Chapter 5

TESTING AND VALIDATION

This chapter provides a critical analysis of the results obtained after the execution of the ESM. To this end, a fictional system with requirements similar to a system as discussed in section 1.1 is sized by the ESM using both theoretical inputs and inputs from the TSM. The chapter commences with a basic description of the requirements of this fictional system, and provides a walkthrough of the application's functional units. The system validation is performed and the ESM results are verified against analytical solutions based on the design criteria of Chapter 4. A results-comparison follows showing the influence of the introduction of the TSM, and comments on other application related parameters. Finally, a summary of the results is presented and concluding remarks are made.

5.1 TESTING METHODOLOGY

For proper system evaluation, we must define a case study where specific REHS-based plant requirements can be fed into the ESM. The outputs of the ESM can then be systematically compared using a scenario-based approach, where each scenario is defined according to the types of outputs presented. The analysis of each scenario is based on a costs-comparison of components which are differentiated by the variation of the effective component output specifications using the TSM, and using theoretical values (based on the datasheet information). A results comparison of the optimal REHS-based plant configurations then follows by looking at specific scenario results and similar costing results as determined by using external software products which use system definitions similar to that of the case study. Firstly, we briefly introduce two software products that are freely available on a trial-basis which are used to compare costing results with that of the ESM.

5.2 EXTERNAL SOFTWARE

In order to perform a results verification and application functionality validation, we need to call in the aid of external software products, which incorporate functionality similar to that of the ESM. While the ESM is a unique application, specifically created for the sizing and costing of an REHS-based plant, the modules that it is constituted of may be comparable to other software products. For the purposes of results-verification of some of these ESM modules by users, we introduce two software products that incorporate renewable energy sources for the sizing of proprietary systems.

5.2.1 HOMER

The first application is called the Hybrid Optimization Model for Electric Renewables (HOMER), and is a computer model that simplifies the task of designing both on-grid and off-grid distributed generation systems [50]. When looking at the system capability, it allows for the custom creation of a system based on different technologies and adds the capability to import many different energy sources and loads. The results generated are more focused on the technical aspects of the sized system, although the costing aspects are thoroughly incorporated.

5.2.2 Rentech

The second comparative software package used for the verification of results was designed by Rentech, a South African company and a division of Battery Technologies (Pty) Ltd [51].

The company is a leading provider of PV equipment and system solutions for the rural electrification, grid-connect and telecommunications markets for both South Africa and the African market.

The specific application used in the proceeding comparisons, provides a detailed interface based in Microsoft Excel. It must be noted that the application was specifically created for the sizing of a PV installation where MPPT is implemented. The application can also output an approximate costing summary which includes the component costs for the PV modules, installation costs, sensor costs and battery costs. Using this module, we may be able to provide a degree of verification for the results of the PV array sizing module.

5.3 CASE STUDY

In order to show how the ESM Graphical User Interfaces work, and in order to analyse the results as outputted by the ESM we need to define a case-study which represents the possible design criteria of an imaginary client. To this end, we continue to specify certain requirements that are to be inputted into the ESM.

5.3.1 Renewable energy requirements

The requirements are summarised in *Table 5.1*. Here we choose a system that has two main loads, namely the electrolyser array and the battery bank. The client also wants a combination of solar and wind technologies for renewable energy power generation. Other general requirements are added that must be brought into consideration when the total costs are determined by the ESM.

Table 5.1 – Case study requirements summary

Class	Main requirement description	Constraints
Energy	Wind turbine implementation	Turbine manufacturers limited to Whisper and Kestral
Energy	PV panel implementation	Panel manufacturers limited to SolarWorld and Tenesol
Energy	Optimal allocation of wind and solar technologies for plant at Alexander Bay	All costs to be considered
Load	Hydrogen production rate of at least 6kg per day	
Load	A battery bank must provide power when renewable energy sources do not produce electricity	Full power must be supplied to the electrolyser
General	Two 3000W air conditioning units must be installed	
General	Ten lighting units each housing two 60W fluorescent tubes	
General	Two CompactRIO controllers for system monitoring and control	
General	A seperate unit for meteorological measurement	100m from the control centre
General	Two temperature sensors	Forms part of the weather unit
General	One anemometer	Forms part of the weather unit
General	One pyranometer	Forms part of the weather unit
General	One byranometer	Forms part of the weather unit
General	One higrometer	Forms part of the weather unit

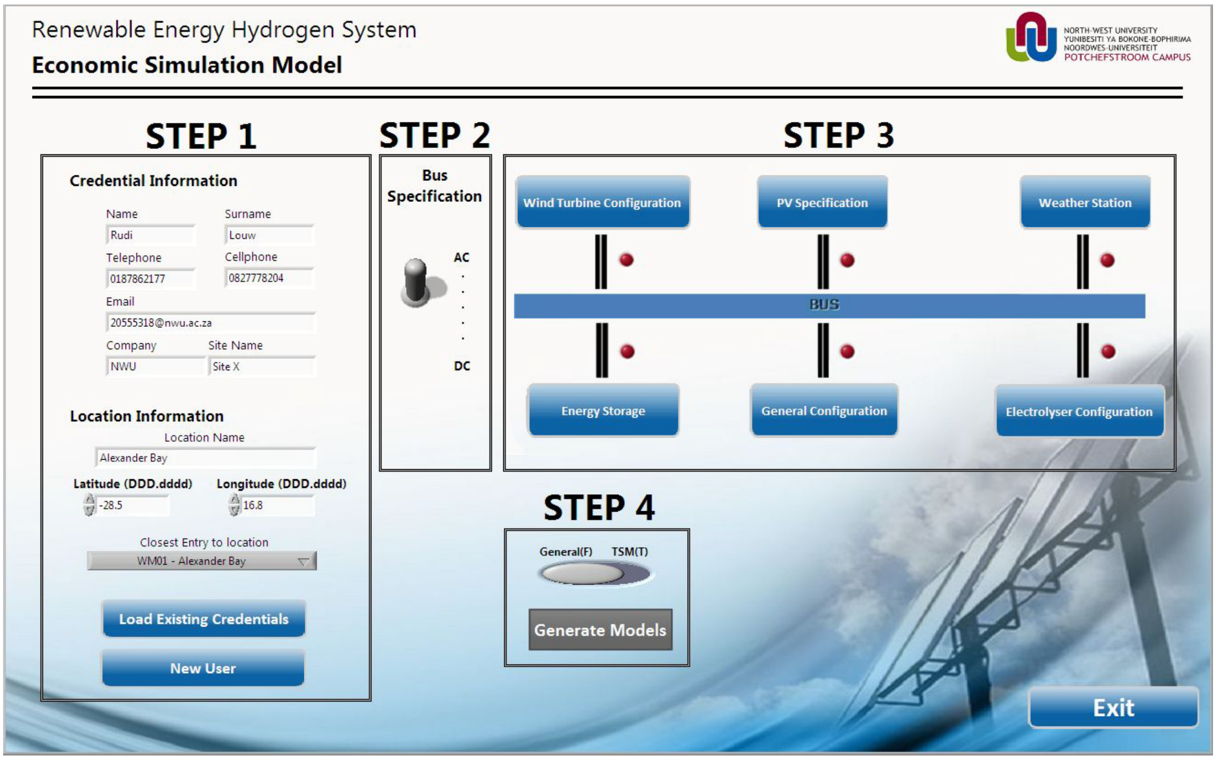
To demonstrate how the requirements listed in *Table 5.1* are inputted into the ESM, we continue to describe the application interfaces, with each associated interface showing the inputted requirements.

5.4 APPLICATION DESCRIPTION

The ESM LabVIEW application uses a front panel VI which calls a multitude of subVI's (VI's containing functional units used by the main VI, and only perform a specific function) for proper application functionality. This is very much the same as defining "functions" in a text-based coding language such as C#. The front panel is a collective term where most of the interfaces with which the user interacts, is present. This section will look at a step-wise application configuration process which uses the case-study requirements as inputs. Also, basic integration of the TSM is shown where applicable.

5.4.1 Front Panel

The front panel is the main interface with which the user specifies all the required component information. The first set of information that the ESM needs, and as shown in *Figure 5.1*, relates to the user credentials and location information. While the credential information is only used for model configuration references and backups, the location information forms a very important part of the proceeding steps.



Name: Rudi
Surname: Louw
Telephone: 0187862177
Cellphone: 0827778204
Email: 20555318@nwu.ac.za
Company: NWU
Site Name: Site X
Location Name: Alexander Bay
Latitude (DDD.dddd): -28.5
Longitude (DDD.dddd): 16.8
Closest Entry to location: WM01 - Alexander Bay

Figure 5.1 – ESM Front Panel

As described by a tooltip on the front panel, the entering of GPS coordinates for the specific site is a requirement of the TSM's solar modules, since, as stated in *section 4.1.2,* the solar data at that site is extracted for the sizing techniques. The selection of a "closest entry" to the specified location, as discussed in *section 4.1.2,* is used for wind power calculations, as wind speed information is limited to specific sites in the country. When a new user uses the ESM, all this information must be entered manually before continuing to the next step. Existing users may extract their information, and edit the information if necessary.

The next step involves the specification of plant component information. The diagram shown here is based on a general configuration of an REHS-based plant. The specific entity selection interfaces are discussed in the proceeding sections.

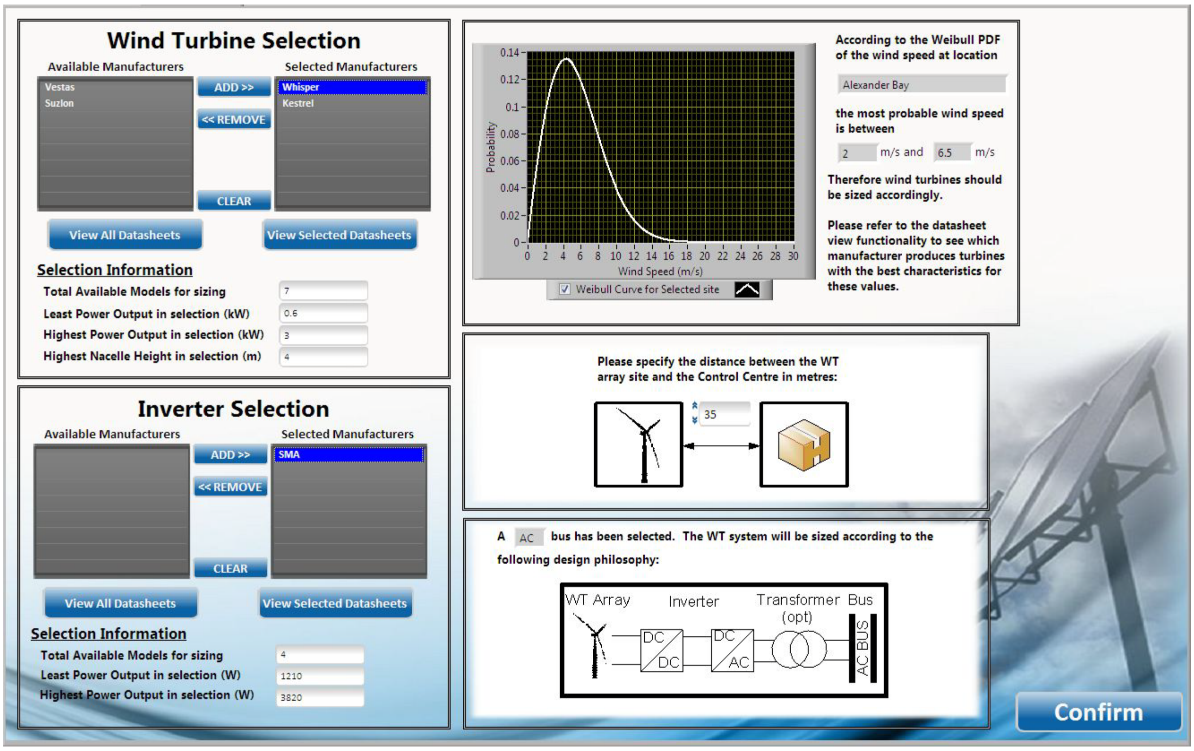
When this selection process is complete, the user may continue to the final step. Here, one first chooses whether general datasheet information is used for the optimal sizing procedures, or if the TSM information must be used. Using general datasheet values must only be done for comparative purposes, as this may result in a completely inaccurate plant configuration, as no existing meteorological data are brought into consideration.

When choosing the option where the TSM is integrated, the resulting plant configuration is much better suited to the locations meteorological characteristics. The TSM's integration methodology is discussed in detail in *Chapter 4* of this dissertation.

After the selection, the user can execute the optimal sizing procedure based on the specification inputs, by clicking on the "Generate Models" button. When this process has been completed, the user is presented with a file containing all the information pertaining to the optimal ratio of renewable energy source usage, the associated plant components and all costs that must be incurred for plant construction and lifetime maintenance.

5.4.2 Wind turbine configuration

The wind turbine array configuration interface, shown in *Figure 5.2*, allows the user to specify the information upon which the wind turbine sizing procedure is based.



Wind Turbine Selection – Available Manufacturers: Vestas, Suzlon; Selected Manufacturers: Whisper, Kestrel

Selection Information

Total Available Models for sizing: 7
Least Power Output in selection (kW): 0.6
Highest Power Output in selection (kW): 3
Highest Nacelle Height in selection (m): 4

Inverter Selection – Selected Manufacturers: SMA

Selection Information

Total Available Models for sizing: 4
Least Power Output in selection (W): 1210
Highest Power Output in selection (W): 3820

According to the Weibull PDF of the wind speed at location Alexander Bay the most probable wind speed is between 2 m/s and 6.5 m/s

Therefore wind turbines should be sized accordingly.

