Chapter 4

DEVELOPMENT

In this chapter, the methods that were proposed in Chapter 3 are developed and the ESM-integration techniques are shown. We start off by showing how the various renewable energy sources are sized according to characteristic parameters. Thereafter, the rest of the general constituents of the REHS plant description are defined. Finally, we look at an optimisation technique that has been incorporated for final plant optimal solution determination in terms of the component choices, and the allocation of power generation between wind and solar technologies as defined by the PAT in section 1.2.

4.1 REHS COMPONENT SIZING

4.1.1 Introduction

The sizing of PV arrays and/or wind turbine arrays is a process very similar to the sizing of batteries or other power sources in a circuit. The problem comes in when we must specify the array characteristics while taking input and output limits of certain components into consideration. These limits impose minimum and maximum outputs on the arrays, so that they can be successfully integrated into a renewable energy system.

Sections 4.1.3 & 4.1.4 show the techniques that were developed and integrated into the LabVIEW ESM application that are responsible for the sizing of all possible configurations of PV arrays and wind turbine arrays usable in the REHS-based system. *Sections 4.1.5* to *4.1.7* continue to describe the approaches taken for the rest of the REHS component sizing techniques. *Section 4.2* proceeds to show the development of an optimisation technique based on the genetic algorithm which is used for faster optimal plant configuration selection. *Section 4.3* brings all this together as we discuss how the optimisation technique has been integrated for complete system sizing and the performing of costing analyses using the PAT as baseline for renewable energy distribution. For the purposes of clarification, we also provide the reader with pseudo-code for each implementation. Using it as reference, the actual LabVIEW code provided in Addendum A can be easily followed.

4.1.2 Meteorological Data Retrieval

The solar irradiance data was procured from an open-source NASA site [42], which strives to provide global meteorological information. This data has been integrated into the TSM by De Klerk [2], and is therefore indirectly used by the ESM through the appropriate interfaces.

The data used for accurate wind analyses was procured via the Wind Atlas for South Africa (WASA) [43], which has been created by a consortium of bodies in the country. They provide accurate wind speed measurements at different heights, for specific sites in South Africa. These data have been integrated by De Klerk [2] into the TSM.

4.1.3 Solar Systems

By using the solar power characteristics as discussed in *section 2.1.2*, we now create an algorithm which the ESM can use for proper PV array sizing which satisfy the power requirements as defined by the PAT. The PV module information stored in the system database, features all relevant module parameters and characteristic information. The nominal power output of each of these modules is one of the important sizing parameters around which the sizing algorithm is created. The appropriate sizing parameters required by the ESM for the PV modules have been identified in *Figure 4.1*.

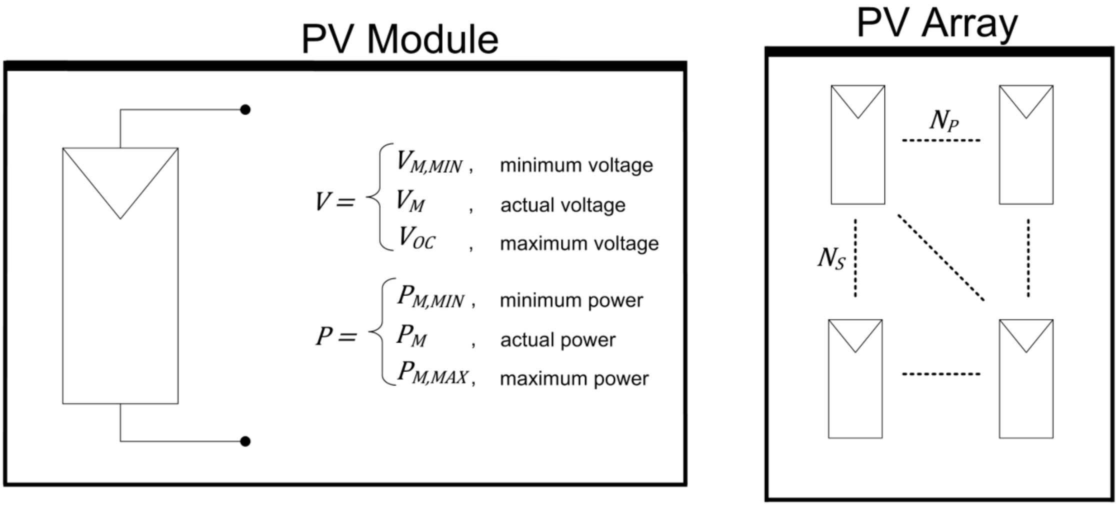

Figure 4.1 – PV Modules and PV array sizing parameters

The algorithm also looks at the sizing parameters from the perspective of the DC/AC inverters or DC/DC converters (from here on referred to as the inverters/converters); this means that the PV array outputs must satisfy these components' input specifications. The input parameters of the inverter/converter components are illustrated in *Figure 4.2*:

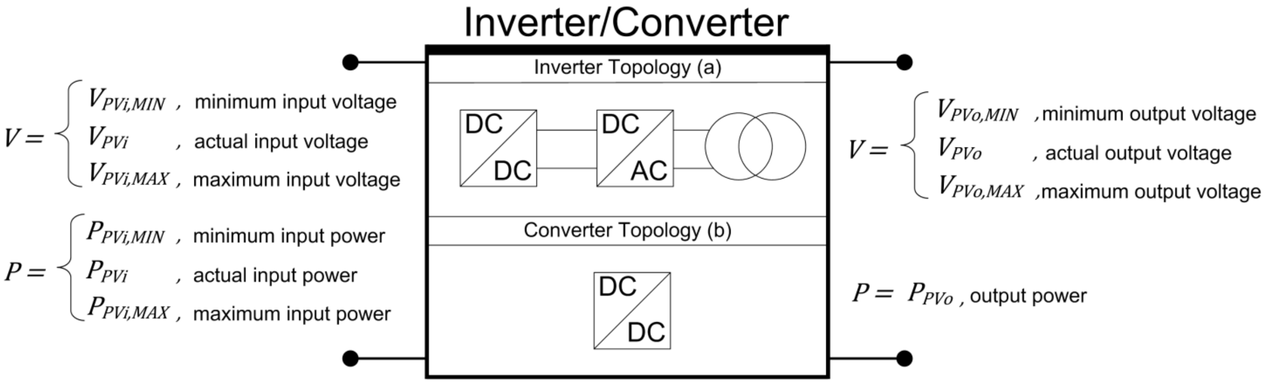

Figure 4.2 – PV inverter sizing parameters

Figure 4.2 shows two possible topologies for the PV array inverter/converter configurations. The only factor that influences the choice between the two topologies is the REHS-based plant's system bus design (AC or DC). When the ESM is executed, the choice is presented to the user between the implementation of an AC or DC bus to be used. This choice is then relayed to the PV sizing modules, where only the applicable hardware is set available to the algorithms for inclusion into the sizing procedure.

