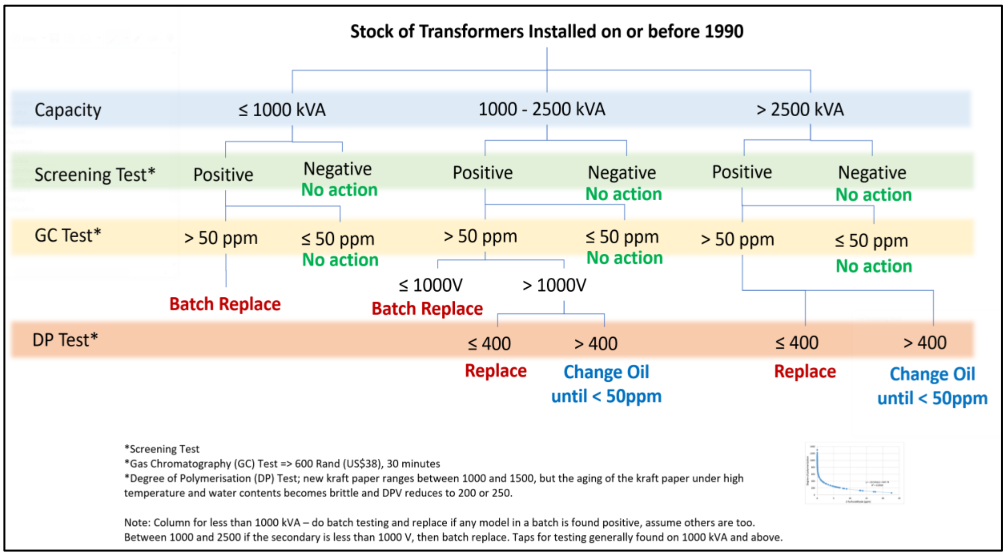

Figure 5. Flow diagram depicting the three tests conducted to determine PCB contamination and appropriate action to take depending on the capacity of the transformer.

	Screening Test	Gas Chromotagraphy Test	Degree of Polymerisation Test
	% Failure	*% Failure*	*% Failure*
Pass	**20%**	**10%**	**50%**
Fail	**80%**	**90%**	**50%**
Pass, Starting Estima	20%	10%	50%
Fail, Starting Estimat	80%	90%	50%

Capacity	Quantity of units pre-1990	# of pre-1990 that need to be Replaced	Percent Needing Replacement
kVA	*number*	*number*	*%*
50	3	3	100%
100	13	10	77%
250	17	13	76%
315	31	23	74%
500	41	30	73%
800	9	7	78%
1,500	4	2	50%
5,000	2	1	50%
10,000	16	6	38%
30,000	10	4	40%
100,000	2	1	50%
Total # transformers:	**148**	**100**	

Figure 6. The yellow cells depict where the users should enter the percentages of pass/fail for each of the three tests, and the table below shows how these percentages translate into numbers of transformers that are PCB contaminated and need to be replaced.

Input #4. Price and Performance of Transformers that need replacement

For each of the transformer ratings shown, please update the yellow cells (see Figure 7) to show the typical losses (at 100% load) for a non-evaluated (low efficiency) transformer and for a high efficiency unit. The price of the high efficiency unit should also be entered since the spreadsheet calculates the number of years before the new unit fully pays for itself through energy savings. Please also enter the average loading for this particular kVA rating (root mean square).