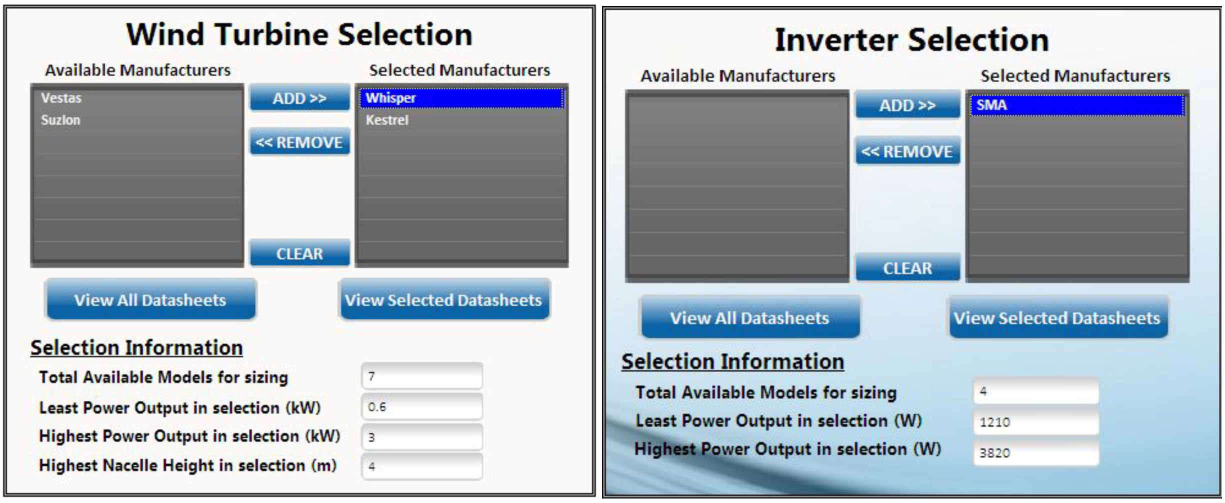
Please refer to the datasheet view functionality to see which manufacturer produces turbines with the best characteristics for these values.

Please specify the distance between the WT array site and the Control Centre in metres: 35

A AC bus has been selected. The WT system will be sized according to the following design philosophy:

Figure 5.2 – WT Configuration Interface

The first selection set refers to the selection of manufacturers of wind turbines and associated inverters/converters, and is shown in *Figure 5.3*.



Wind Turbine Selection – Available Manufacturers: Vestas, Suzlon; Selected Manufacturers: Whisper, Kestrel

Selection Information

Total Available Models for sizing: 7
Least Power Output in selection (kW): 0.6
Highest Power Output in selection (kW): 3
Highest Nacelle Height in selection (m): 4

Inverter Selection – Selected Manufacturers: SMA

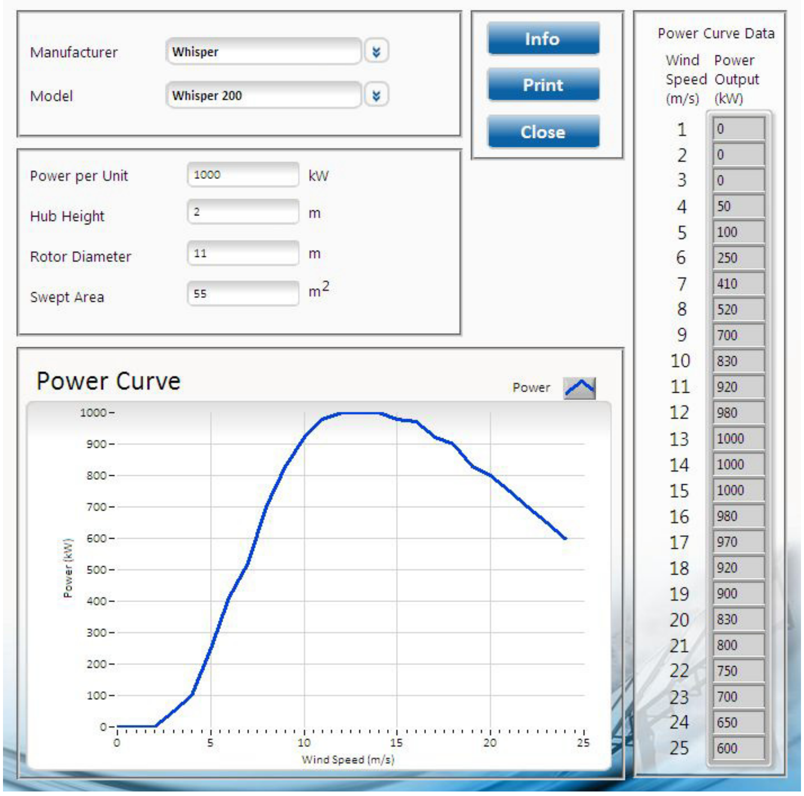
Selection Information

Total Available Models for sizing: 4
Least Power Output in selection (W): 1210
Highest Power Output in selection (W): 3820

Figure 5.3 – First WT Selection Set – Manufacturer Selection

All manufacturers listed in the database are shown in the "available manufacturers" list-boxes. When the user has selected the manufacturers, basic information based on the selection is displayed underneath the list-box units. The two turbine manufacturers listed in the case study requirements have been selected here.

For more specific wind turbine technical information, like a specific model's power curve, the user may click on "View All Datasheets" for complete database model listings, or "View Selected Datasheets" for viewing information only pertaining to models of the selected manufacturers. This interface is shown in *Figure 5.4*.



Manufacturer Whisper
Model Whisper 200

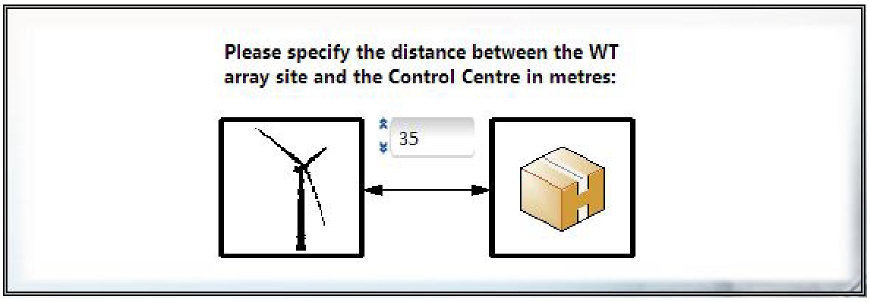
Power per Unit 1000 kW
Hub Height 2 m
Rotor Diameter 11 m
Swept Area 55 m^2

Power Curve Data

Wind Speed (m/s)	Power Output (kW)
1	0
2	0
3	0
4	50
5	100
6	250
7	410
8	520
9	700
10	830
11	920
12	980
13	1000
14	1000
15	1000
16	980
17	970
18	920
19	900
20	830
21	800
22	750
23	700
24	650
25	600

Figure 5.4 – WT Information Set – Turbine Database

The second selection set, shown in *Figure 5.5*, simply allows the user to specify the distance between the WT array site, and the control centre.



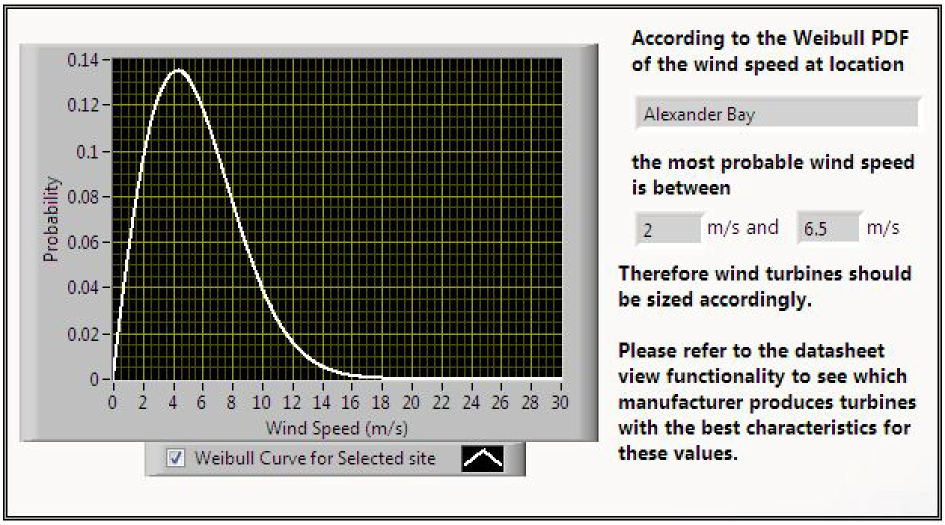
Please specify the distance between the WT array site and the Control Centre in metres:

35

Figure 5.5 – WT Selection – Distance specification

This input is then relayed to the optimal costing module where the transmission costs are brought into consideration. The information sets are used to relay additional information relating to the general WT system to the user, and may help finding an optimal solution faster (since the ESM will be limited to certain models, and doesn't have to cycle through all models in the database.

The first information set uses the Weibull PDF (Probability Density Function) module by De Klerk [2] to show the probability that a specified wind speed is to occur at a given site (in this case, Alexander Bay, as per case study). The integration of this module forms part of the optional requirements as specified in *section 1.2.*



According to the Weibull PDF of the wind speed at location

Alexander Bay

the most probable wind speed is between

2 m/s and 6.5 m/s

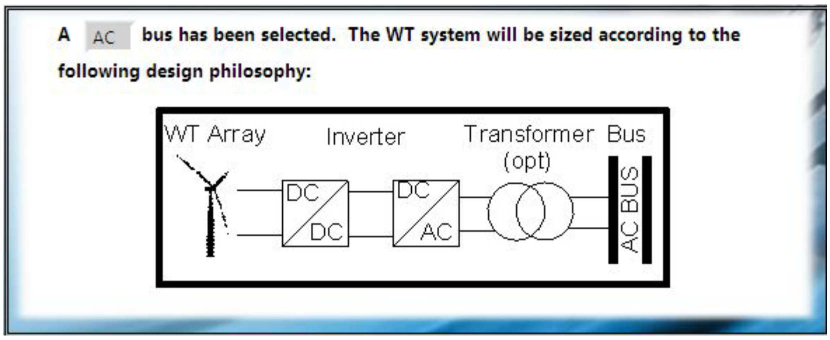
Therefore wind turbines should be sized accordingly.

Please refer to the datasheet view functionality to see which manufacturer produces turbines with the best characteristics for these values.

Figure 5.6 – WT Information Set – Probable Wind Speed

For this case study, the accompanying data informs the user that the most probable wind speed is found between $2\ m.s^{-1}$ and $6.5\ m.s^{-1}$. If the user wants to reduce calculation time of the optimal sizing procedure, only the manufacturers that manufacture a turbine that has good power characteristics between these two values should be selected. This can be done by executing the "Database View" module as described earlier.

The final information set for wind turbine configuration, illustrated by *Figure 5.7*, shows the user how the wind turbines and inverters/converters are to be connected, based on the choice of system bus. For the purposes of this case study, we chose an AC bus. The ESM dynamically updates the configuration diagram based on the choice of a system bus.



A AC bus has been selected. The WT system will be sized according to the following design philosophy:

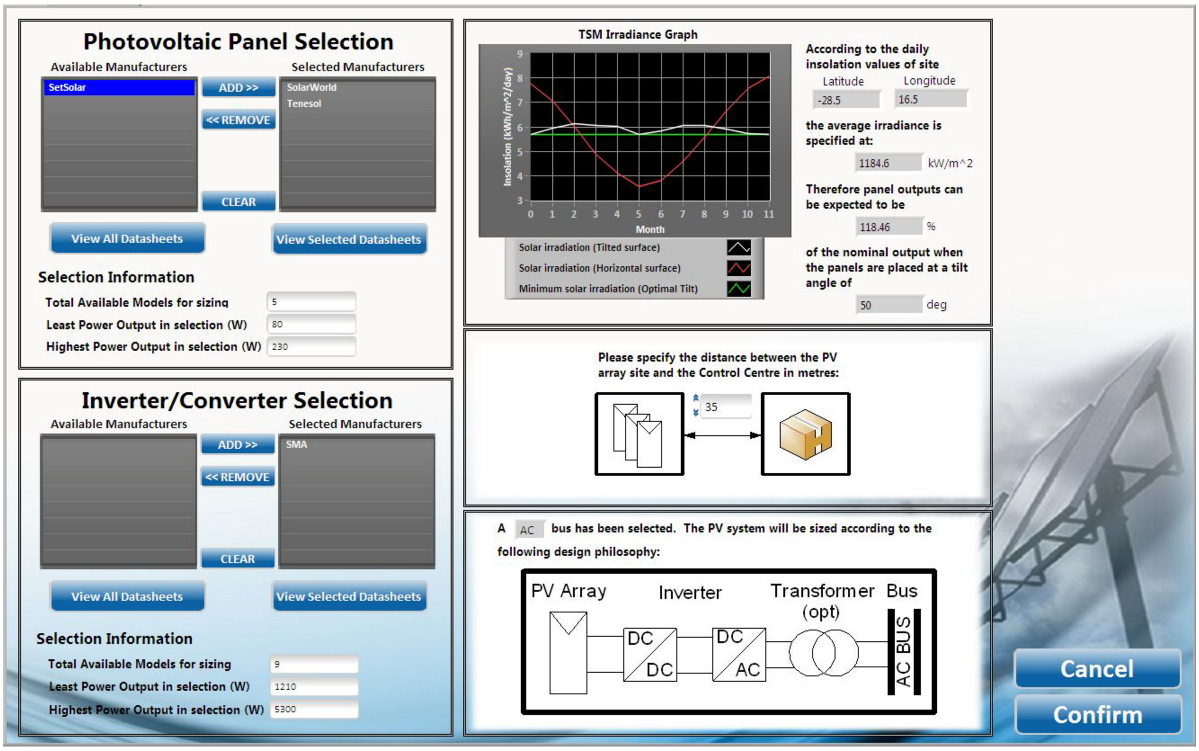
Figure 5.7 – WT Information – Connection philosophy

For the connection philosophy of a system using other configurations, refer to *Figure 4.5.*

When the user has completed the selection of the wind turbine system components, he/she may use the “Confirm” button to confirm the wind turbine selection and continue back to the front panel for further system specification.

5.4.3 PV array configuration

The PV array configuration interface, shown in *Figure 5.8*, allows the user to specify the information upon which the PV array sizing procedure is based.