Topology *Figure 4.2*(a) shows the case where an AC bus is implemented. The inverter that is used features a DC/DC converter which performs MPPT, and the inverter unit which converts the input DC power to AC output power. If there is a mismatch between the output voltage of the inverter and the input voltage of the bus, a transformer is integrated into the configuration. The checks on which a mismatch is identified is contained in the following constraints:

$$V_{PVo,MIN} < V_{BUS} \quad and \tag{11}$$

$$V_{PVo,MAX} < V_{BUS}, \tag{12}$$

where $V_{PVo,MIN}$ and $V_{PVo,MAX}$ refer to the minimum and maximum inverter output voltages, and V_{BUS} refers to the AC bus voltage. In the case of *equation (11)* a step-up transformer is added to the configuration, and in the case of *equation (12),* a step-down transformer is added to the system configuration. Both these cases are implemented in a way similar to that shown in *Figure 4.2.*

Topology *Figure 4.2*(b) shows the case where a DC bus is implemented. Here the converter performs MPPT, and outputs directly to the bus.

Using *Figure 4.1* and *Figure 4.2* as parameter references, we can commence with the sizing process, as these parameters are common among the two topologies, and can therefore be used to size either type.

4.1.3.1 *Array voltage specification*

The first part of the algorithm is created to specify the number of PV modules that are required in a PV array string (one string of series connected modules) to satisfy the voltage requirements of the system. As per elementary electronics, the voltage of energy sources connected in series can be added together to determine the overall voltage across the terminals. Since a PV array must provide power to the inverter/converter it is connected to within a specified envelope, the PV array string voltage must always be above a certain minimum ($V_{PVi,MIN}$) and below a certain maximum ($V_{PVi,MAX}$) so that the system voltage is sufficient for the proceeding specified components. The minimum number of PV modules ($N_{S,MIN}$) is determined using *equation (13)* as listed below:

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

where $V_{PVi,MIN}$ refers to the minimum input voltage of the inverter/converter, and $V_{M,MIN}$ refers to the minimum output voltage at the maximum power point of the PV module. This equation specifies the number of panels required in series by taking the minimum required inverter/converter voltage, and dividing it with the PV module minimum output voltage at the maximum power point $(V_{M,MIN})$.

The maximum number of PV modules $(N_{S,MAX})$ is determined using *equation (14)*:

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

Here we use the maximum specified inverter/converter input voltage $(V_{PVi,MAX})$ with the maximum PV module voltage (V_{OC}) as the dividing factor.

While the logical case may be that we should choose the number of PV modules as close to the maximum $(N_{S,MAX})$ as possible, it may be the case that the maximum resulting power generated by each of these strings is too high for the inverter/converter input specifications.

Therefore we must consider *equation (15)* which ensures that this is mitigated:

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

where $P_{PVi,MAX}$ refers to the maximum input power of the inverter/converter, and $P_{M,MAX}$ refers to the power at the maximum power point of each PV module. Incorporating this constraint with *equation (14)* we can complete the voltage specification with *equation (16):*

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

which specifies the number of PV modules connected in series as being between $N_{S,MIN}$ and the lowest maximum (supremum) that satisfies *(14) and (15).*

4.1.3.2 *Array power specification*

The second part of the algorithm looks at the amount of parallel branches in the PV array. Since it is a common fact that parallel-connected power sources deliver a total current equal to the sum of the individual parallel components, and since the voltage has already been specified, we can specify the maximum amount of parallel-connected PV array strings ($N_{P,MAX}$) by using *equation (17):*

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

where $P_{PVi,MAX}$ refers to the maximum input power of the inverter/converter, N_S refers to the number of PV modules connected in series for voltage specification, and $P_{M,MAX}$ refers to the power output of the modules at the maximum power point.

The minimum number of panels does not need explicit calculation, as we want to exploit the full capabilities of the inverter/converter units. We can therefore continue to define the total number of PV modules per array (N_{array}) using *equation (18):*

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

where N_S refers to the amount of series-connected PV modules and $N_{P,MAX}$ the required amount of parallel PV array strings.

4.1.3.3 *PV system sizing*

The final required element of this algorithm requires that we now consider the number of PV arrays that the system requires for satisfying the plant's total power requirements. As discussed in *section 2.1.4.2,* each array is connected to a single inverter/converter. Since the above equations implement the constraints of connectivity between the arrays and their inverters/converters, it is simple to define the total amount of required PV modules in the system by firstly defining the number of inverters/converters (x_i) required by the system, using *equation (19)*:

$$x_i = round_{up}\left(\frac{P_{MAX}}{P_{PVo,i}}\right), \tag{19}$$

where P_{MAX} represents total required power of the REHS-based plant to be generated by solar power, as specified by the ESM PAT, and $P_{PVo,i}$ refers to the maximum power output of each inverter/converter model (i) present in the database of components. We can therefore determine the total number of required PV modules $\left(N_{PV,total}\right)$ with *equation (20):*

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

where N_{array} represents the total number of PV modules per array, and x_i the number of required inverters.

This total will be calculated for each model of inverters/converters available in the database of components. This procedure is repeated for all models of PV modules and PV inverters/converters listed in the database, in conjunction with the sizing optimisation process as detailed in *section 4.3.*

4.1.3.4 *PV system pseudo-code*

A pseudo-code implementation of the discussed algorithm is shown in *Figure 4.3* in terms of a descriptive flow-chart. We begin by noting that two loops are introduced for the reading of the models of both the selected inverter/converter models, and the models of the PV modules. The loop structure ensures that a PV array based on a specific PV module type is sized for each model of inverter/converter in the database.

Since the user may choose between using the TSM for model parameter input, or manual input, a section of code is written which allows the sizing algorithm to either get input parameters from the TSM, or using specified values as inputs. This block is shown in blue in *Figure 4.3.*

The solar modules in the TSM calculate the probable power output of a PV module given the REHS-based plant's location. Therefore, this parameter provides a much more accurate and realistic view of how much power a specified PV module will be able to deliver. Using the TSM for model parameter inputs will therefore provide the client with a better sized PV system.