of filled ner	Low Efficiency Transformer Price	Core Losses of Low Efficiency Transformer	Coil Losses of Low Efficiency Transformer	High Efficiency Transformer Price	Core Losses of High Efficiency Transformer	Coil Losses of High Efficiency Transformer	Percentage Loading on Transformer	Low Effi Transfo Annual l
	USD	*Watts*	*Watts*	*USD*	*Watts*	*Watts*	*(RMS)*	*kWh/y*
	$ 1,000	190	1,200	$ 1,800	90	720	40%	3,34
	$ 1,800	320	2,100	$ 3,240	140	1,260	50%	7,40
	$ 3,600	700	4,000	$ 6,480	310	2,400	50%	14,8
	$ 4,300	920	4,600	$ 7,740	410	2,760	50%	18,1
	$ 6,000	1,300	7,000	$ 10,800	580	4,200	50%	26,7
	$ 8,500	1,800	9,200	$ 15,300	810	5,520	50%	35,9
	$ 11,000	2,800	14,000	$ 16,000	1,250	8,400	50%	55,1
	$ 26,000	7,300	40,000	$ 35,000	3,300	24,000	50%	151,5
	$ 44,000	13,500	65,000	$ 59,000	6,000	39,000	50%	260,6
	$ 91,000	35,000	140,000	$ 115,000	16,000	84,000	50%	613,2
	$ 228,000	69,000	350,000	$ 287,000	31,000	210,000	50%	1,370,

Figure 7. The yellow cells depict where the user can enter the typical losses for low-efficiency transformer and a high efficiency transformer and the anticipated RMS loading.

Part 2. Calculation Methodology

Collecting data on the installed stock of transmission and distribution transformers from the countries participating in this GEF PCB project was difficult. The only country for which we were able to secure a complete set of the installed stock of transformers was Mozambique. We therefore used this stock of transformers for Mozambique and then the output from the UNEP United for Efficiency (U4E) transformer stock model estimates the number and age of the installed stock of transformers in each country. These numbers are only estimates, and where the utilities subsequently develop, locate and gather new and better data on their actual installed stock, so the inputs can be adjusted to reflect the new data from the field. At this stage of the project however, it was decided to conclude this effort – after two years – using estimates due to the unavailability of actual field data.

Step 1. Estimating pre-1990 installed stock of T&D Transformers

Mozambique provided a complete database of the number and age of installed transformers in their transmission and distribution network. There are a total of 443 transformers in service in Mozambique that were installed in 1990 or earlier. The two graphs in Figure 8 below present the number of units by capacity and number of units.

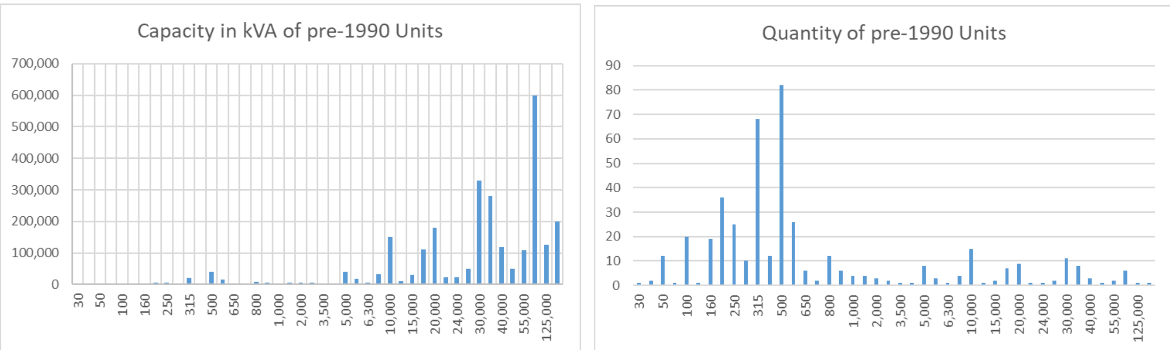

Figure 8. Illustration of the installed stock of pre-1990 transformers in Mozambique, on the left by total kVA capacity by kVA rating and on the right by numbers of individual kVA ratings.

Due to the fact that there are over 44 different kVA ratings between 30 and 200,000 kVA in the Mozambique database, these have to be simplified in order to create a manageable number of representative kVA ratings that are used in the calculations for investment and savings. This step happens automatically, as shown by the table below.