Photovoltaic Panel Selection

Available Manufacturers: SetSolar

Selected Manufacturers: SolarWorld, Tenesol

Selection Information

Total Available Models for sizing: 5
Least Power Output in selection (W): 80
Highest Power Output in selection (W): 230

Inverter/Converter Selection

Selected Manufacturers: SMA

Selection Information

Total Available Models for sizing: 9
Least Power Output in selection (W): 1210
Highest Power Output in selection (W): 5300

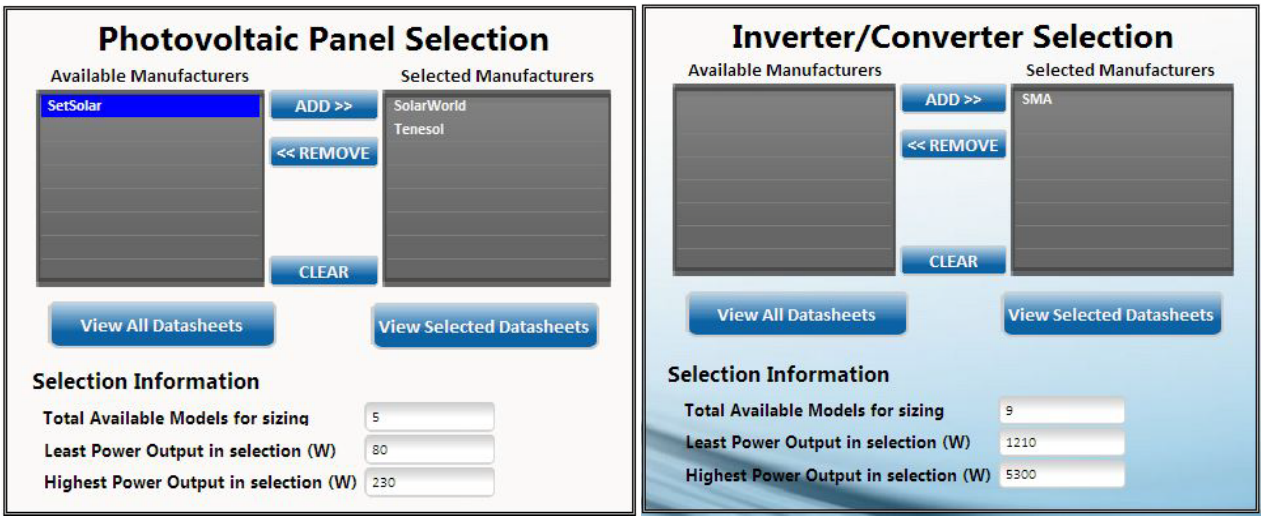
According to the daily insolation values of site
Latitude: -28.5
Longitude: 16.5
the average irradiance is specified at: 1184.6 kW/m^2
Therefore panel outputs can be expected to be 118.46 %
of the nominal output when the panels are placed at a tilt angle of 50 deg

Please specify the distance between the PV array site and the Control Centre in metres: 35

A AC bus has been selected. The PV system will be sized according to the following design philosophy:

Figure 5.8 – PV Configuration Interface

The first selection set refers to the selection of manufacturers of PV panels and inverters/converters, and is shown in *Figure 5.9*. All manufacturers listed in the database are shown in the "available manufacturers" list-boxes. When the user has selected the manufacturers, basic information based on the selection is displayed underneath the list-box units.



Selection Information

Total Available Models for sizing: 5
Least Power Output in selection (W): 80
Highest Power Output in selection (W): 230

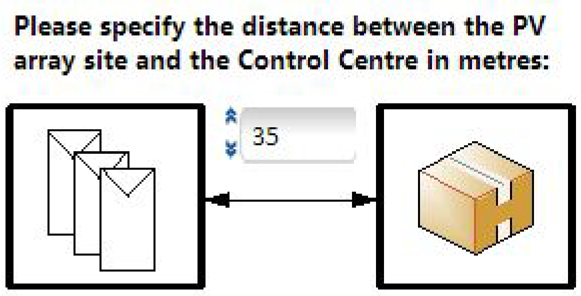
Selection Information

Total Available Models for sizing: 9
Least Power Output in selection (W): 1210
Highest Power Output in selection (W): 5300

Figure 5.9 – First PV Selection Set – Manufacturer Selection

As is the case for the wind turbine specification, the user may click on "View All Datasheets" for complete database model listings, or "View Selected Datasheets" for viewing technical information only pertaining to models of the selected manufacturers.

The second selection set, shown in *Figure 5.10*, allows the user to specify the distance between the PV array site, and the control centre. This value is separate to the value for the wind turbine site distance as configured by the set shown in *Figure 5.5*.



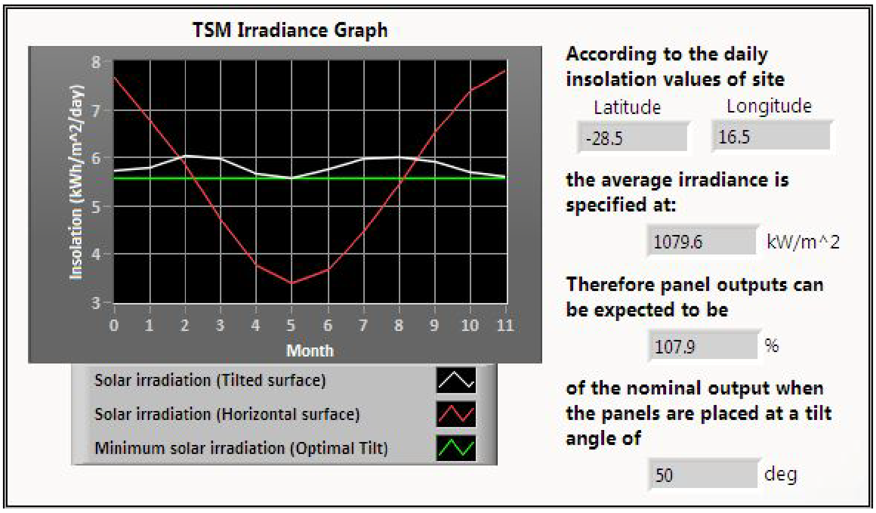
Please specify the distance between the PV array site and the Control Centre in metres: 35

Figure 5.10 – PV Selection – Distance specification

This input is also relayed to the optimal costing module where the transmission costs are brought into consideration.

The information sets are used to relay additional information relating to general PV system information to the user. The irradiance information set uses the optimal tilt module by De Klerk [2] to show how the location's average irradiance affects the PV module outputs. The integration of this module forms part of the optional requirement as specified in *section 1.2.*

The graph in *Figure 5.11* shows the yearly irradiance at the specified location incident on a horizontal surface (red) and the effective irradiance at the same location when the panels are tilted by the optimal amount (white).



According to the daily insolation values of site

Latitude: -28.5
Longitude: 16.5

the average irradiance is specified at: 1079.6 kW/m^2

Therefore panel outputs can be expected to be 107.9 %

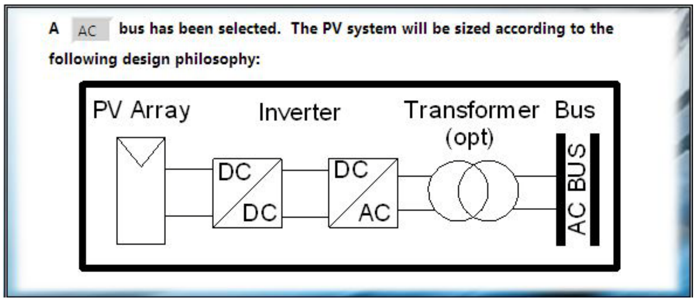
of the nominal output when the panels are placed at a tilt angle of 50 deg

Figure 5.11 – PV Information Set – Irradiance

For this case study, the accompanying information informs the user that the module outputs will equal to *107.9%* of the rated (at STC) outputs, based on the irradiance ratios.

As stated in *section 5.4.1*, the user may choose between the implementation of the TSM for the sizing procedure, and the usage of theoretical values as per the component datasheets. When the TSM is implemented, the altered output values given by the TSM solar modules are relayed to the sizing modules of the ESM, which ensures location-optimised results.

The final information set for PV configuration, illustrated by *Figure 5.12*, shows the user how the PV array(s) and inverters/converters are to be connected, based on the choice of system bus. For the purposes of this case study, we chose an AC bus.



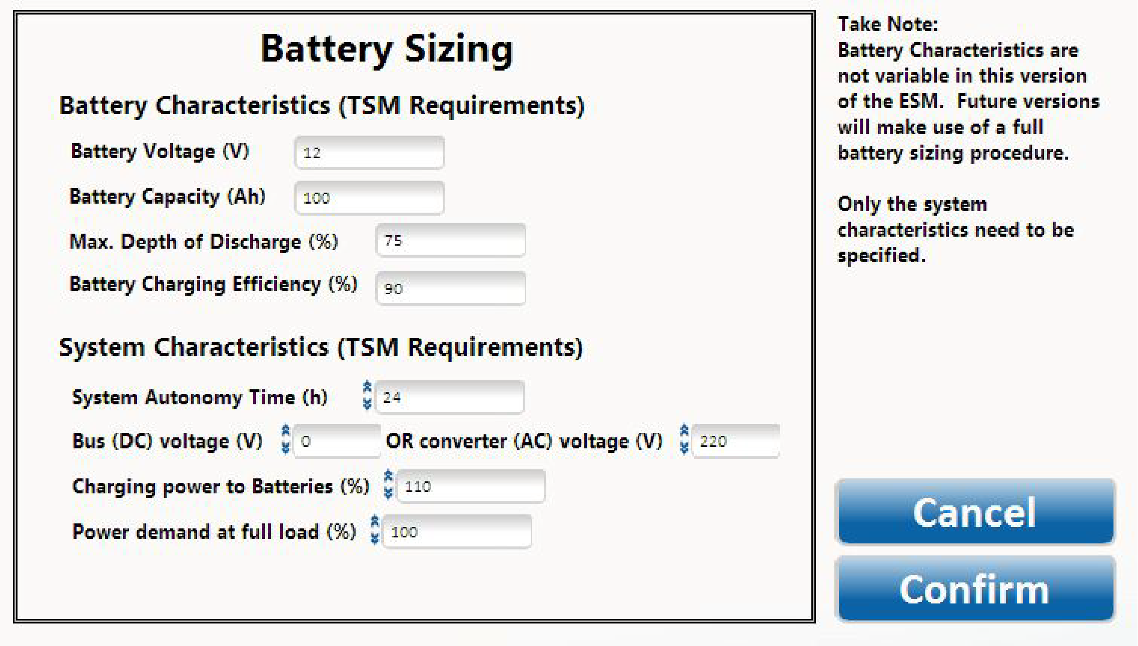
A AC bus has been selected. The PV system will be sized according to the following design philosophy:

Figure 5.12 – PV Information – Connection philosophy

For the connection philosophy of a system using a DC bus, refer to *Figure 4.2.* When the user has completed the selection of the PV system components, he/she may use the "Confirm" button to confirm the PV selection and continue back to the front panel for further system specification.

5.4.4 Output Storage

As specified in the requirements section of this thesis in *section 1.2,* and in *Chapter 4* where the development procedure was discussed, the current version of the ESM does not incorporate an economic sizing procedure for the battery bank. Therefore the current version implements a very simple interface which is directly linked to the TSM's battery sizing module by De Klerk [2]. This interface is shown in *Figure 5.13*. A single battery model is used for the ESM sizing procedure, with unchangeable battery characteristic values.



Battery Sizing

Battery Characteristics (TSM Requirements)

Battery Voltage (V) 12
Battery Capacity (Ah) 100
Max. Depth of Discharge (%) 75
Battery Charging Efficiency (%) 90

System Characteristics (TSM Requirements)

System Autonomy Time (h) 24
Bus (DC) voltage (V) 0 OR converter (AC) voltage (V) 220
Charging power to Batteries (%) 110
Power demand at full load (%) 100

Take Note:
Battery Characteristics are not variable in this version of the ESM. Future versions will make use of a full battery sizing procedure.

Only the system characteristics need to be specified.

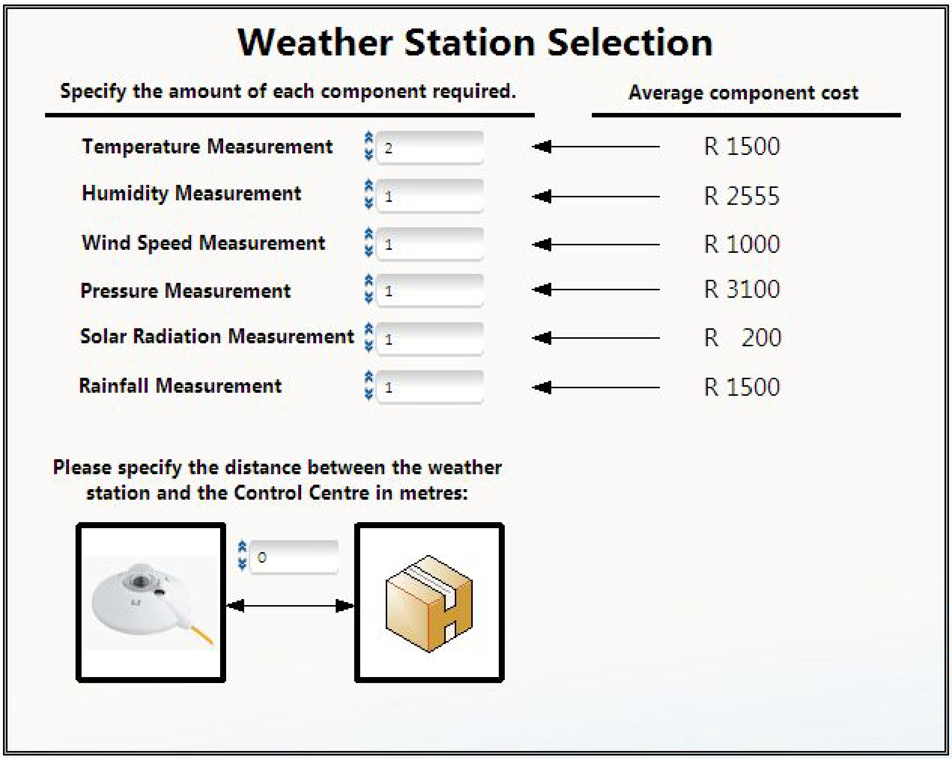
Figure 5.13 – Output Storage configuration

When the sizing procedure is executed, the ESM relays the required information to the TSM, which consequently outputs the number of batteries required to the optimisation procedure. This is not an optimal solution as only one model is used for the selection process. A similar sizing procedure to that of the wind and solar sizing will be added to later versions of the ESM.

For this case study, the required system autonomy and charge-and-discharge values inputted using the interface. When the user has completed the specification of the above-mentioned parameters, he/she may use the “Confirm” button to confirm the output storage specification and continue back to the front panel for further system specification.