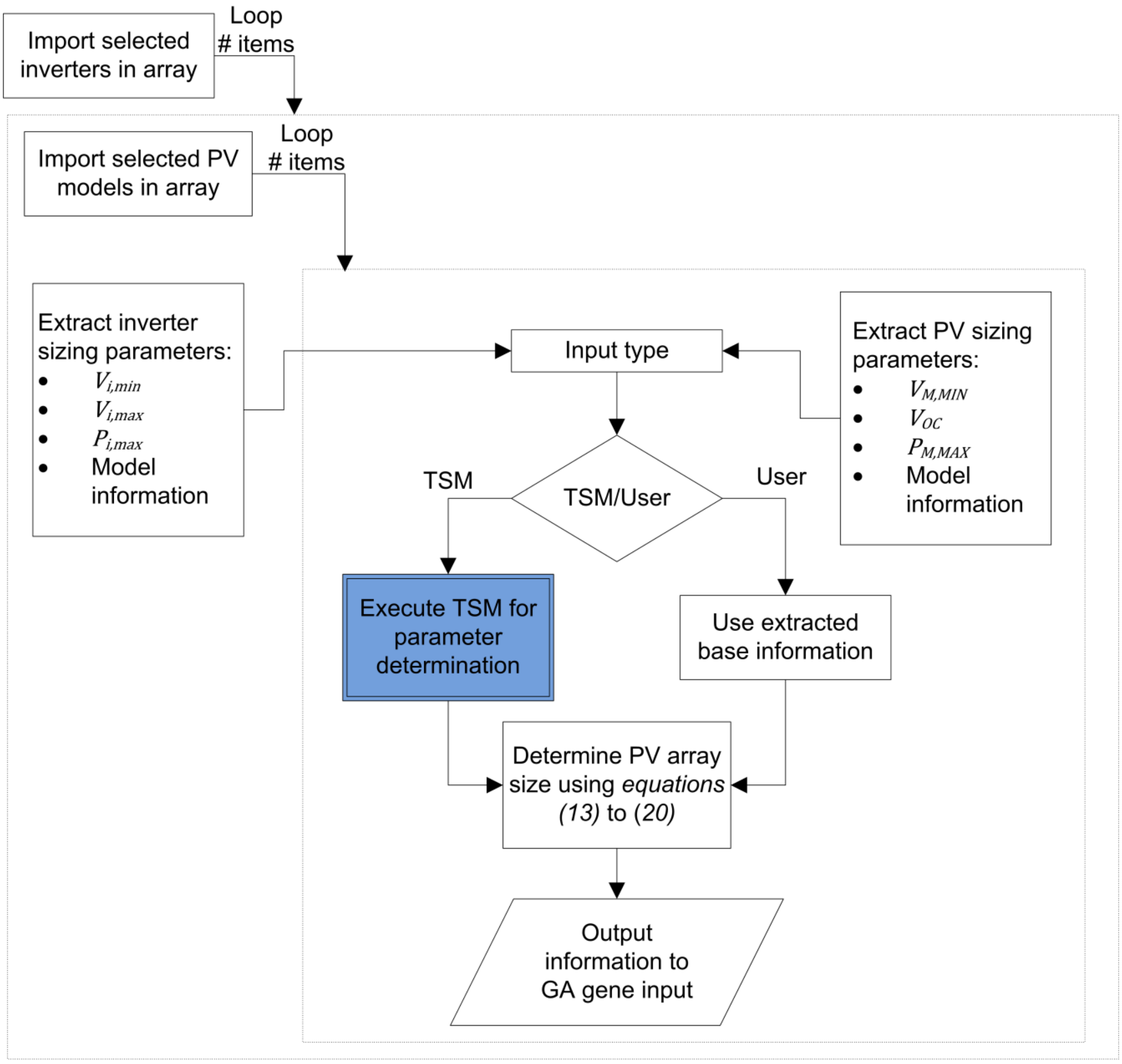

Figure 4.3 – Diagrammatical pseudo-code for PV array sizing

After the applicable parameters have been chosen, they are inputted to the array sizing module which incorporates *equations (13)* to *(20)*, and finally outputting an array of all possible combinations of PV arrays adhering to the power requirements. This information is then outputted to proceeding optimisation modules which use the component count and total array efficiency to determine the best solution.

4.1.4 Wind Systems

As mentioned in *section 2.2,* for a REHS-based application the required power inputs are between 1kW and 30kW, depending on the size of the load, which in the case of the REHS, is primarily the electrolyser. This implies that when wind power is brought into the system specification, the relative size of the wind turbine(s) will be on the smaller end of the available size spectrum. The output parameters for wind turbine system sizing are shown in *Figure 4.4*:

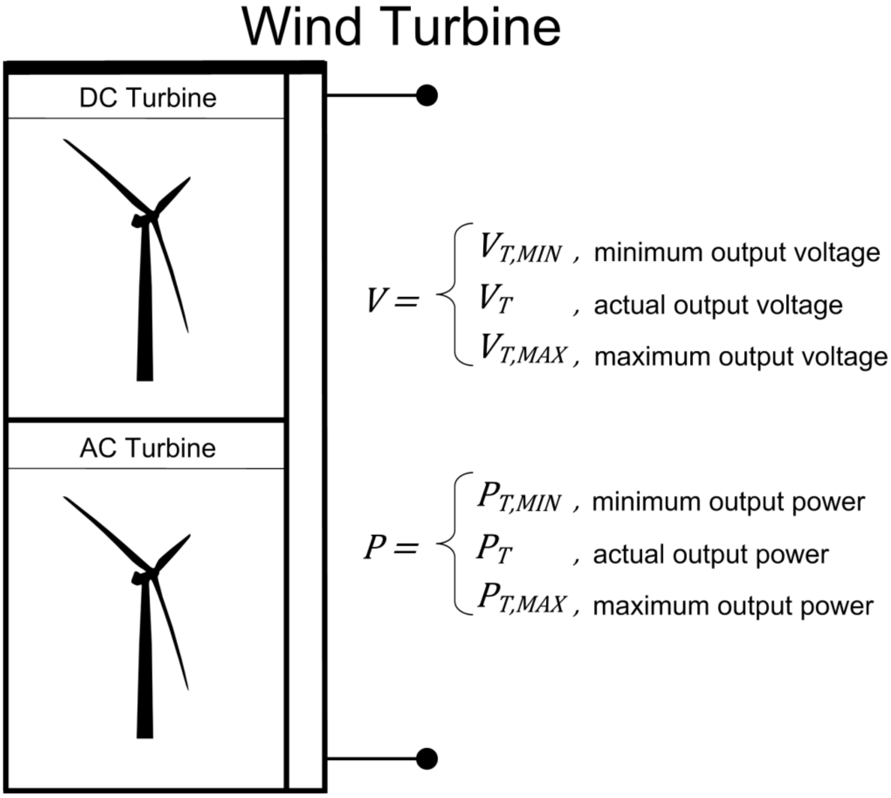

Figure 4.4 – Wind turbine sizing parameters

It can also be noted that, as stated in *section 2.2*, wind turbines are usually connected to a dedicated inverter/converter for synchronisation (in the case of an AC design) or size specific (in both AC and DC cases) purposes. Therefore, voltage-specific sizing is not required, but in the case of AC voltage matching, we need to decide if a step-up or step-down transformer is required. This is illustrated in *Figure 4.5* where the different possible connection topologies are shown.