Table 1. Simplification of the Number of kVA Ratings Used in the Model

Representative kVA Rating in the Model	kVA Rating on the Low End of the Range	kVA Rating on the High End of the Range	Mozambique kVA Ratings Included in the Range of the Representative kVA Rating
50	30	70	30, 40, 50, 70
100	100	160	100, 150, 160
250	200	250	200, 250
315	300	400	300, 315, 400
500	500	650	500, 630, 650
800	750	1000	750, 800, 850, 1000
1500	1500	2500	1500, 2000, 2500
5000	3500	6300	3500, 4000, 5000, 6000, 6300
10000	8000	20000	8000, 10000, 12000, 15000, 16000, 20000
30000	22500	55000	22500, 24000, 25000, 30000, 35000, 40000, 50000, 55000
100000	100000	200000	100000, 125000, 200000

As discussed in the inputs part of this document (Input #1), the user selects the country they are interested in, and when doing so, the installed stock on which the whole model changes to reflect the estimates for that country. The user may select: Botswana, Eswatini, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Seychelles, Tanzania, Zambia and Zimbabwe.

When making this selection the installed stock estimates of transformers between 2020 and 2030 are summed together and compared with Mozambique to develop a 'scalar' for adjusting the known stock of Mozambique and thereby preparing an estimate for the country selected. Mozambique has the largest number of transformers in its stock, and the other countries are as shown in Table 2.

Table 2. Scalars calculated for each country to adjust the stock of Mozambique to their estimate

Country	Average, 2020-2030
Botswana	37%
Eswatini	17%
Lesotho	9%
Madagascar	22%
Malawi	18%
Mauritius	33%
Mozambique	100%
Namibia	44%
Seychelles	3%
Tanzania	52%
Zambia	74%
Zimbabwe	79%

Thus, the known number of pre-1990 transmission and distribution transformers found in Mozambique are scaled according to these percentages to arrive at estimates of the number of pre-1990 transformers in each of the other 11 countries. If new data becomes available for the country selected, the user can simply type those numbers into the yellow shaded cells, replacing the links that are scaling the stock from the Mozambique adjusted stock. In this way, all of the subsequent calculations can be based on actual / more accurate data.

Step 2. Calculate the Number of PCB Contaminated Units

With an estimate of the stock of transformers installed in or before 1990 in the country, the next step is to determine which ones have PCB contamination. According to interviews with ESKOM, the decision-matrix for whether a transformer contains PCBs and how to treat it depends on the rating of the transformer and one or more of three tests.