5.4.5 Weather station

The interface shown in *Figure 5.14* is created so that the user may specify meteorological measurement devices, as is specified by the REHS-plant definition. The interface shows how much each units costs. These costs are finally translated to the final configuration, and added as a constant by the tertiary algorithm as described in *section 4.2.4.*



Weather Station Selection

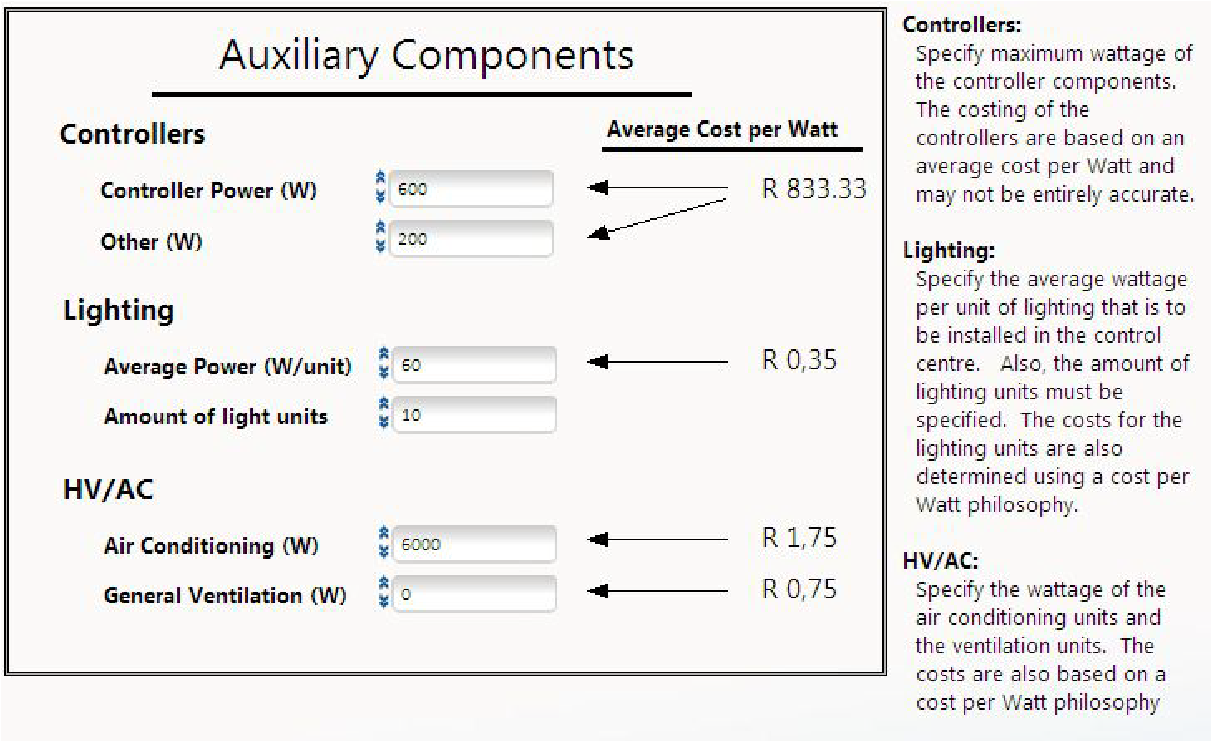
Specify the amount of each component required.		Average component cost
Temperature Measurement	2	R 1500
Humidity Measurement	1	R 2555
Wind Speed Measurement	1	R 1000
Pressure Measurement	1	R 3100
Solar Radiation Measurement	1	R 200
Rainfall Measurement	1	R 1500

Please specify the distance between the weather station and the Control Centre in metres: 0

Figure 5.14 – Weather Station configuration

5.4.6 Auxiliary systems

The interface shown in *Figure 5.15* enables the user to specific general component power ratings and component amounts. This module is included in the system sizing procedure for the sake of completeness, since these components are still important when considering the definition of an REHS-based plant.



Auxiliary Components

Controllers

Average Cost per Watt

Controller Power (W): 600 — R 833.33

Other (W): 200

Lighting

Average Power (W/unit): 60 — R 0,35

Amount of light units: 10

HV/AC

Air Conditioning (W): 6000 — R 1,75

General Ventilation (W): 0 — R 0,75

Controllers:
Specify maximum wattage of the controller components. The costing of the controllers are based on an average cost per Watt and may not be entirely accurate.

Lighting:
Specify the average wattage per unit of lighting that is to be installed in the control centre. Also, the amount of lighting units must be specified. The costs for the lighting units are also determined using a cost per Watt philosophy.

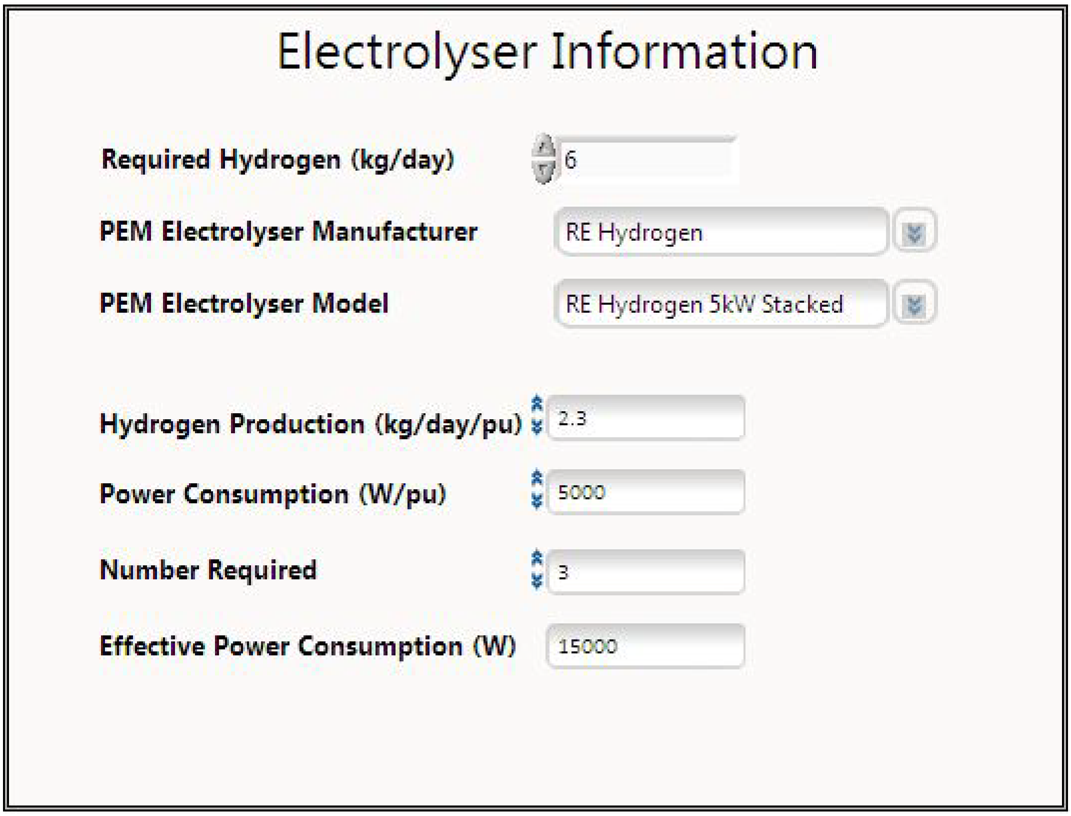
HV/AC:
Specify the wattage of the air conditioning units and the ventilation units. The costs are also based on a cost per Watt philosophy

Figure 5.15 – Auxiliary System configuration

Similar to the weather station, these costs are finally translated to the final configuration, and added as a constant by the tertiary algorithm as described in *section 4.2.4.*

5.4.7 Electrolyser configuration

The final interface shown in *Figure 5.16* shows this version of the ESM's electrolyser specification inputs. Since the focus of this version of the ESM was the integration of optimal sizing techniques for the renewable energy sources, the electrolyser specification is extremely simple. The choice of electrolysers is limited to one manufacturer and one model of electrolyser. Also, the required amount hydrogen to be produced is inputted, which determines how many of the listed model is required.



Electrolyser Information

Required Hydrogen (kg/day): 6

PEM Electrolyser Manufacturer: RE Hydrogen

PEM Electrolyser Model: RE Hydrogen 5kW Stacked

Hydrogen Production (kg/day/pu): 2.3

Power Consumption (W/pu): 5000

Number Required: 3

Effective Power Consumption (W): 15000

Figure 5.16 – Electrolyser Specification

Future versions of the ESM will focus on the implementation of proper electrolyser sizing modules, where more models can be made available for the sizing procedure.

With the walkthrough of the application complete, we may now continue to verify the results as outputted by each of the relevant modules as discussed in this section.

5.5 SCENARIO EVALUATION

In order to perform a thorough results-analysis, the best approach would be to define specific scenarios in which all intermediary results (results generated by sizing procedures and used by optimisation procedures) and optimised results (final results showing optimal configurations) can be evaluated individually. To this end, we introduce four scenarios based on a structure that ensures proper results verification of the implemented sizing procedures as per *section 4.1*.

In each case, we start off by comparing the results when using general power inputs vs. the results when using TSM-specified power inputs. By doing this we can comment on the effects that the TSM has on the system configuration and the corresponding costs. Hereafter, the run-times of the sub-applications are extracted for each method of power input specification, allowing us to perform a trade-off between application performance and accuracy. Finally, the results are verified analytically by comparing one permutation derived by the ESM to a permutation based on the same components, but using the developed equations for an analytical solution.

The information from these scenarios can then be used in the proceeding section for general comparisons. Due to time constraints, a minimal amount of components have been selected for the ESM sizing procedures investigated in scenario 1 and scenario 2. The ESM results based on the case study are investigated in scenario 3 and scenario 4.

5.5.1 Scenario 1 – Wind turbine sizing

The results presented in this scenario were generated by the ESM’s wind turbine sizing module. This module is responsible for creating viable permutations of wind turbines and their corresponding inverters/converters, configured to satisfy a required amount of system input power. For this case, we assume that the system’s power requirement for wind generation is set at 15kW. As this scenario is only presented to investigate the functionality of the wind sizing module, it is entirely independent of the requirements as defined by the case study.

As shown in *Figure 4.6*, this sizing procedure uses *equations (25) to (27)* for the generation of wind turbine and inverter/converter configurations. The costing values are determined using *equation (30)* and its individual constituents as defined in *section 4.2.1.* We now continue by presenting the results of executing the wind sizing procedure as discussed.

5.5.1.1 *Results using general inputs vs. TSM inputs*

In order to present a comparison between the results of the wind system sizing module when using general and TSM wind turbine power inputs, we provided the ESM with a single DC wind turbine manufacturer, namely "Whisper", and a single inverter manufacturer, namely "SMA". The lists of available models for these two components are given in *Table 5.2* and *Table 5.3* respectively.

Table 5.2 – Wind turbine model summary

Turbine Manufacturer	Model Name	$P_{max}\ (W)$ $(General)$	$P_{max}\ (W)$ (TSM)	Capital Cost
Whisper	Whisper 100	900	136	R 21 150.00
Whisper	Whisper 200	1000	269	R 29 530.00
Whisper	Whisper 500	3000	612	R 66 905.00

Table 5.2 shows the different wind turbine models listed in the database which are manufactured by "Whisper". It also gives the theoretical maximum output power, $P_{max}\ (W)(General)$, and the maximum output power, $P_{max}\ (W)(TSM)$, as determined by the TSM for the given site at Alexander Bay for each model. Basic costing information for each wind turbine model concludes this list.

Table 5.3 shows the different inverter models listed in the database which are manufactured by "SMA". It continues to show the maximum DC input power of the inverter, $P_{max,dc}\ (W)$. The nominal AC output power of the inverter is given by $P_{nom,ac}\ (W)$.

Table 5.3 – Wind turbine inverter summary

Inverter Manufacturer	Model Name	$P_{max,dc}$ (W)	$P_{nom,AC}$ (W)	Capital Cost
SMA	Windy Boy 3300	3820	3300	R 22 980.00
SMA	Windy Boy 2500	2700	2500	R 18 715.00
SMA	Windy Boy 1700	1850	1550	R 14 537.00
SMA	Windy Boy 1100	1210	1000	R 11 230.00

The wind turbine sizing procedure was executed for two individual cases using the specifications as listed above. In the first case, we used the general wind turbine power outputs, and in the second case we used the TSM-specified wind turbine power outputs.

- **General wind turbine power outputs (Case 1)**

Using the general wind turbine output power ratings, the sizing procedure was executed, and the results obtained were truncated to four permutations. These results are listed in *Table 5.4* for the wind turbines and in *Table 5.5* for the inverters. To view all table contents, please refer to tables A.1 and A.2 on the attached compact disc.

Table 5.4 – Truncated Wind turbine sizing results – General power outputs.

Permutation Index	WT Manufacturer	WT Model	WT Count	WT Maintenance Costs	WT Installation Costs	WT Capital Costs	Total Costs	Actual Turbine Output
1	Whisper	Whisper 100	17	R 317 339.00	R 169 348.00	R 359 550.00	**R 846 237.00**	900
2	Whisper	Whisper 200	15	R 390 948.00	R 208 629.00	R 442 950.00	**R 1 042 527.00**	1000
3	Whisper	Whisper 500	5	R 295 252.00	R 157 561.00	R 334 525.00	**R 787 338.00**	3000
4	Whisper	Whisper 100	17	R 317 339.00	R 169 348.00	R 359 550.00	**R 846 237.00**	900

Table 5.5 – Truncated wind turbine inverter sizing results – General power outputs.

Permutation Index	I/C Manufacturer	I/C Model	I/C Count	I/C Installation Costs	I/C Capital Cost s	Total Costs
1	SMA	Windy Boy 3300	5	R 54 118.00	R 114 900.00	**R 169 018.00**
2	SMA	Windy Boy 3300	5	R 54 118.00	R 114 900.00	**R 169 018.00**
3	SMA	Windy Boy 3300	5	R 54 118.00	R 114 900.00	**R 169 018.00**
4	SMA	Windy Boy 2500	7	R 61 703.00	R 131 005.00	**R 192 708.00**

The two tables are linked together by the permutation index. For effective wind turbine system costs, we can combine these tables using the permutation index as primary key. The resulting list is given by *Table 5.6*.

Table 5.6 – Total wind turbine system costs using general power inputs.

Permutation Index	WT Model	WT Count	I/C Model	I/C Count	Total WT Costs	Total I/C Costs	Wind Turbine System Cost
1	Whisper 100	17	Windy Boy 3300	5	R 846 237.00	R 169 018.00	**R 1 015 255.00**
2	Whisper 200	15	Windy Boy 3300	5	R 1 042 527.00	R 169 018.00	**R 1 211 545.00**
3	Whisper 500	5	Windy Boy 3300	5	R 787 338.00	R 169 018.00	**R 956 356.00**
4	Whisper 100	17	Windy Boy 2500	7	R 846 237.00	R 192 708.00	**R 1 038 945.00**

The time elapsed for the execution is determined by taking the difference in date-stamps before and after the sizing procedure has been executed. Therefore, user active-time does not influence the result. The elapsed time for the specified models is shown in *Table 5.7*:

Table 5.7 – Procedure execution time (General wind turbine power inputs)

	Turbine models	Inverter Models	Permutations	Elapsed Time (s)
Wind Sizing Procedure (General inputs)	3	4	12	0.324013

The number of turbine models and inverter models listed in *Table 5.7*, stem from the initial number of models we included for the permutation creation process. The elapsed time thus refers to the time the application took to process these models, using the specified technique where we don't implement the TSM. We now continue to perform the same procedure on the TSM-specified wind turbine power outputs.