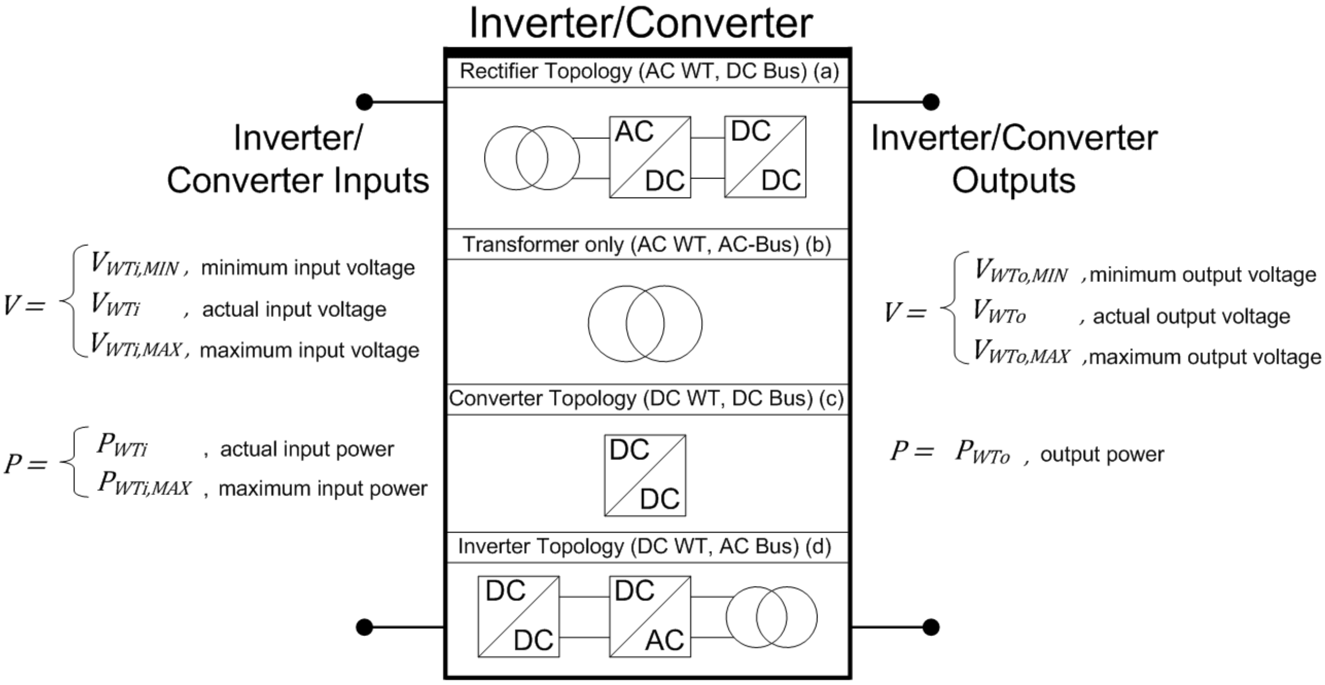

Figure 4.5 – WT inverter/converter sizing parameters

Figure 4.5 shows four possible topologies for the wind turbine inverter/converter configurations. Two factors influence the topology type, namely the wind turbine design (AC or DC) and the REHS-based plant's system bus design (AC or DC). As mentioned in *section 1.3.2, w*hen the ESM is executed, the choice is presented to the user between the implementation of an AC or DC bus to be used. Choosing between the implementation of AC or DC turbines is done separately for the wind module.

Topology *Figure 4.5*(a) shows the case where an AC wind turbine and a DC bus is implemented. If there is a mismatch between the output voltage of the turbine, and the input voltage of the rectifier, a transformer is integrated into the configuration. The checks on which a mismatch is identified is contained in the following constraints:

$$V_{T,MIN} < V_{WTi,MIN} \quad and \tag{21}$$

$$V_{T,MAX} > V_{WTi,MAX}, \tag{22}$$

where $V_{T,MIN}$ and $V_{T,MAX}$ refer to the minimum and maximum wind turbine output voltages, and $V_{WTi,MIN}$ and $V_{WTi,MAX}$ refer to the minimum and maximum inverter/converter input voltages.

In the case of *equation (21)* a step-up transformer is added to the configuration, and in the case of *equation (22),* a step-down transformer is added to the system configuration. Both these cases are implemented in a way similar to that shown in *Figure 4.5*.

Topology *Figure 4.5*(b) shows the case where an AC wind turbine is used with a system designed with an AC bus. A transformer may be incorporated if there is a mismatch between the voltage specifications of the turbine and the bus in a similar fashion to the topology in *Figure 4.5*(a), but using a modified pair of constraints:

$$V_{WTo,MIN} < V_{BUS}, \tag{23}$$

$$V_{WTo,MAX} < V_{BUS}, \tag{24}$$

where $V_{WTo,MIN}$ & $V_{WTo,MAX}$ refer to the minimum and maximum inverter output voltages, and V_{BUS} refers to the AC bus input voltage. In the case of *equation (23)* a step-up transformer is added to the configuration, and in the case of *equation (24),* a step-down transformer is added to the system configuration. Both these cases are implemented in a way similar to that shown in *Figure 4.5*.

Topology *Figure 4.5*(c) shows the case where a DC wind turbine is used with a system designed with a DC bus. The DC/DC converter shown is mainly concerned with performing MPPT.

Finally, topology *Figure 4.5*(d) shows the case where a DC turbine is connected to an system featuring an AC system bus. Firstly, the DC/DC converter performs MPPT, where after the inverter switches the DC input power to AC output power. If there is a mismatch between the inverter unit output voltage, and the system bus voltage, a transformer may be incorporated in the same fashion as discussed for *Figure 4.5*(b).

Using *Figure 4.4* and *Figure 4.5* as parameter references, we can commence with the sizing process of the wind turbine array.

4.1.4.1 *DC Turbine-converter sizing*

When specifying the number of AC turbines connected to an inverter, we limit the maximum number to one, since the power output of AC wind turbines are usually very large, and require either one dedicated inverter, or more than one inverter. With DC turbines this is usually also the case. A minor problem arises in cases where DC turbine power is much lower than available converter input power specifications. Here, we can specify the number of turbines $(N_{T,MAX})$ connected to a converter as:

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

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

4.1.4.2 *AC Turbine-inverter sizing*

When power generation requirements dedicated to wind energy as allocated by the PAT become very large, larger wind turbines may be the most cost-effective solution. Although this case is highly unlikely for an REHS application, it must be brought into consideration. It must be noted that larger wind turbines are usually AC machine-based, so we limit the discussion to this case. In terms of the connectivity of such a system, multiple inverters may be connected to a single turbine. In such a case, the minimum amount of required inverters $(N_{i,total})$ can be given by *equation (26):*

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

where $P_{WTi,MAX}$ refers to the maximum input power of the inverter, and P_T output power of the turbine. This is a special case, which will require specific user inputs in order for the system to perform the sizing procedure accordingly.

4.1.4.3 *Wind turbine sizing*

In terms of total wind turbine count, another problem arises. As stated in *section 2.2*, the actual power generated by a wind turbine is greatly dependant on the immediate wind speed. Since the system must be designed for continuous operation, the amount of wind turbines must always provide enough power to satisfy the system input requirements.

We therefore size the system according to a minimum power availability scheme. The calculation of the minimum average power $(P_{T,MIN})$ generated by the turbine forms part of the requirements of the TSM, therefore the ESM will use this value as an input. Thus *equation (27)* determines the amount of turbines $(N_{wt,total})$ which are required for a specific selected turbine 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. When the wind turbine array provides more power than is required by the REHS-specified loads, the additional energy is stored in a battery bank. This is discussed in *section 4.1.6*.