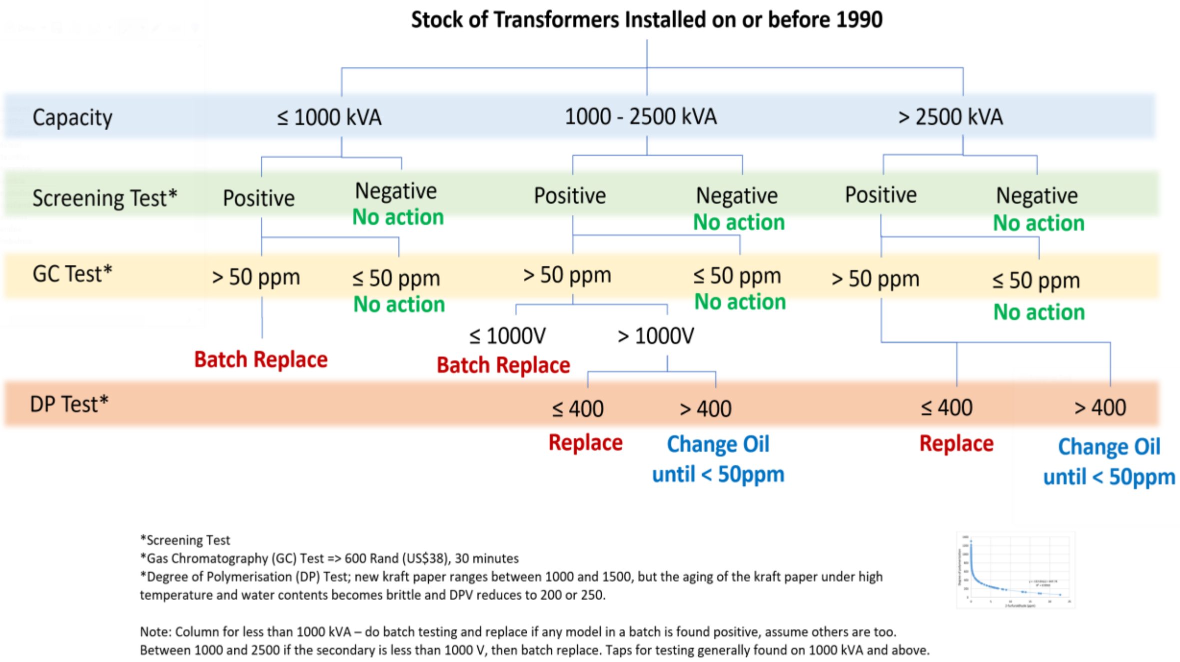

Figure 9. Flow diagram depicting the three tests conducted to determine PCB contamination and appropriate action to take depending on the capacity of the transformer.

The starting values (working assumptions) based on internal discussion within the team are as presented in Table 3 below.

Table 3. Initial Values Used for Tests to Determine if a Unit Passes or Fails on PCB Contamination

Outcome of Test	Screening Test	Gas Chromatography Test	Degree of Polymerisation Test
Pass (not >50 ppm)	20%	10%	50%
Fail (>50 ppm PCB)	80%	90%	50%

The user must adjust the values contained in the yellow highlighted cells in order to determine a reasonable estimate of the number of units that need to be replaced. Depending on the kVA rating and the percentages, transformers can be 'batch replaced' or 'replaced' or simply have their cooling fluid flushed multiple times until the ppm concentration of PCBs is low enough not to pose a threat (i.e., <50 ppm).

Step 3. Transformer Market Information – Cost and Performance for Your Utility
Having an estimate of the number of units that have to be replaced, the next step is to calculate the necessary investment to replace those that need to be replaced. For this step in the calculation, the model relies on market estimates that were developed in June 2022 with input from the International Copper Association and a freelance transformer consultant who operates in the SADC region. The table below provides the kVA rating and voltages, as well as the losses and price associated with that design at each of the representative kVA ratings. These are shown in Table 3.

Table 4. Initial Estimates of Price and Performance of Standard and High Efficiency Transformers

Capacity	High Volt	Low Volt	Standard Price	Core Losses	Coil Losses	High Eff. Price	HE Core Losses	HE Coil Losses	Loading	Electricity Cost
kVA	kV	kV	USD	Watts	Watts	USD	Watts	Watts	(RMS)	($/kWh)
50	22	0.4	$1,000	190	1,200	$1,800	90	720	40%	0.10
100	22	0.4	$1,800	320	2,100	$3,240	140	1,260	50%	0.10
250	22	0.4	$3,600	700	4,000	$6,480	310	2,400	50%	0.10
315	22	0.4	$4,300	920	4,600	$7,740	410	2,760	50%	0.10
500	22	0.4	$6,000	1,300	7,000	$10,800	580	4,200	50%	0.10
800	11	0.4	$8,500	1,800	9,200	$15,300	810	5,520	50%	0.10
1,500	11	5.5	$11,000	2,800	14,000	$16,000	1,250	8,400	50%	0.10
5,000	22	6.6	$26,000	7,300	40,000	$35,000	3,300	24,000	50%	0.10
10,000	33	11	$44,000	13,500	65,000	$59,000	6,000	39,000	50%	0.10
30,000	220	113	$91,000	35,000	140,000	$115,000	16,000	84,000	50%	0.10
100,000	220	110	$228,000	69,000	350,000	$287,000	31,000	210,000	50%	0.10

These values – both the price and the performance - can be modified by the end-user to reflect the actual values they have in their most recent tender offers at their utility for those or similar ratings.

Next, the spreadsheet calculates the cost of replacing all the contaminated old transformers with new, higher-efficiency ones. The total cost of replacing all the PCB units is then divided by six, to spread out evenly (in Nominal Terms) the investment necessary in the T&D network over a six year period, starting in 2023 and running through 2028, which is the deadline in the Stockholm Convention.