- **TSM wind turbine power outputs (Case 2)**

Using the TSM-specified wind turbine output power ratings, the sizing procedure was executed, and the results obtained were also truncated to four permutations. These results are listed in *Table 5.8* for the wind turbines and in *Table 5.9* for the inverters. To view all table contents, please refer to tables A.3 and A.4 on the attached compact disc.

Table 5.8 – Truncated wind turbine sizing results – TSM-specified power outputs.

Permutation Index	WT Manufacturer	WT Model	WT Count	WT Maintenance Costs	WT Installation Costs	WT Capital Costs	Total Costs	Actual Turbine Output
1	Whisper	Whisper 100	111	R 2 072 036.00	R 1 105 743.00	R 2 347 650.00	**R 5 525 429.00**	136
2	Whisper	Whisper 200	56	R 1 459 538.00	R 778 883.00	R 1 653 680.00	**R 3 892 101.00**	269
3	Whisper	Whisper 500	25	R 1 476 259.00	R 787 806.00	R 1 672 625.00	**R 3 936 690.00**	612
4	Whisper	Whisper 100	111	R 2 072 036.00	R 1 105 743.00	R 2 347 650.00	**R 5 525 429.00**	136

Table 5.9 – Truncated wind turbine inverter sizing results – TSM-specified outputs.

Permutation Index	I/C Manufacturer	I/C Model	I/C Count	I/C Installation Costs	I/C Capital Cost s	Total Costs
1	SMA	Windy Boy 3300	33	R 357 178.00	R 758 340.00	**R 1 115 518.00**
2	SMA	Windy Boy 3300	19	R 205 648.00	R 436 620.00	**R 642 268.00**
3	SMA	Windy Boy 3300	23	R 248 942.00	R 528 540.00	**R 777 482.00**
4	SMA	Windy Boy 2500	40	R 352 591.00	R 748 600.00	**R 1 101 191.00**

The two tables are also linked together by the permutation index. Following the same procedure as with *Table 5.6*, we combine these tables using the permutation index as primary key. The resulting list is given by *Table 5.10*.

Table 5.10 – Total WT system costs using TSM-specified power inputs.

Permutation Index	WT Model	WT Count	I/C Model	I/C Count	Total WT Costs	Total I/C Costs	Wind Turbine System Cost
1	Whisper 100	111	Windy Boy 3300	33	R 5 525 429.00	R 1 115 518.20	**R 6 640 947.20**
2	Whisper 200	56	Windy Boy 3300	19	R 3 892 101.00	R 642 268.20	**R 4 534 369.20**
3	Whisper 500	25	Windy Boy 3300	23	R 3 936 690.00	R 777 482.00	**R 4 714 172.00**
4	Whisper 100	111	Windy Boy 2500	40	R 5 525 429.00	R 1 101 191.00	**R 6 626 620.00**

The elapsed time for the specified models, using TSM-specified power outputs, is shown in *Table 5.11*:

Table 5.11 – Procedure execution time (TSM-specified wind turbine power inputs)

	Turbine models	Inverter Models	Permutations	Elapsed Time (s)
Wind Sizing Procedure (TSM inputs)	3	4	12	8.39434

The number of turbine models and inverter models listed in *Table 5.11*, stem from the initial number of models we included for the permutation creation process, as discussed in the previous section. The elapsed time thus refers to the time the application took to process these models, using the specified technique implementing the TSM, as opposed to not using the TSM. Using these two cases, we compare the respective results and comment on any items of significance.

- **Results comparison**

The main purpose behind the integration of the TSM and the ESM is the generation of more accurate results which define an REHS-based system whilst taking the meteorological information of that site into consideration. Using this information as reference we can clearly see the significance of the information relayed by *Figure 5.17*.

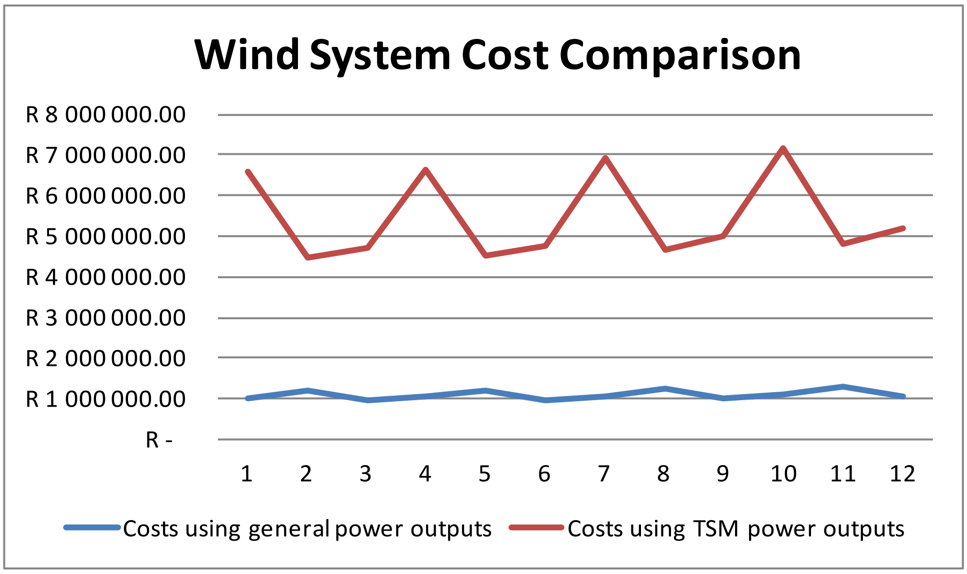


Figure 5.17 – Wind System Cost Comparison

When sizing a system based on theoretical power outputs, the implementation of wind systems may seem to be a very cost-effective solution. When the actual wind data of a specific site is taken into consideration though, the picture changes significantly. At the predefined site, wind resource availability is not very high. This is clearly reflected in the difference in system costs between the two cases. Using the TSM to determine the effective power output of the selected turbines, we see that we need a far greater amount of wind turbines to satisfy the system power requirements of $15kW$ than if we use rated power outputs. The integration of the TSM is thus of critical importance when sizing a wind system for use in an REHS-based application.

In terms of the required calculation times, we observe a near 26-fold increase in execution time when using the TSM for effective power generation output determination according to *Table 5.12*. While the difference seems negligible in this case, the execution time starts to become an issue when the database size increases.

Table 5.12 – Execution time differences using general power inputs vs. TSM power inputs

	Turbine models	Inverter Models	Permutations	Elapsed Time (s)
Wind Sizing Procedure (General inputs)	3	4	12	0.324013
Wind Sizing Procedure (TSM inputs)	3	4	12	8.39434
			Difference (%)	**2591**

In light of the major advantage which the integration of the TSM brings in terms of costing estimation however, the increases in execution time can deemed acceptable.

To test the validity of the results as determined by the wind turbine system sizing module, the best procedure is to use the theoretical basis upon which the module is built and manually determine the results using specific components as listed in the database. To this end, we proceed to *section 5.5.1.2* where the results are verified analytically.

5.5.1.2 *Analytical results verification*

The final step of the evaluation process of this scenario is concerned with the analytical determination of a permutation based on two specific components. When the resulting values coincide with the values as listed in the table generated by the ESM for the same components, we can conclude that the sizing techniques were correctly implemented into the ESM application. For this process, we choose one wind turbine model, and one inverter model. These choices are listed in *Table 5.13*.

Table 5.13 – Component selection for analytical comparison

	Manufacturer	Model	Rated Output Power (W)	Output Power (W)	Input Power (W)	Permutation Index	Capital Cost
Wind Turbine	Whisper	Whisper 200	1000	269	NA	2	R 29 530.00
Inverter/Converter	SMA	Windy Boy 3300	3300	NA	3820	2	R 22 980.00

As previously stated, the wind turbine system sizing module uses *equations (25) to (27)* for the sizing procedures. To recap, these equations are re-listed:

$$N_{T,MAX} = round_{down}\left(\frac{P_{WTi,MAX}}{P_T}\right), \tag{25}$$

where $P_{WTi,MAX}$ refers to the maximum input power of the inverter, and P_T the nominal output power of the turbine.

$$N_{i,total} = round_{up}\left(\frac{P_T}{P_{WTi,MAX}}\right), \tag{26}$$

where $P_{WTi,MAX}$ refers to the maximum input power of the inverter, and $\mathrm{P_T}$ output power of the turbine. *Equation (27)* determines the number of turbines ($N_{wt,total}$) which are required for a specific model:

$$N_{wt,total} = round_{up}\left(\frac{P_{W,MAX}}{P_{T,MIN}}\right), \tag{27}$$

where $P_{W,MAX}$ refers to the maximum amount of required system power dedicated for wind power generation according to the PAT and $P_{T,MIN}$ is the minimum average output power of a selected turbine type.

As per design procedure developed in *section 4.1.4*, we commence with the determination of the maximum amount of turbines that can be connected to a single inverter. Since the wind turbine that we selected for this evaluation is a DC machine based design, we use *equation (25)* for the specification of the number of turbines required in order to satisfy the selected inverter's input power specifications:

$$N_{T,MAX} = round_{down}\left(\frac{P_{WTi,MAX}}{P_T}\right) \tag{25}$$

$$\begin{aligned} N_{T,MAX} &= round_{down}\left(\frac{3820}{1000}\right) \\ &= round_{down}(3.820) \\ &= \mathbf{3} \end{aligned}$$

Finally, we use *equation (27)* for the specification of the number of turbines required in order to satisfy the system power requirement of 15kW:

$$N_{wt,total} = round_{up}\left(\frac{P_{W,MAX}}{P_{T,MIN}}\right) \tag{27}$$

$$N_{wt,total} = round_{up}\left(\frac{15000}{269}\right)$$

$$= round_{up}(55.762)$$

$$= \mathbf{56}$$

The total number of inverters can now easily be extrapolated from these results, by dividing the results of *(25)* and *(27):*

$$N_{i,total} = round_{up}\left(\frac{N_{wt,total}}{N_{T,MAX}}\right)$$

$$= round_{up}\left(\frac{56}{3}\right)$$

$$= \mathbf{19}$$

Proceeding to the verification of the costing procedure for the wind turbine system, we refer to *equation (30)* as defined in *section 4.2.1:*

$$C_{wt} = N_{i,tinv,TOTAL} \cdot \left(C_{i,tinv,MOD} + I_{i,tinv}\right) + N_{j,wt,TOTAL} \cdot \left(C_{j,wt,MOD} + lifetime.M_{j,wt} + I_{j,wt}\right) \tag{30}$$

Using the costing information shown in *Table 5.13* and the results as outputted by *(25)* and *(27),* we can calculate the total cost for the wind turbine system. For this cost determination, we remind the reader about *section 4.2.1* which explained that the installation costs for a wind turbine system accounts for up to 32% of the total system capital costs, and the maintenance costs for wind turbine systems is equal to approximately 3% of the total system cost per year over 20 years. For this case study, the parameters in *equation (30)* can be modified as follows:

$$N_{i,tinv,TOTAL} = N_{i,total}$$

$$N_{j,wt,TOTAL} = N_{wt,total}$$

$$C_{i,tinv,MOD} = R\ 22\,980$$

$$C_{j,wt,MOD} = R\ 29\,530$$

$$I_{i,tinv} = \left(\frac{32}{68}\right) \times \left(C_{i,tinv,MOD}\right)$$

$$= \left(\frac{32}{68}\right) \times (R\ 22\ 980) \cong \boldsymbol{R\ 10\ 814}$$

$$I_{j,wt} = \left(\frac{32}{68}\right) \times \left(C_{j,wt,MOD}\right)$$

$$= \left(\frac{32}{68}\right) \times (\ R\ 29\ 530) \cong \boldsymbol{R\ 13\ 896}$$

$$M_{j,wt} = 0.03 \times \left(C_{j,wt,MOD} + I_{j,wt}\right)$$

$$= 0.03 \times (R\ 29\ 530 + R\ 13\ 896) = \boldsymbol{R\ 1302.78}$$

Now using the modified terms, we can calculate the total wind system costs:

$$C_{wt} = \mathbf{19} \cdot (R\ 22\ 980 + R\ 10\ 814) + \mathbf{56} \cdot (R\ 29\ 530 + 20 \times R\ 1302.78 + R\ 13\ 896)$$

$$C_{wt} = \mathbf{19} \cdot (R\ 33\ 794) + \mathbf{56} \cdot (R\ 69\ 482)$$

$$\boldsymbol{C_{wt} = R\ 4\ 533\ 078}$$

- **Results comparison**

Comparing the sizing results obtained by the ESM, and using the analytical techniques, we find that the ESM is able to determine the correct amount of components as described by the procedure in *section 4.1.4*. This comparison is shown in *Table 5.14*.

Table 5.14 – ESM WT sizing results vs. Analytical WT sizing results

Permutation Index	WT Count (ESM)	WT Count (Analytical)	**Difference (%)**	I/C Count (ESM)	I/C Count (Analytical)	**Difference (%)**
2	56	56	**0**	19	19	**0**

Comparing the costing results, we find that the difference between the costs determined by the ESM and the costs as determined analytically as described in *section 4.2.1*, are very similar. This comparison is shown in *Table 5.14*.

Table 5.15 – ESM WT costing results vs. Analytical WT costing results

Permutation Index	WT System Costs (ESM)	WT System Costs (Analytical)	**Difference (R)**	**Difference (%)**
2	**R 4 534 369.20**	**R 4 533 078.00**	**1291.2**	**0.03**

This difference in cost is negligible, and can be attributed to possible rounding of result values.

The results in both *Table 5.14* and *Table 5.15* shows that in the implementation of the developed sizing techniques have been performed successfully. According to this, the user may be confident that the results outputted by the ESM wind turbine system module are accurate, and conform to good sizing criteria.