4.1.4.4 *Wind system pseudo-code*

A pseudo-code implementation of the discussed wind turbine sizing algorithm is shown in *Figure 4.6* in terms of a descriptive flow-chart. As in the case for the PV sizing procedure, we begin by noting that two loops are introduced for the reading of the models of both the selected inverter models, and the models of the wind turbines. The loop structure ensures that the wind turbine arrays are sized for each model of inverter in the database.

Since the user may choose between using the TSM for model parameter input, or manual input, a section of code is written which allows the sizing algorithm to either gather input parameters from the TSM, or using specified values as inputs. This block is shown in green in *Figure 4.6.* The wind modules in the TSM calculate the probable power output of a wind turbine given the selected site’s wind data.

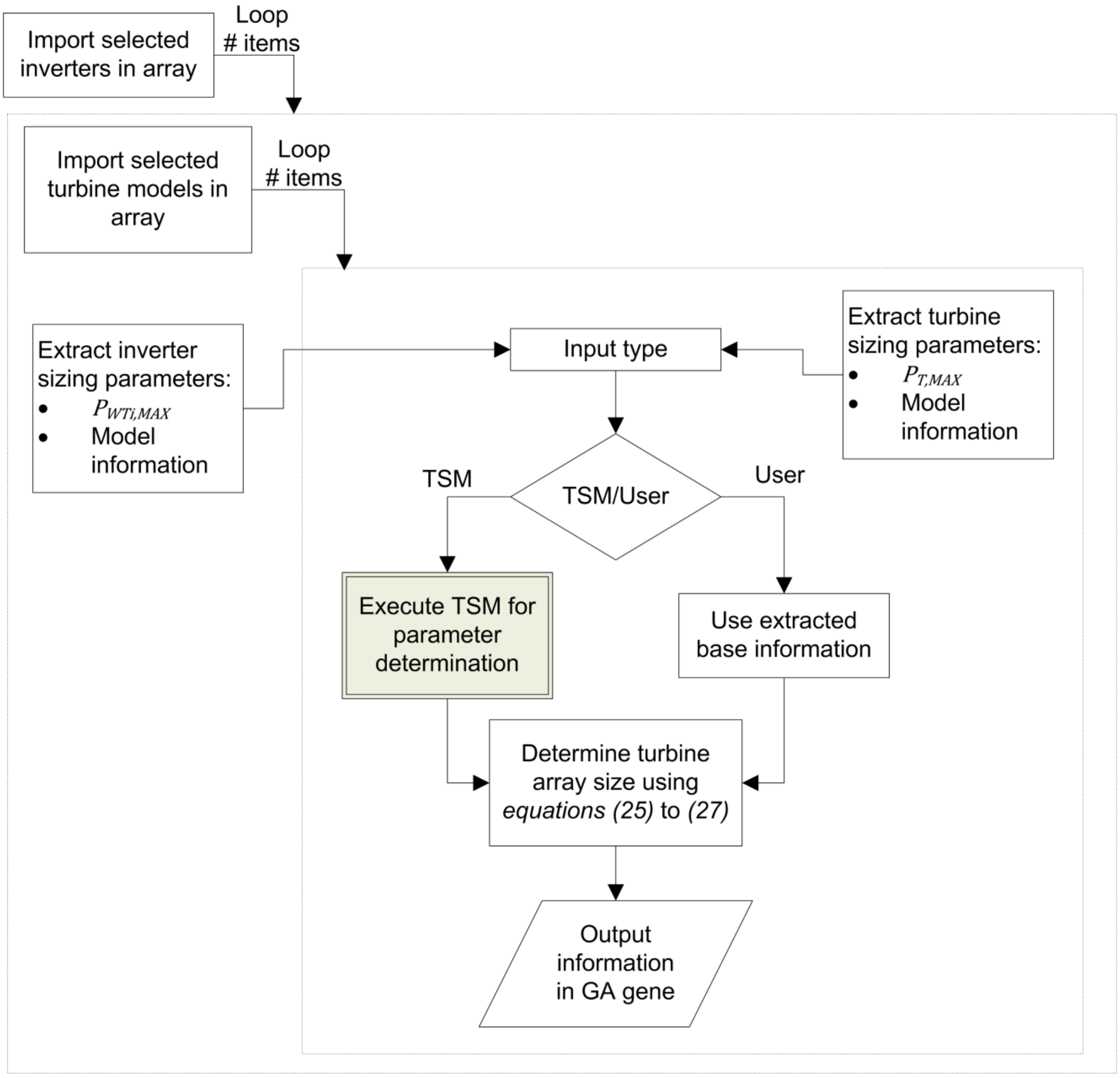

Figure 4.6 – Diagrammatical pseudo-code for wind turbine array sizing

After the applicable parameters have been chosen, they are also inputted to the array sizing module which incorporates *equations (25) to (27)* and finally outputting an array of all possible combinations of wind turbine arrays adhering to the power requirements attributed to wind generation. This information is then outputted to proceeding optimisation modules which, similar to the PV sizing procedure, uses the component count and total array efficiency to determine the best solution.

4.1.5 Weather Station

The weather station module is very simple, as the application only requires sensor-number specification. Special cases include the sensors used for measuring wind parameters where functionality is added allowing the user to choose between different sensor types.

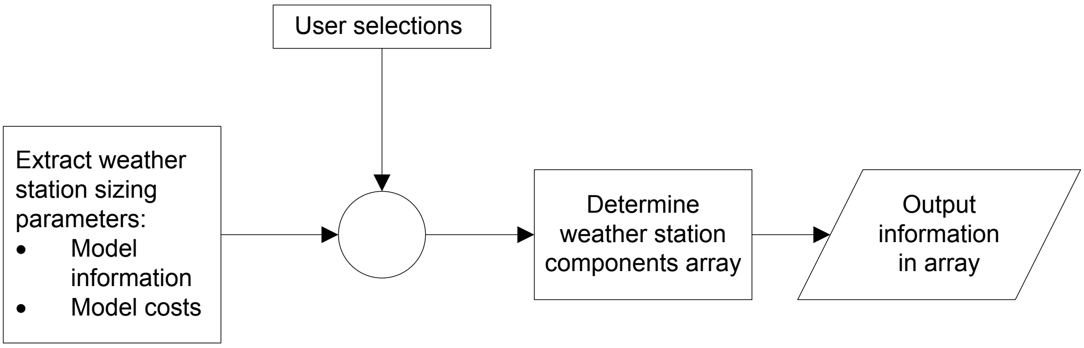

Figure 4.7 – Diagrammatical pseudo-code for weather station components array sizing

For the sake of simplicity, only one model per sensor type is added in the database, with the basic selection process shown in *Figure 4.7*.

4.1.6 Storage System

The storage system relates to the addition of batteries to the REHS-based plant, as discussed in *section 3.1.* The scope of the ESM does not include the detailed sizing procedures of storage systems, as a detailed implementation of such an algorithm has been integrated into the TSM which sizes the battery bank according to the requirements of the load. When the load (in the case of an REHS-based plant, mainly the electrolyser(s), controllers and other process related instrumentation) needs to run for a certain time per day, and the renewable energy sources are unable to directly provide power (e.g. when the systems only uses solar energy generation which effectively provides energy during 5 hours of the day, and the load runs for more than this), the system is sized in such a way that batteries provide the power for the load.