These values are then calculated on a time series table, and the nominal values are discounted according to the discount rate declared by the user. The table looks at the time period from 2023 (assume year of programme implementation) through to 2035. The transformers are expected to continue in service for decades after this, accruing savings, but the calculation stops there because the initial capital investment has been recovered and now net savings are being achieved. This can be seen in the figure below which depicts the situation for Mozambique. From this table, all the results figures are derived.

	Discount Rate:	8%											
	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Investment:	$ 1,012,603	$ 1,012,603	$ 1,012,603	$ 1,012,603	$ 1,012,603	$ 1,012,603							
Savings	$ -	$ 187,946	$ 375,892	$ 563,838	$ 751,784	$ 939,730	$ 1,127,676	$ 1,127,676	$ 1,127,676	$ 1,127,676	$ 1,127,676	$ 1,127,676	$ 1,127,676
Discounted Investment	$ 1,012,603	$ 937,596	$ 868,144	$ 803,837	$ 744,294	$ 689,161							
Discounted Savings	$ -	$ 174,024	$ 322,267	$ 447,593	$ 552,584	$ 639,565	$ 710,627	$ 657,988	$ 609,248	$ 564,119	$ 522,332	$ 483,641	$ 447,816
Cumulative Discounted Investment	$ 1,012,603	$ 1,950,199	$ 2,818,343	$ 3,622,180	$ 4,366,474	$ 5,055,635							
Cumulative Discounted Savings	$ -	$ 174,024	$ 496,291	$ 943,884	$ 1,496,468	$ 2,136,032	$ 2,846,659	$ 3,504,648	$ 4,113,896	$ 4,678,015	$ 5,200,347	$ 5,683,988	$ 6,131,804
NPV Investment	$ 5,055,635												
NPV Savings	$ 6,131,804												

Figure 10. Illustration of the calculation of nominal and discounted dollars for the investment in Energy-Efficient Transformers.

Part 3. Results

The results of the calculation are presented on the first tab, named "Inputs and results". The results are presented below the inputs, from rows 76 through 88, and in columns A through I. There are tabular and graphical results. Everything is labelled and are reproduced here with the sample results for Botswana.

Results		
Country:		Botswana
Total Investment Needed over 6 years, nominal USD:	$	1,899,160
Annual investment for each year in USD, 2023-2028 (six years):	$	316,527
Net Present Value of Investment, cumulative 2023-2028 (2022 USD):	$	1,580,326
Net Present Value of Savings, cumulative 2023-2035 (2022 USD):	$	1,885,697
Annual Energy Savings after replacing all PCB transformers (kWh):		3,467,912
Annual Network Savings in USD after replacing all PCB transformers:	$	346,791
Annual CO2 Savings after replacing all PCB transformers (metric tonnes):		475
Value of annual CO2 savings at USD $24.27 per tonne (USD)	$	11,531

Figure 11. Tabular results showing the total investment needed in the country to replace all the PCB transformers that were estimated to be in the installed stock.