5.5.2 Scenario 2 – PV array sizing

The results presented in this second scenario were generated by the ESM's PV array sizing module. This module is responsible for creating viable permutations of PV module arrays and their corresponding inverters/converters, configured to satisfy a required amount of system input power. Similar to the case for the wind turbine system sizing, we assume that the system's power requirement for solar generation is set at $15kW$. This scenario is also entirely independent of the requirements as defined by the case study. As shown in *Figure 4.3*, this sizing procedure uses *equations (13) to (20)* for the generation of PV array and inverter/converter configurations. The costing values are determined using *equation (29)* and its individual constituents as defined in *section 4.2.1.* We now continue by presenting the results that are outputted when executing the solar sizing procedure as discussed.

5.5.2.1 *Results using general inputs vs. TSM inputs*

For the purposes of performing a comparison between the results of the PV array sizing module when using general and TSM PV module power inputs, we provided the ESM with a single PV panel manufacturer, namely "SetSolar", and a single inverter manufacturer, namely "SMA". The lists of available models for these two components are given in *Table 5.16* and *Table 5.17* respectively.

Table 5.16 – PV module model summary

PV Module Manufacturer	Model Name	$P_{max,stc}$ (W) $(General)$	P_{max} (W) (TSM)	Capital Cost
SetSolar	M750P-80W	80	80	R 2 384.40
SetSolar	M1300P-130W	130	125	R 3 613.88
SetSolar	M2000P-210W	210	204	R 6 661.63

Table 5.16 shows the different PV module models listed in the database which are manufactured by “SetSolar”. It also gives the theoretical maximum output power at STC, $P_{max,stc}\ (W)(General)$, and the maximum output power, $P_{max}\ (W)(TSM)$, as determined by the TSM for the given site GPS coordinates at Alexander Bay for each model. Costing information (Capital Cost per module) is added for further reference.

Table 5.17 shows the different inverter models listed in the database which are manufactured by “SMA”. It continues to show the maximum DC input power of the inverter, $P_{max,dc}\ (W)$. The nominal AC output power of the inverter is given by $P_{nom,ac}\ (W)$.

Table 5.17 – PV array inverter summary

Inverter Manufacturer	Model Name	$P_{max,dc}$ (W)	$P_{nom,\,AC}$ (W)	Capital Cost
SMA	Sunny Boy SB1100	1210	1000.00	R 11 005.00
SMA	Sunny Boy SB1200	1320	1200.00	R 13 023.00
SMA	Sunny Boy SB1700	1850	1550.00	R 17 020.00
SMA	Sunny Boy SB2500	2700	2300.00	R 20 156.00
SMA	Sunny Boy SB3000	3200	2750.00	R 23 200.00
SMA	Sunny Boy SB3000TL	3200	3000.00	R 24 063.98
SMA	Sunny Boy SB4000TL	4200	4000.00	R 29 563.05
SMA	Sunny Boy SB4000TL/V	4200	3680.00	R 31 541.03
SMA	Sunny Boy SB5000TL	5300	4600.00	R 33 556.00

Similar to the wind turbine sizing procedure, the solar sizing procedure was executed for two individual cases using the specifications as listed above. We now continue do define these cases.

- **General PV module power outputs (Case 1)**

Using the general PV module output power ratings, the sizing procedure was executed, and the results obtained were truncated to four permutations. These results are listed in *Table 5.18* for the PV modules and in *Table 5.19* for the inverters. To view all table contents, please refer to tables A.5 and A.6 on the attached compact disc.

Table 5.18 – Truncated solar sizing results – General power outputs.

Permutation Index	PV Manufacturer	PV Model	PV Parallel Count	PV Series Count	PV Total Count	PV Maintenance Costs	PV Installation Costs	PV Capital Costs	Total	Actual PV Module Output (W)
1	SetSolar	M750P-80W	3	19	228	R 128 410.00	R 58 368.00	R 583 680.00	**R 770 458.00**	80
2	SetSolar	M1300P-130 W	2	20	160	R 146 432.00	R 66 560.00	R 665 600.00	**R 878 592.00**	130
3	SetSolar	M2000P-210 W	1	13	52	R 76 877.00	R 34 944.00	R 349 440.00	**R 461 261.00**	210
4	SetSolar	M750P-80W	2	19	190	R 107 008.00	R 48 640.00	R 486 400.00	**R 642 048.00**	80

Table 5.19 – Truncated Inverter Sizing results – General power outputs.

Permutation Index	I/C Manufacturer	I/C Model	I/C Count	I/C Installation Costs	I/C Capital Costs	Total Costs
1	SMA	Sunny Boy SB5000TL	4	R 13 422.00	R 134 224.00	**R 147 646.00**
2	SMA	Sunny Boy SB5000TL	4	R 13 422.00	R 134 224.00	**R 147 646.00**
3	SMA	Sunny Boy SB5000TL	4	R 13 422.00	R 134 224.00	**R 147 646.00**
4	SMA	Sunny Boy SB4000TL/V	5	R 15 771.00	R 157 705.00	**R 173 476.00**

When we have a brief look at the values listed, basic consistency of values look acceptable. We can therefore continue by looking at the total PV systems cost. One must still note that the two tables are linked together by the permutation index. The combination of entries between the two tables of the same permutation index represents one configuration. As was done for the wind system sizing procedure, we combine these tables, resulting in the list as given by *Table 5.20*.

Table 5.20 – Total WT system costs using general power inputs.

Permutation Index	PV Module Model	PV Count	I/C Model	I/C Count	Total PVCosts	Total I/C Costs	PV Array System Cost
1	M750P-80W	228	Sunny Boy SB5000TL	4	R 770 458.00	R 147 646.00	**R 918 104.00**
2	M1300P-130 W	160	Sunny Boy SB5000TL	4	R 878 592.00	R 147 646.00	**R 1 026 238.00**
3	M2000P-210 W	52	Sunny Boy SB5000TL	4	R 461 261.00	R 147 646.00	**R 608 907.00**
4	M750P-80W	190	Sunny Boy SB4000TL/V	5	R 642 048.00	R 173 476.00	**R 815 524.00**

The time elapsed for the execution is also determined by taking the difference in date-stamps before and after the sizing procedure has been executed. The elapsed time for the specified module is shown in *Table 5.21*:

Table 5.21 – Procedure execution time (General wind turbine power inputs)

	PV models	Inverter Models	Permutations	Elapsed Time (s)
PV Array Sizing Procedure (General inputs)	3	9	27	0.392016

We now continue to perform the same procedure on the TSM-specified PV module power outputs, in case 2.

- **TSM PV module power outputs (Case 2)**

Using the TSM-specified PV module output power ratings, the sizing procedure was executed, and the results obtained were truncated to 4 permutations as in all previous cases. These results are listed in *Table 5.22* for the PV modules and in *Table 5.23* for the inverters. To view all table contents, please refer to tables A.7 and A.8 on the attached compact disc.

Table 5.22 – Truncated PV module sizing results – TSM-specified power outputs.

Permutation Index	**PV Manufacturer**	**PV Model**	**PV Parallel Count**	**PV Series Count**	**PV Total Count**	**PV Maintenance Costs**	**PV Installation Costs**	**PV Capital Costs**	**Total**	**Actual PV Module Output (W)**
1	SetSolar	M750P-80W	3	19	228	R 128 410.00	R 58 368.00	R 583 680.00	**R 770 458.00**	77
2	SetSolar	M1300P-130 W	2	20	160	R 146 432.00	R 66 560.00	R 665 600.00	**R 878 592.00**	120
3	SetSolar	M2000P-210 W	2	13	78	R 115 315.00	R 52 416.00	R 524 160.00	**R 691 891.00**	196
4	SetSolar	M750P-80W	2	19	228	R 128 410.00	R 58 368.00	R 583 680.00	**R 770 458.00**	77

Table 5.23 – Truncated inverter sizing results – TSM-specified outputs.

Permutation Index	I/C Manufacturer	I/C Model	I/C Count	I/C Installation Costs	I/C Capital Costs	Total Costs
1	SMA	Sunny Boy SB5000TL	4	R 13 422.00	R 134 224.00	**R 147 646.00**
2	SMA	Sunny Boy SB5000TL	4	R 13 422.00	R 134 224.00	**R 147 646.00**
3	SMA	Sunny Boy SB5000TL	4	R 13 422.00	R 134 224.00	**R 147 646.00**
4	SMA	Sunny Boy SB4000TL/V	5	R 15 771.00	R 157 705.00	**R 173 476.00**

The two tables are also linked together by the permutation index. Following the same procedure as in *Table 5.20*, we combine these tables using the permutation indices as primary key. The resulting list is given by *Table 5.24*. The illegal permutation is also brought forward to this results set.

Table 5.24 – Total PV system costs using TSM-specified power inputs.

Permutation Index	PV Module Model	PV Count	I/C Model	I/C Count	Total PVCosts	Total I/C Costs	PV Array System Cost
1	M750P-80W	228	Sunny Boy SB5000TL	4	R 770 458.00	R 147 646.00	**R 918 104.00**
2	M1300P-130 W	160	Sunny Boy SB5000TL	4	R 878 592.00	R 147 646.00	**R 1 026 238.00**
3	M2000P-210 W	78	Sunny Boy SB5000TL	4	R 691 891.00	R 147 646.00	**R 839 537.00**
4	M750P-80W	228	Sunny Boy SB4000TL/V	5	R 770 458.00	R 173 476.00	**R 943 934.00**

The elapsed time for the specified models, using TSM-specified power outputs, is shown in *Table 5.25*:

Table 5.25 – Procedure execution time (TSM-specified PV module power inputs)

	PV models	Inverter Models	Permutations	Elapsed Time (s)
PV Array Sizing Procedure (TSM inputs)	3	9	27	18.8238

- **Results comparison**

Since the main purpose behind the integration of the TSM and the ESM is the generation of more accurate results which define an REHS-based system, we apply it to all variable selection procedures. In the case of the wind turbine system specification, the impact that the TSM result had on the sizing results were immense. *Figure 5.18* shows the impact that the TSM has on the PV system sizing results.

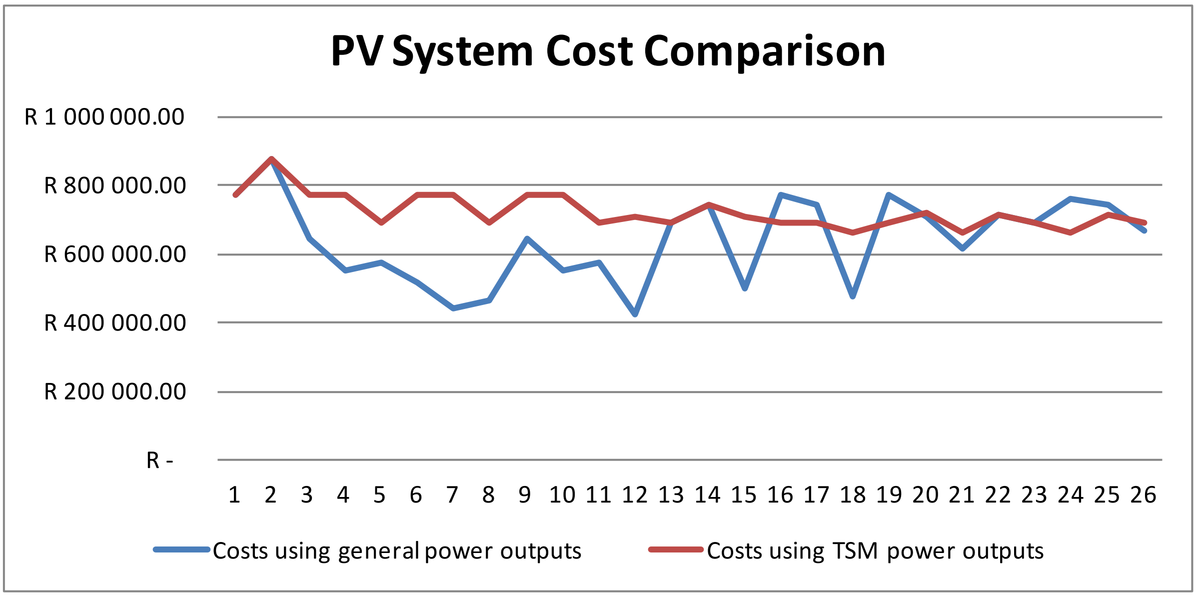


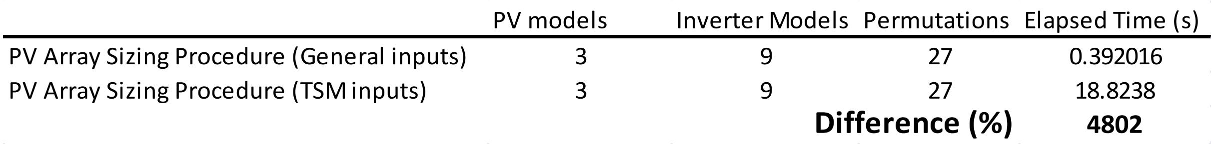
Figure 5.18 – PV Array System Cost Comparison

Here we can see that the initial differences between the two cases are quite high, with a reduction of the magnitude of the difference as we move along the permutation indices. When considering table A.8, one can see that as the permutation index increases, the size (i.e. power rating) of the inverters used decreases. This is consistent with the reduction of discrepancy seen in *Figure 5.18*. Therefore, we can indirectly claim that the changes which the TSM's PV module power output brings to the system are less pronounced on the system sizing when more inverters are used, due to the fact that the ESM adds more low-power PV modules to the configuration if the amount of inverters specified increases.

As for the specific comparisons of the average costs of the permutations created by using the general power values versus the TSM's power values, we find that the sizing results when using TSM generated output power values are much more consistent. This makes more sense, and adds credibility to the results.

In terms of the required calculation times, for this module we observe a near 48-fold increase in execution time when using the TSM for effective power generation output determination according to *Table 5.26*. This is a very significant increase, but must be brought into relative perspective to the differences in the results accuracy.

Table 5.26 – Execution time differences using general power inputs vs. TSM power inputs



	PV models	Inverter Models	Permutations	Elapsed Time (s)
PV Array Sizing Procedure (General inputs)	3	9	27	0.392016
PV Array Sizing Procedure (TSM inputs)	3	9	27	18.8238
			Difference (%)	**4802**

In light of this, when the user chooses a large set of PV modules for sizing, it may prove to be beneficial to use the general output power specifications if a faster solution that still guarantees average accuracy is required; although using the TSM is still recommended.

To test the validity of the results as determined by the PV array system sizing module, we proceed to *section 5.5.2.2* where the results are verified analytically in a similar fashion to the procedure followed in *section 5.5.1.2*.