The ESM therefore, must only provide functionality to allow for the sizing of a system using a specified number of batteries connected in such a way so as to satisfy the design criteria of the TSM. Basic algorithms which are directly linked to the outputs of the TSM are thus incorporated to specify the number of batteries required, and determining the cost of such a configuration. Future versions of the ESM may include an economic sizing procedure for the development of the most cost-effective battery bank configurations.

4.1.7 Electrolyser

Similar to the weather station module, the module which introduces the electrolysers to the system is also very simplistic. The user is offered a choice of electrolysers which vary on hydrogen production figures, and thus on input power requirements. This information may come either from the TSM, or it can be user-specified. The ESM uses this power requirement parameter, together with other system-component power requirements to determine the total amount of system power draw, which in turn is used for the renewable energy sizing procedures.

4.2 OPTIMISATION PROCEDURE

By following the procedures as described in *section 4.1* one gets a feel for the potential complexity that is attributed to the choosing of an optimal total system configuration. To this end, a method was developed that is based on a GA as discussed in *section 2.4.1.1* that incorporates these sizing techniques and performs then in tandem as a single optimal sizing algorithm.

As with most optimisation techniques, we must first define an **objective function** which is to be minimised or maximised, depending on the nature of the function and the requirements of the user. This objective function must be calculated for every possible permutation of system components.

Using a methodology derived from [44], we continue to define two algorithms which are to work together for the final optimisation procedures. The main algorithm is responsible for variable parameter sizing of the PV arrays and associated inverter/converter units, and the secondary algorithm is responsible for the variable parameter sizing of the wind turbine arrays and its associated inverter/converter units. Both these algorithm contain a third decision variable, related to the ratio of renewable energy power generation as defined by the PAT.

Thereafter, as per definition of the genetic algorithm, we correspondingly define a **fitness function** to each algorithm which is used for solution convergence. Since each GA chromosome is a potential solution of the optimisation problem, the fitness function evaluates the cost of each combination relative to others in the population.

Finally, following a process similar to that derived by Yang et al. [45], we show how this algorithm is implemented into the ESM software environment.

4.2.1 Objective function

Since the system component configuration algorithms have already been developed for preceding modules, the genetic algorithm constraints are directly imported from these modules. The techniques described in *sections 4.1.3 to 4.1.7* already output system configuration information in the form of component totals, effective permutation costs and efficiency characteristics.

We can therefore define an objective function which must be minimised in terms of the following costs:

- PV systems costs in terms of the initial capital costs (R) of the modules, the maintenance costs per year $(R/year)$ and the corresponding installation costs. According to Belfkira et al. [46], a good approximation for the maintenance costs for each unit per year, and the installation costs of each component, can be set at 1% and 10% respectively for the corresponding capital costs. In consideration of these parameters, we also note that the system lifetime is 20 years, which is the accepted maximum life-span for PV modules, and features the longest life-span of all REHS-based components. This approximation will be integrated into the objective function.
- Wind system costs in terms of the initial capital costs (R) of the wind turbines, the yearly maintenance costs $(R/year)$ and the initial installation costs. The costs involved for the installation, operation and maintenance on wind turbine systems are subject to many variables. According to Morthorst [47], installation costs of turbine projects in Europe account for between 20% and 30% of the initial capital cost of the project. The yearly operation and maintenance costs are within 3% and 4% of the initial cost capital costs. For the purposes of this dissertation, we escalate the installation costs to 32% of the initial capital cost of the project, to represent a worst-

case scenario. We assume that the term “wind turbine” represents a collective term for both the hub-and-rotor assembly, and the tower upon which the hub is mounted.

- Capital costs for the batteries (R), together with their respective maintenance and installation costs. Due to the fact that the expected lifetime of batteries in a hybrid storage setup is extremely subjective to charging characteristics, as well as battery type, for the purposes of this implementation, we assume a lifetime of 20 years, consistent with the average lifetime of other system-critical components.

- General systems capital, maintenance and installation costs in similar terms as the previous costing factors. These components are ESM-specific and must be manually specified by the user.

- Electrolyser costs based on a generalised costing approximation in terms of cost per Watt $(R/Watt)$.

- Finally, the weather station components’ initial capital costs, yearly maintenance and installation costs, as well as device replacement costs.

When taking these defining points into consideration, we can construct an objective function that is to be minimised during the optimisation procedure. We call this function the total cost function $P(\boldsymbol{x})$, which is defined in *(28)*:

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

where $\boldsymbol{x_i}$ is the vector for a specific component configuration (i). C_{pv} is the total cost of the PV array with its respective power components, C_{wt} is the total cost of the wind turbine array with its respective power components and C_{aux} is the cost of all other components that are not dynamically sized by the ESM.

For the proper definition of *equation (28)* each parameter needs individual attention. To this end, we firstly show the cost parameter involved which determines the total PV system cost, by first looking at the vector function C_{pv} in *equation (29)*:

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

where $N_{i,pv,TOTAL}$ is the total amount of the *i-th* PV model in the vector $\boldsymbol{x}$;

$N_{j,inv,TOTAL}$ is the total amount of the j-th inverter model in the vector $\boldsymbol{x}$;

$C_{i,pv,MOD}$ is the cost of a single PV module of the *i-th* type;

$C_{j,inv,MOD}$ is the cost of a single inverter/converter of the j-th type;

$M_{i,pv}$ represents the maintenance costs per year of the PV panels and

$I_{i,pv}$ and $I_{j,inv}$ represents the respective component installation costs.

$lifetime$ is 20 years (pre-selected).

Equation (29) shows how the lifetime of the system (which is chosen as 20 years) is incorporated in the costing procedure by multiplying the yearly maintenance parameter, $M_{i,PV}$ with 20. It is assumed that the maintenance costs per year remain the same throughout the duration of the systems functional lifespan, although there are implementations where inflation is taken into consideration [48].

The second parameter is the vector function C_{wt} which donates the total cost of the wind energy system, and is defined by *equation (30)*:

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

where $N_{i,tinv,TOTAL}$ is the total amount of the i-th inverter model in the vector $\boldsymbol{x}$;

$N_{j,wt,TOTAL}$ is the total amount of the *j-th* wind turbine model in the vector $\boldsymbol{x}$;

$C_{i,tinv,MOD}$ is the cost of a single inverter of the i-th type;

$C_{j,wt,MOD}$ is the cost of a single WT model of the *j-th* type;

$M_{j,wt}$ represents the maintenance cost of the wind turbine;

$I_{i,tinv}$ and $I_{j,wt}$ represents the respective component installation costs and

$lifetime$ is 20 years (pre-selected).