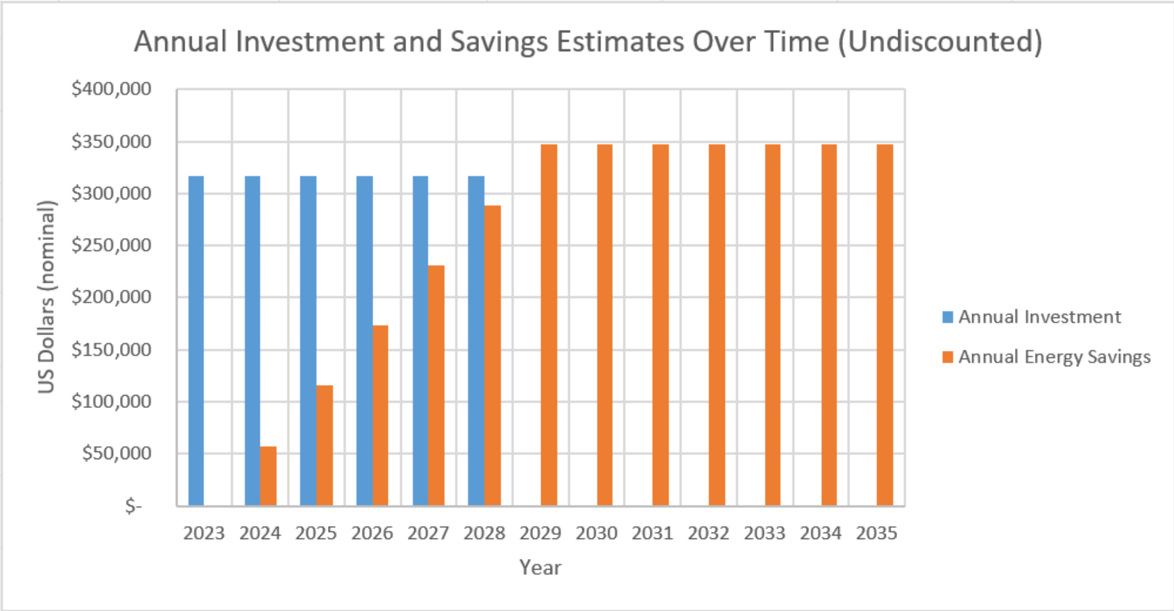

Figure 12. Graphical results showing the annual investment and savings over a 13 year time period – undiscounted (nominal) US dollars.

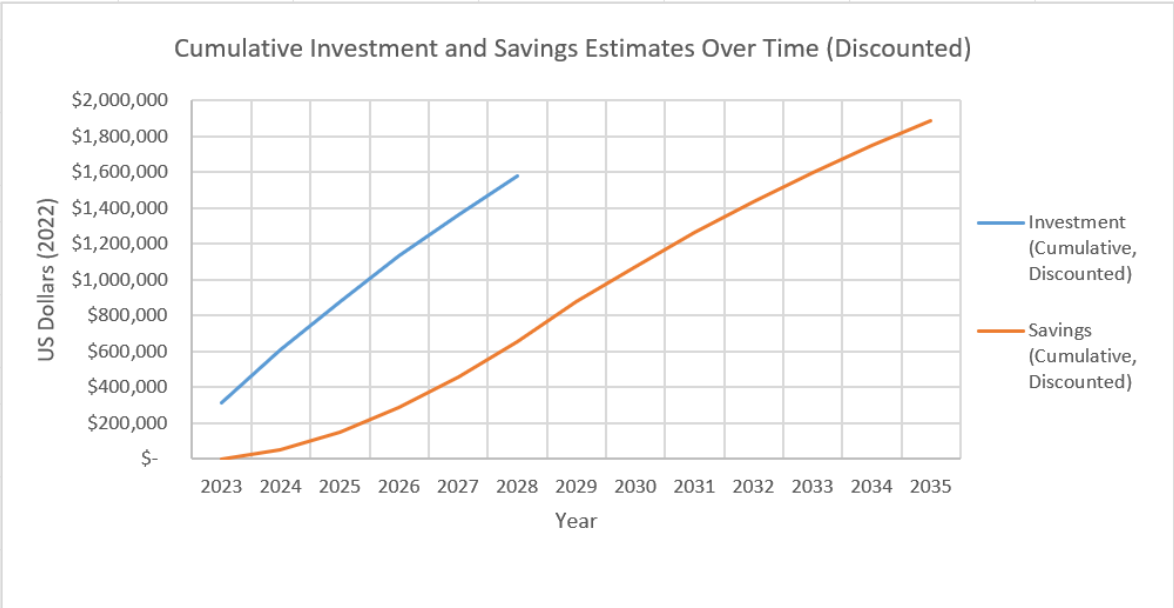

Figure 13. Graphical results showing the cumulative investment and savings over a 13 year time period – discounted 2022 US dollars.