5.5.2.2 *Analytical results verification*

The final step of the evaluation process of this scenario is also concerned with the analytical determination of a permutation based on two specific components. For this process, we choose one PV module model, and one inverter model. This selection is listed in *Table 5.27*.

Table 5.27 – Component selection for analytical comparison

	Manufacturer	Model	Rated Output Power (W)	Output Power (W)	Input Power (W)	Permutation Index	Capital Cost
PV Module	SetSolar	M1300P - 130W	130	125	NA	2	R 4 160.00
Inverter/Converter	SMA	Sunny Boy SB5000TL	4600	NA	5300	2	R 33 556.00

As previously stated, the PV array system sizing module uses *equations (13) to (20)* for the sizing procedures. Due to space constraints, the existing equations are not re-listed. Instead, we continue with the sizing evaluation. For parameter descriptions, the reader is urged to refer to *section 4.1.3*.

For this procedure we need to know the required PV module and inverter technical specifications. The required parameters for the PV module are listed in *Table 5.28* and the required parameters for the inverter are listed in *Table 5.29*.

Table 5.28 – PV module technical specifications

Module Manufacturer	Model Name	$P_{max, stc}$ (W)	Voc (V)	Isc (A)	V_{mpp} (V)	I_{mpp} (A)
SetSolar	M1300P-130W	130	21.90	7.80	17.60	7.60

Table 5.29 – PV inverter technical specifications

Inverter Manufacturer	Model Name	$P_{max, pv\ dc\ stc}$ (W)	$V_{mpp,min}$ (V)	$V_{mpp,max}$ (V)	$P_{nom, AC}$ (W)
SMA	Sunny Boy SB5000TL	5300	175	440	4600

As per design procedure developed in *section 4.1.3*, we commence with the determination of the PV array voltage specification. We use *equation (13)* for the specification of the minimum number of PV modules to be connected in series to satisfy the input voltage requirements of the inverter selected:

$$N_{s,MIN} = round_{up}\left(\frac{V_{PVi,MIN}}{V_{M,MIN}}\right) \tag{13}$$

$$N_{s,MIN} = round_{up}\left(\frac{175}{17.60}\right)$$

$$= \mathbf{10}$$

Next, we use *equation (14)* for the specification of the maximum number of PV modules that can be connected to the selected inverter:

$$N_{s,MAX} = round_{down}\left(\frac{V_{PVi,MAX}}{V_{OC}}\right) \tag{14}$$

$$N_{s,MAX} = round_{down}\left(\frac{440}{21.90}\right)$$

$$= \mathbf{20}$$

As per *section 4.1.3*, the following constraint must be satisfied:

$$N_{s,MAX} \ \leq round_{down}\left(\frac{P_{PVi,MAX}}{P_{M,MAX}}\right) \tag{15}$$

$$N_{s,MAX} \ \leq round_{down}\left(\frac{5300}{130}\right)$$

$$= \mathbf{40}$$

The choice between these two values can be made using the following constraint:

$$N_{S,MIN} \leq N_s \leq \sup\left\{N_{S,MAX}\, , round_{down}\left(\frac{P_{PVi,MAX}}{P_{M,MAX}}\right)\right\} \tag{16}$$

$$10 \leq N_S \leq \sup\{20\, , 40\}$$

$$10 \leq N_S \leq 20$$

In order to maximise system efficiency, we must choose the value for N_s to be closest to the maximum. We therefore set $N_S = 20$. We continue to use *equation (17)* for the determination of the PV array power characteristics:

$$N_{P,MAX} = round_{down}\left(\frac{P_{PVi,MAX}}{N_S P_{M,MAX}}\right) \tag{17}$$

$$N_{P,MAX} = round_{down}\left(\frac{5300}{20 \times 130}\right)$$

$$= \mathbf{2}$$

The total amount of PV modules in a PV array is therefore given by:

$$N_{array} = N_S(N_{P,MAX}) \tag{18}$$

$$N_{array} = 20(2)$$

$$= \mathbf{40}$$

For the specification of the number of inverters required for the system, we continue to analyse the component selection using *equations (19) and (20)*. The required number of inverters is given by:

$$x_i = round_{up}\left(\frac{15000}{4600}\right) \tag{19}$$

$$= \mathbf{4}$$

The total number of PV modules in the PV array system is therefore:

$$N_{pv,total} = x_i N_{array} \tag{20}$$

$$N_{pv,total} = 4 \times 40$$

$$= \mathbf{160}$$

Proceeding to the verification of the costing procedure for the PV array system, we refer to *equation (29)* as defined in *section 4.2.1:*

$$C_{pv}(\boldsymbol{x_i}) = N_{i,pv,TOTAL} \cdot \left(C_{i,pv,MOD} + lifetime.M_{i,pv} + I_{i,pv}\right) + N_{j,inv,TOTAL} \cdot \left(C_{j,inv,MOD} + I_{j,inv}\right) \tag{29}$$

Using the costing information shown in *Table 5.27* and the results as outputted by *(13)* to *(20),* we can calculate the total cost for the PV array system. For this cost determination, we remind the reader that the installation costs for a PV array system accounts for up to 10% of the total system capital costs, and the maintenance costs for PV array systems is equal to approximately 1% of the total system cost per year over 20 years. For this case study, the parameters in *equation (29)* can be modified as follows:

$$N_{j,inv,TOTAL} = x_i$$

$$N_{i,pv,TOTAL} = N_{pv,total}$$

$$C_{j,inv,MOD} = R\ 33\ 556$$

$$C_{i,pv,MOD} = R\ 4\ 160$$

$$I_{j,inv} = (0.1) \times \left(C_{j,inv,MOD}\right)$$

$$= (0.1) \times (R\ 33\ 556) \cong \boldsymbol{R\ 3\ 355.6}$$

$$I_{i,pv} = (0.1) \times \left(C_{i,pv,MOD}\right)$$

$$= (0.1) \times (\ R\ 4\ 160) \cong \boldsymbol{R\ 416}$$

$$M_{i,pv} = 0.01 \times \left(C_{i,pv,MOD} + I_{i,pv}\right)$$

$$= 0.01 \times (R\ 4\ 160 + R\ 416) = \boldsymbol{R\ 45.60}$$

Now using the modified terms, we can calculate the total wind system costs:

$$C_{pv} = \mathbf{160} \cdot (R\ 4\ 160 + 20 \times R\ 45.76 + R\ 416) + \mathbf{4} \cdot (R\ 33\ 556 + R\ 3\ 355.60)$$

$$C_{pv} = \mathbf{160} \cdot (R\ 5\ 491.20) + \mathbf{4} \cdot (R\ 36\ 911.60)$$

$$\boldsymbol{C_{pv} = R\ 1\ 026\ 238.40}$$

- **Results comparison**

Comparing the sizing results obtained by the ESM, and using the analytical techniques, we find that the ESM is able to determine the correct amount of components as described by the procedure in *section 4.1.3*. This comparison is shown in *Table 5.30*.

Table 5.30 – ESM PV sizing results vs. Analytical PV sizing results

Permutation Index	PV Count (ESM)	PV Count (Analytical)	**Difference (%)**	I/C Count (ESM)	I/C Count (Analytical)	**Difference (%)**
2	160	160	**0**	4	4	**0**

Comparing the costing results, we find that the difference between the costs determined by the ESM and the costs as determined analytically as described in *section 4.2.1* virtually zero. This comparison is shown in *Table 5.31*.

Table 5.31 – ESM PV costing results vs. Analytical PV costing results

Permutation Index	PV System Costs (ESM)	PV System Costs (Analytical)	**Difference (R)**	**Difference (%)**
2	**R 1 026 238.00**	**R 1 026 238.40**	**0.4**	**0.00**

Looking at the results, the validity of the ESM's PV array sizing module is perfectly coherent with that of the sizing and costing techniques developed in previous-mentioned sections. Together with the proven results generation capability of the wind turbine sizing module, we can be certain that the optimisation techniques receives good inputs for the final optimal plant costing analysis.

5.5.3 Scenario 3 – ESM Optimised configuration (Non-GA)

The optimisation algorithm that has been integrated into the ESM for optimal plant sizing (see *section 4.2*) has two main setbacks. The first is that when the population is small, the GA-based algorithm may take much longer to determine the optimal solution than a generic algorithm. The second is that, given a population of a certain size (sufficiently large to offset the first issue), the optimal solution as determined by the GA-based algorithm may not be the best solution, although it should be quite near to it.

In order to evaluate the accuracy of the GA-based solution, we must first define a scenario where all of the solutions are incrementally determined, with the exact optimal solution given as a result. The reader must note, that the non-variable system components e.g. batteries, auxiliary units etc. are not brought into consideration for this scenario as their costs will remain the same for all permutations in this version of the ESM.

5.5.3.1 *Scenario considerations*

To provide the necessary results, the initially developed optimisation module had to be removed from the ESM. The procedure that was used for this technique is illustrated in *Figure 5.19*. The exact solution requires that all the models of all components be compared to one another for all variations of the assignment values of the PAT. Since the PAT assigns the renewable energy ratios (between 0% and 100% of the total required system power), we can state that the analytical sizing procedure must be repeated in a fashion such as defined by *equation (36):*

$$Sizing_{tot} = 101 \times Q_{pv} \times 101 \times Q_{wt}, \tag{36}$$

where $Sizing_{tot}$ is the total amount of permutations of all components, taking all assignment values of the PAT into consideration. The parameter Q_{pv} represents the amount of permutations generated by the PV array system sizing procedure, which is equal to the number of PV modules selected for sizing multiplied with the number of inverters selected.

Similarly, the parameter Q_{wt} represents the amount of permutations generated by the wind turbine system sizing procedure, which is equal to the number of wind turbine models selected for sizing multiplied with the number of inverters selected. The constant “101” represents the amount of possible percentages between 0% and 100% at 1% increments.

These permutations were created using the TSM’s probable power output values. The generation of the respective wind and solar arrays containing all viable configurations as required by the case study is a tedious process. The total elapsed time for this process clocked in at 3125 seconds, or around 52 minutes using the system described in *section 5.1*.

Using *Figure 5.19* as reference, we found that this process can potentially generate 3305124 possible combinations which must be checked for PAT consistency (the constraint W/T + S/T = 1 must be satisfied). But taking the respective permutation counts from the wind turbine sizing in scenario 1 (refer to *Table 5.21*) and the PV array sizing in scenario 2 (refer to *Table 5.25*), we can determine the total number of permutations that should satisfy the PAT constraint:

$$Q_{tot} = 101 \times 12 \times 27 = \mathbf{32724} \tag{37}$$

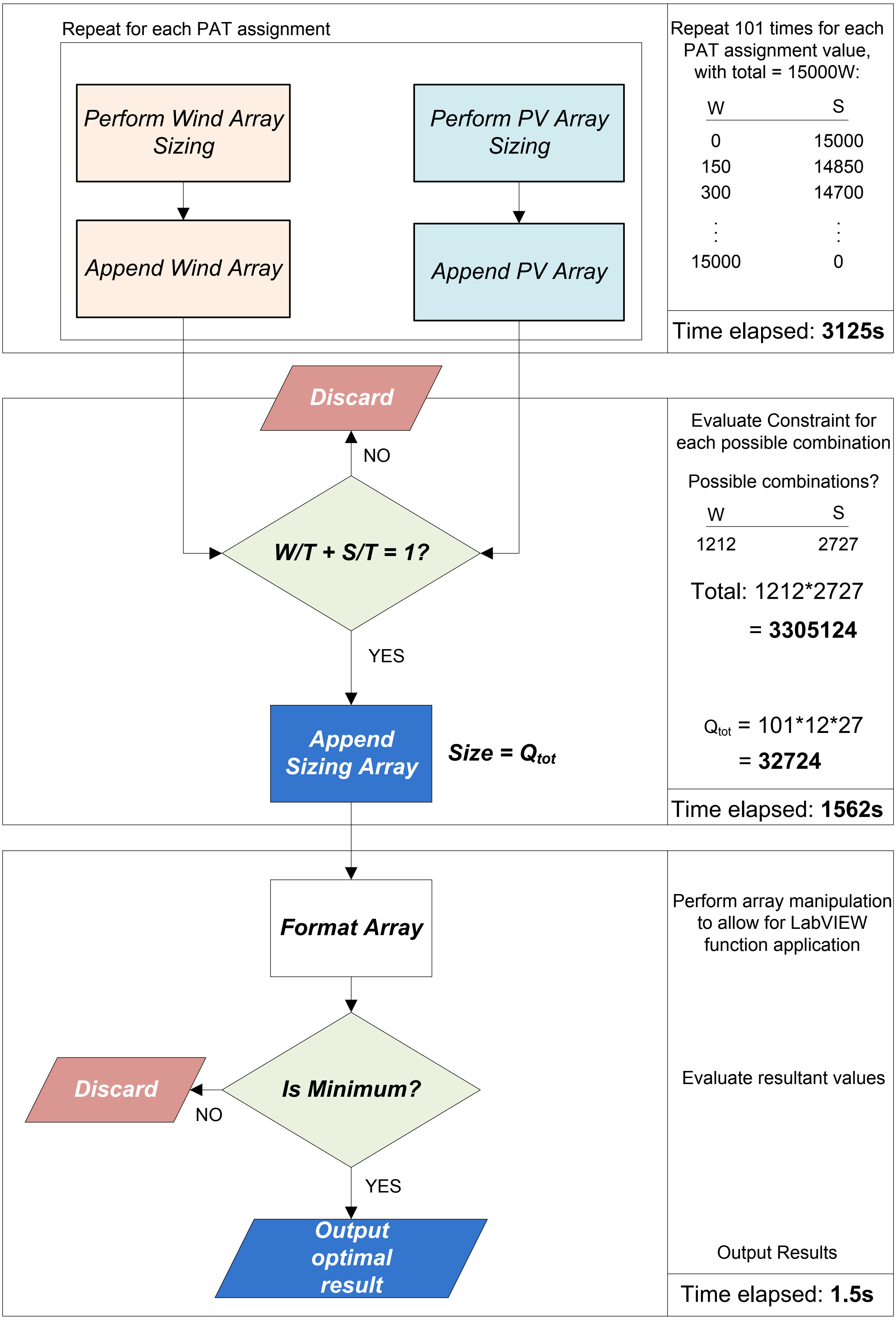
For this small selection of components, a very large number of permutations exist. The total elapsed time for this process clocked in at 1562 seconds, or close to 26 minutes. The results were all possible plant configurations that satisfy the PAT assignment constraint. This once again proves that the integration of an optimisation technique is very important to improve on the efficiency of the application.