The third term in *(28)*, namely C_{aux}, is the total cost for all other plant specific components. These components do not undergo model selection procedures, and are essentially constant. One exception exists in the battery configuration. Although the scope of the ESM does not include sizing procedures for batteries, we still need to specify how many batteries are needed for successful plant integration. This module has been handled by the TSM, where after the ESM receives the number of batteries required as input. In *(31)* we discuss the auxiliary costs parameter (C_{aux}):

$$C_{aux} = N_{bat}.C_{bat} + C_{elec} + C_{ws}, \tag{31}$$

where N_{bat} is the number of batteries as inputted from the TSM, C_{bat} is the cost per battery, C_{elec} is the total cost of the electrolyser assembly and C_{ws} is the cost of the selected weather station units.

We now continue to define three algorithms which may be used for the determination of the mentioned costs. When the optimisation procedure begins, these algorithms are executed consecutively, and when a specified number of iterations have been completed, a global, optimal solution may be presented conforming to the requirements as specified by the objective function in *(28)*.

4.2.2 Main algorithm

The main algorithm is designed to optimise the configuration of all variable components of the PV array. It uses an integer vector with the size equal to the number of possible system combinations of the appropriate, variable type, which adheres to specific constraints. This results in a matrix of vectors with N_m possible combinations (rows). These combinations form the total population of the genetic algorithm. Each element of the vector is a combination of system specifications or characterised parameters. This combination of elements is shown in *Figure 4.8.*

(a)	(b)	(c)	(d)	(e)
PV Module Total	**PV Module type code**	**PV Module Inverter Total**	**PV Module Inverter type code**	**Ratio Solar/Total**

Figure 4.8 – Main algorithm chromosome construction

The parameters integrated into the primary gene are (a) total number of PV modules of a specific type, (b) model designation for the used PV module, (c) the number of inverter(s) required for the specific configuration, (d) the model designation for the inverter(s) and (e) the ratio of solar power to be implemented versus the total power requirements of the system.

Since the determination techniques of parameters (a) to (d) in *Figure 4.8* have already been created in previous modules, those techniques are brought over to the optimisation module. The results of each of the stages are then converted to appropriate integer values. (a) and (c) represent the number of PV panels and the number of PV inverter/converter units, and are therefore already in the correct format. (b) and (d) represent the type of PV module and inverter/converter used for that specific chromosome definition. Therefore, the integer values of these genes represent the row number of the corresponding components in the PV and inverter/converter database respectively. This concept is shown in *Figure 4.9*.

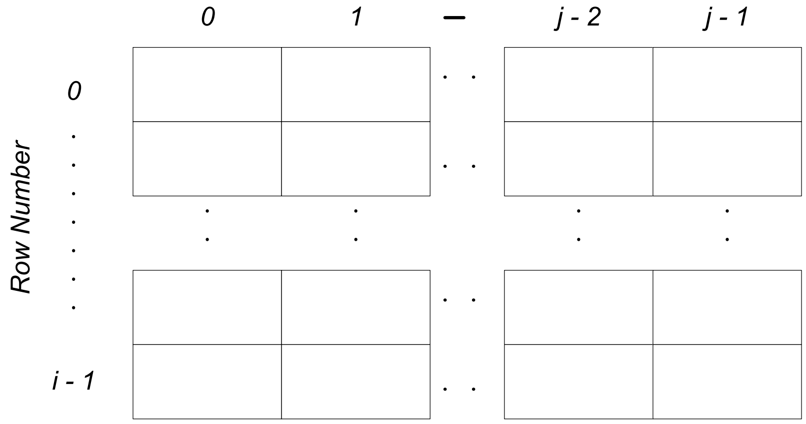

Figure 4.9 – Individual row value consignment from parameters in the appropriate database

This conversion process is reversed when the algorithm has completed its function so that report-related information can be extracted. The parameter (e) in *Figure 4.8* brings important functionality to the optimisation procedure. We will elaborate more on this when describing the secondary algorithm in *section 4.2.3*.

The second requirement for the algorithm is the introduction of a fitness function, which assigns a “degree of quality” to each chromosome in the gene population i.e. each component permutation. This function is defined in *equation (32)*:

$$Fitness_{M,i} = \frac{\left(C_{pv,i}\right) \times N_m}{ratio\left(\frac{S}{T}\right) \sum_i \left(C_{pv,i}\right)}, \quad i = 1 \; .... N_m, \tag{32}$$

where N_m is the main permutation vector size, or total amount of configurations that are initially defined. Parameter $C_{pv,i}$ represents the objective function for the main algorithm as defined by *(29)*, and $ratio\left(\frac{S}{T}\right)$ refers to the ratio of power assigned to solar energy generation relative to the total power requirements of the system. By evaluating the function in *(32)*, we can see that a lower value for the fitness function points to a better solution, since a smaller value will be the result of a permutation with a higher power output at a lower cost. Each iteration (generation) of the GA optimisation process starts with the evaluation of the fitness function for each valid chromosome. The design methodology discussed in *sections 4.1.3 to 4.1.7* is applied to each chromosome in each generation.

4.2.3 Secondary algorithm

The secondary algorithm is designed to introduce the configuration of all variable components of the wind turbine array into the main optimisation procedure. This algorithm uses a chromosome similar to the one defined in *Figure 4.8*, and is defined in *Figure 4.10*:

(a)	(b)	(c)	(d)	(e)
Wind Turbine Total	**Wind Turbine type code**	**Wind Turbine I/C Total**	**Wind Turbine I/C type code**	**Ratio Wind/Total**

Figure 4.10 – Secondary algorithm chromosome construction

The parameters integrated into the secondary gene are (a) total number of wind turbines of a specific type, (b) model designation for the used wind turbine, (c) the number of inverter(s)/converter(s) required for the specific configuration, (d) the model designation for the inverter(s)/converter(s), and (e) the ratio of wind power to be implemented versus the total power requirements of the system.

As discussed for the main algorithm, the determination techniques of parameters (a) to (d) in *Figure 4.10* have already been created in previous modules, and those techniques are brought over to the optimisation module.

The results of each of the stages are also converted to appropriate integer values in the same way as shown in *Figure 4.9*. (a) and (c) represent the number of wind turbines and the number of wind turbine inverter/converter units, and are therefore already in the correct format. (b) and (d) represent the type of wind turbine and inverter/converter used for that specific chromosome definition. Therefore, the integer values of these genes represent the row number of the corresponding components in the wind turbine and inverter/converter database respectively.

Similar to (e) in *Figure 4.8*, (e) in *Figure 4.10* brings important functionality to the optimisation procedure. As specified by the requirements of the ESM, the sizing technique must adhere to two key aspects: one is the optimal sizing of a plant in terms of the amount of energy source generation attributed to wind generation, and the amount of energy generation attributed to solar power generation; and the other is the determination of an optimal plant configuration which fits the system ratio as defined by the first key aspect.

To this end, we introduce the following constraints to ensure the proper optimal sizing of a configuration:

$$Ratio\ \frac{S}{T} + \ Ratio\frac{W}{T} = 1\ , \tag{33}$$

$$Constraints\left(N_{i,pv,Total}, X_{i,pv}, N_{i,wt,Total}, X_{i,wt}\right) = satisfied, \tag{34}$$

where $Ratio\ \frac{S}{T}$ and $Ratio\frac{W}{T}$ refers to the ratio of solar energy generation and wind energy generation relative to the total power requirements respectively as specified in the PAT. The parameters $N_{i,pv,Total}$ and $N_{i,wt,Total}$ refer to the respective totals for PV modules and wind turbines, with $X_{i,pv}$ and $X_{i,wt}$ referring to the number of inverters/converters for the PV arrays and the wind turbine arrays respectively.