5.5.3.2 *Optimal solution results*

The optimal solution refers to the combination of wind and solar generation arrays that satisfy the PAT and can be implemented at the lowest cost. Before we present the results, we quickly recap on the properties of this solution. Firstly, the solution is the result of the minimisation of the costing function as defined in *section 4.2.1.* As discussed, this function is given by *(28)*:

$$\min_{\boldsymbol{x_i}}\{P(\boldsymbol{x_i})\} = \min_{\boldsymbol{x_i}}\{C_{pv}(\boldsymbol{x_i}) + C_{wt}(\boldsymbol{x_i}) + C_{aux}(\boldsymbol{x_i})\}. \tag{28}$$

The associated parameters for this equation have also been discussed in *section 4.2.1.*



W	S
0	15000
150	14850
300	14700
⋮	⋮
15000	0

W	S
1212	2727

Figure 5.19 – Non-GA Optimisation Procedure

The reader must take note that for the sake of simplicity, only the variable terms (those terms representing parameters that undergo the dynamic sizing techniques), C_{pv} and C_{wt}, are represented by this solution discussion, since the non-variable parameter, C_{aux} , is the same regardless of the results of the optimisation process. The exact solution for this case study in terms of the renewable energy source requirements is given in *Table 5.32*.

Table 5.32 – Exact optimal solution as determined by the ESM (non-GA)

	Permutation	Energy Generation manufacturer	Component Model	Component Count	Inverter Model	Inverter Count	Cost
Wind turbine system	40	Whisper	Whisper 200	2	Windy Boy 2500	1	*R 166 534.00*
PV array system	87	SetSolar	M750P-80W	1045	Sunny Boy SB4000TL	26	*R 3 369 272.73*
					Optimal Solution Renewable Energy Cost		***R 3 535 806.73***

Looking at the results listed in *Table 5.32*, the reader may note that the number of PV modules listed is much greater the number of selected wind turbines. As we noted earlier with the differences between the sizing results when using the general wind turbine power output values as opposed to the TSM wind turbine power output values, the wind resources at the selected site does not provide for very effective turbine functioning. This clearly reflects in the system's optimal sizing, as almost no wind generation has been added to the result.

Also, due to this small number of turbines, practical implementation of this result set may also not prove to be feasible. Another point to note is that when looking at the number of PV modules, you may think that the power they provide is much higher than that required. This value has been adjusted to represent a 24-hour functioning period, as opposed to the 5.5-daily maximum operational timeframe of a PV module. This is done to provide a fair comparison to wind turbine functional-times, as wind turbines operate on a 24-hour basis.

5.5.3.3 *Complete system output results*

The requirements of the ESM specify that over and above the results of the optimal distribution of renewable energy sources for an REHS-based plant, the ESM must also provide costing details of all other components needed for the successful implementation of such a plant. To this end we present a summarised results set which is populated by the rest of the ESM's modules. Please note that detail components such as wiring details and electrical support structures have not been added to this version of the ESM's reporting capabilities.

Table 5.33 – Complete sizing results (non-GA) for an REHS-based plant

	Description	Quantity	Unit Price	Total Cost
Wind turbine	See table 5.32 for component descriptions			*R 166 534.00*
PV array system	See table 5.32 for component descriptions			*R 3 369 272.73*
Thermometer		2	R 1 500.00	*R 3 000.00*
Higrometer		1	R 2 555.00	*R 2 555.00*
Anemometer		1	R 1 000.00	*R 1 000.00*
Barometer		1	R 3 100.00	*R 3 100.00*
Pyranometer		1	R 200.00	*R 200.00*
Rain meter		1	R 1 500.00	*R 1 500.00*
Batteries	Battery specification by TSM	2	R 42 065.00	*R 84 130.00*
Controller	Priced per Watt	600	R 833.33	*R 499 998.00*
Lighting	Priced Watt per unit	16	R 35.00	*R 560.00*
HV/AC	Air-conditioning priced per Watt	6000	R 1.75	*R 10 500.00*
	Optimal Solution Cost			***R 4 142 349.73***

Finally, we must consider the duration of time elapsed by executing this sequence of modules. By applying date stamps to the individual modules, the time duration of each step could be determined. These results have been added to *Figure 5.19*, and are summarised in *Table 5.34*:

Table 5.34 – Execution time for determining the exact optimal solution for case study (Non-GA)

	Sizing Procedure (TSM Inputs) (s)	Results Combination (s)	Optimal Solution Determination (s)	**TOTAL TIME (s)**
Elapsed Time	3125	1562	1.5	4688.5

The results in *Table 5.34* show that this procedure takes very long to complete its predefined functions. When considering that the data sets used for the sizing procedures in this case study is very small, we can immediately conclude that the implementation of an optimisation technique is very important, as an increase in components to be used by the ESM for sizing procedures may render the application unusable for all intents and purposes.

5.5.4 Scenario 4 – ESM optimised configuration (GA)

The results as presented in the previous scenario (see *section 5.5.3*) showed that the implementation of an optimisation technique for the finding of an optimal solution is justified based on the time it takes the ESM in this case to determine the best solution. To this end, we now present the final module of the ESM, which implements the technique developed in *section 4.2*.

5.5.4.1 *Scenario considerations*

In this scenario, we strictly follow the procedure as discussed in *section 4.3*. The first step has already been completed in the previous scenario, where we define the applicable costing functions. For the next steps, we need to know how many models of components are available for sizing in the selection of the case study. For the PV array sizing case, this has already been determined in *Table 5.16* as three PV modules and in *Table 5.17* as nine inverter models. In the case of the wind turbine components, we have determined the number of wind turbine models as three in *Table 5.2* and the number of wind turbine inverters as four in *Table 5.3*. To continue, we restructure *Figure 4.12*, where to GA implementation code is discussed into *Figure 5.20*.

- **Step 1** (Blue processes in *Figure 5.20*)
  Generate $N_m = 2000$ random vectors structured according to *Figure 4.8*. Firstly generate random numbers for gene *Figure 4.8*(e) between zero and one. Thereafter generate random numbers between one and three for gene *Figure 4.8*(b) (PV module selection) and also random numbers between one and nine for gene *Figure 4.8*(d) (Inverter model selection). When these numbers have been selected, the PV optimisation algorithm determines the amount of PV modules and inverter models required and stores the result in their corresponding gene placeholders. In addition to this, each component's cost is determined, and the costing function *(29)* is calculated.

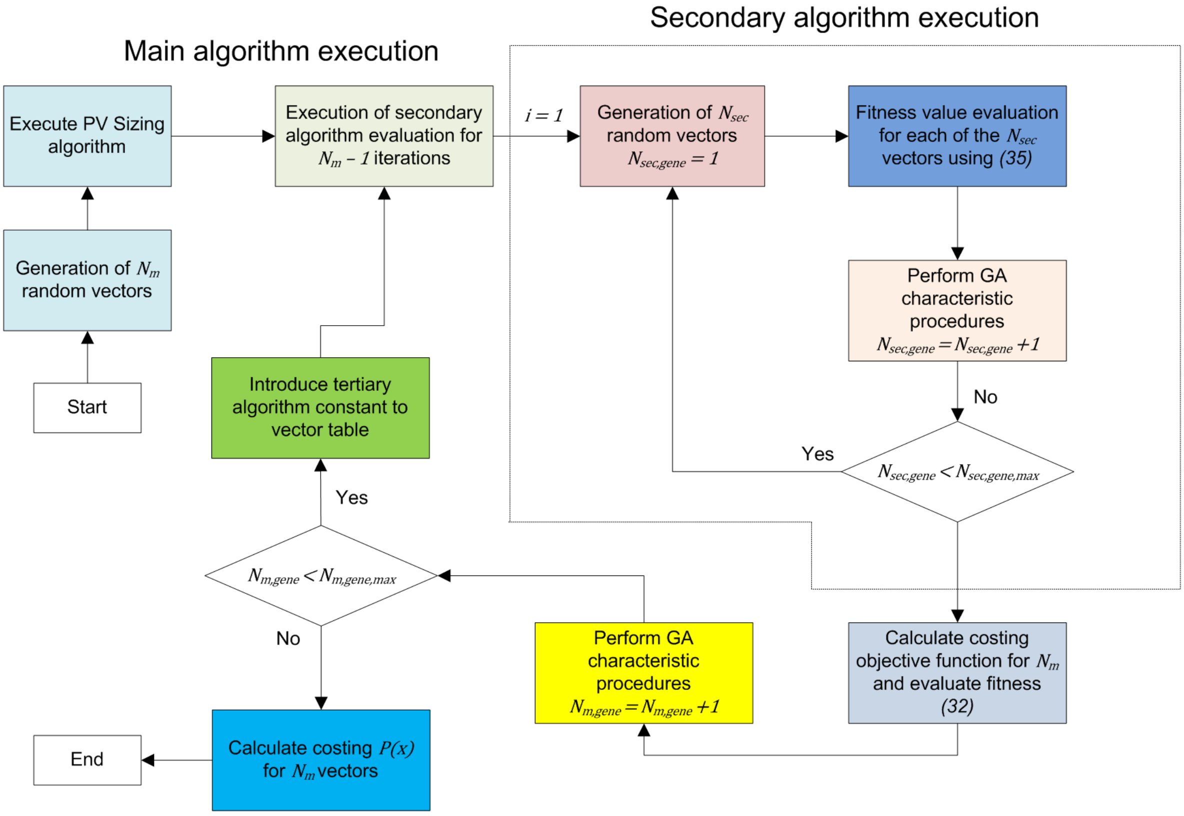


Figure 5.20 – Restructured GA implementation methodology

- **Step 2** (Light green process in *Figure 5.20*)

  In a for-loop, define $N_m - 1 = 1999$ iterations.

- **Step 3** (Red process in *Figure 5.20*)

  Define $N_{sec} = 1000$ random vectors structured according to *Figure 4.10*. Firstly generate random numbers for gene *Figure 4.10*(e) between zero and one. Thereafter generate random numbers between one and three for gene *Figure 4.10*(b) (Wind turbine model selection) and also random numbers between one and four for gene *Figure 4.10*(d) (Inverter model selection). When these numbers have been selected, the wind turbine optimisation algorithm determines the amount of wind turbines and inverter models that are required and stores the result in their corresponding gene placeholders, *Figure 4.10*(a) and *Figure 4.10*(c) respectively. In addition to this, each component's cost is determined, and the costing function *(30)* is calculated.

- **Step 4** (Dark blue process in *Figure 5.20*)

  The fitness function requires the values for the wind turbine permutation's costs. This has already been determined in step 3. Continue to evaluate the fitness function for the current chromosome.

- **Step 5** (Pink process in *Figure 5.20*)

  Mutation and crossover is now performed on this chromosome, dependant on the resulting fitness function value, and the choices of parameters for the mutation rate and the rate of crossover. Increment the chromosome count. Continue steps 3 to 5 until the amount of secondary chromosomes are equal to the maximum specified.

- **Step 6** (Grey process in *Figure 5.20*)

  With the secondary algorithm complete, determine the costing values for all N_m vectors and evaluate the fitness of the vectors.

- **Step 7** (Yellow process in *Figure 5.20*)

  Mutation and crossover is now performed on all main algorithm vectors, with the specific rates dependant on the resulting fitness function value, and the choices of parameters for the mutation rate and the rate of crossover. Increment the chromosome count. Continue entire process until the main algorithm permutation count reaches the maximum specified population. When the process continues, the result of the tertiary algorithm is introduced. In this case, it is only treated as a constant.

- **Step 8** (Blue process in *Figure 5.20*)

  When the population limit has been reached, the solution should have converged to the optimal configuration if the mutation and crossover values, together with the choice of population size were sufficient. The objective function of this solution may be determined and outputted.

The resultant optimally selected vector is listed in *Table 5.35*:

Table 5.35 – Optimal solution (GA) for renewable energy systems

	Permutation	Energy Generation manufacturer	Component Model	Component Count	Inverter Model	Inverter Count	Cost
Wind turbine system	59	Whisper	Whisper 500	1	Windy Boy 1100	3	*R 207 026.00*
PV array system	121	SetSolar	M2000P-210W	322	Sunny Boy SB3000	23	*R 3 443 229.00*
					Optimal Solution Renewable Energy Cost (GA)		***R 3 650 255.00***

Looking at the results listed in *Table 5.35*, the reader may note that the picture looks similar to the results determined by the incremental model in *Table 5.32*. The number of PV modules listed is much greater the number of selected wind turbines. The resulting cost however is higher than that of the solution determined by the incremental model. This means that the effectiveness of the GA can still be improved upon, by determining new values for the mutation and crossover rates on a trial and error basis.

Finally, we must consider the duration of time elapsed by executing this optimisation algorithm. By applying date stamps to the individual modules, the time duration of each step could be determined. These results have been summarised in *Table 5.36*:

Table 5.36 – Execution time for determine the exact optimal solution for case study (non-GA vs. GA)

	Incremental method (non-GA) time (s)	GA method time (s)	**Difference (S)**	**Difference (%)**
Elapsed Time	4688.5	2485.1	**2203.4**	**47.00**

This implementation of the GA definitely shows great promise in terms of the performance increase it brings to the ESM. While the accuracy of the determination of the optimal solution is still not perfect, a 47% increase in computation speed definitely justifies the small difference in system solution determination accuracy.

5.6 REVIEW

This chapter presented a case study which was introduced into the ESM to test the functional units that were implemented. The functionality and interfaces were shown throughout this process as a means of validating the application's functionality against the requirements as specified.

The verification of the results that are outputted by the ESM is an important consideration, since the resulting system must be able to perform as expected should the configuration be used for practical REHS-based plant sizing. In order to perform this verification process, we defined several scenarios, each testing a specific element/module of the ESM. The first scenarios focussed on the integration of the TSM modules, so that the results from both theoretical component power generation, and practical power generation could be compared.

By applying the same algorithmic techniques to both sets of data inputs, we found that the integration of the TSM, which has been developed by De Klerk [2], had a great influence on the accuracy of the resulting plant configurations with respect to the specific site's meteorological information. The case was more strongly put forward by the wind modules, as even though solar irradiance is quite good over most of the country, the same cannot be said for wind resources.

The proceeding scenarios continued with the verification process, by comparing theoretical calculations with the results outputted by the ESM. These results were found to be coherent, and we can conclude that the ESM will provide accurate results for optimally sizing an REHS-based plant.

In final sections, we discussed the EMS's functionality as a whole. The implementation of an optimal sizing technique based on a genetic algorithm was verified by comparing the results with an incremental model generation method, which is able to determine an exact solution.