Together, the two parameters as defined in *(33)* ensure the most cost-effective ratio between the implementation of wind and solar energy generation for an REHS application at a specific location. This is ensured, since every iteration (generation) of the GA checks if this constraint is met by the resulting chromosomes. Once the optimisation procedure is complete, all variations of the ratio in *(33)* will have been evaluated, and the best solution conforming to the objective function in equation *(28)* will be outputted.

Similar to the main algorithm, the second requirement is the introduction of a fitness function, which assigns a “degree of quality” to each chromosome in the gene population i.e. each component permutation. This function is defined in *equation (35)*:

$$Fitness_{S,j} = \frac{\left(C_{wt,j}\right) \times N_{sec}}{ratio\left(\frac{W}{T}\right)\sum_{j}\left(C_{wt,j}\right)}, \quad j = 1 \; \ldots . N_{sec}, \tag{35}$$

where N_{sec} is the secondary algorithm permutation count, or the amount of configurations in the secondary algorithm. Parameter $C_{wt,j}$ represents the objective function for the secondary algorithm as defined by *(30)*, and $ratio\left(\frac{W}{T}\right)$ refers to the ratio of power assigned to wind energy generation relative to the total power requirements of the system. As in the case where we evaluated the fitness function of the main algorithm, we can see in *(35)* that a lower value for the fitness function also points to a better solution, since a smaller value will be the result of a permutation with a higher power output at a lower cost.

4.2.4 Tertiary algorithm

The third algorithm is designed to introduce the configuration of all stationary components (where model selection is not implemented) into the main optimisation procedure. Due to the nature of its constituting parameters, it only serves as a constant value for input into the main algorithm for this version of the ESM. The individualisation of it however, enables future modifications to the optimisation algorithm to be easily incorporated, such as the inclusion of dynamic battery sizing.

(a)	(b)	(c)	(d)	(e)	(f)
HVAC Cost	**Lighting Cost**	**Electrolyser Cost**	**Battery cost**	**Controller Cost**	**WS Cost**

Figure 4.11 – Tertiary algorithm chromosome construction

The parameters integrated into the tertiary gene are (a) Heating, Ventilation and Air Conditioning, (b) costs for lighting in substations, (c) the cost of the electrolyser(s), (d) the cost of the battery bank as determined by the TSM, (e) the cost of controllers for instrumentation control and (f) weather station component costs.

The determination techniques of parameters (a) to (f) in *Figure 4.11* have already been created in previous modules, and those techniques are brought over to the optimisation module. As previously mentioned, the implementation of the tertiary algorithm in this version of the ESM is equivalent to the addition of a constant to the optimisation technique i.e. with every iteration of the optimisation process, its value remains the same. The following section describes the implementation process of the three algorithms as discussed in this section.

4.3 IMPLEMENTATION OF THE OPTIMISATION PROCEDURE

A systematic approach is now taken to implement the techniques discussed in *section 4.2.* In order to clearly illustrate the process that is about to be discussed, *Figure 4.12* has been provided, which shows a diagrammatical pseudo-code section of the implementation methodology.

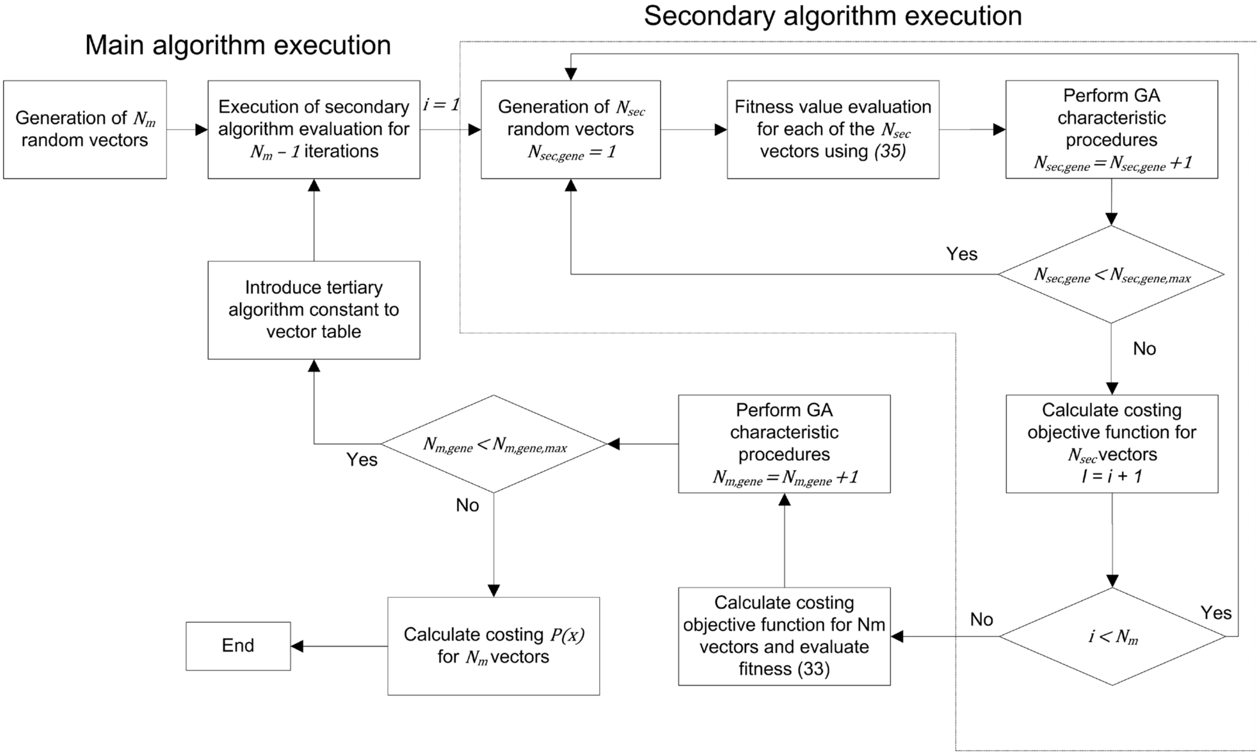

Figure 4.12 – Diagrammatical pseudo-code for genetic algorithm implementation

To begin the procedure, we define N_m vectors (the number of permutations for the main algorithm, relating to the configurations of the PV modules) randomly, according the specified format as discussed in *section 4.2.2*, each one representing a combination of components adhering to the sizing constraints. For each of these vectors, the secondary algorithm is executed. This ensures that for every valid permutation of components, a respective wind turbine solution is found.

Functionally, N_{sec} vectors (similarly, the number of permutations for the secondary algorithm) are obtained for each N_m vector. They, in turn, adhere to the definition and specified format as discussed in *section 4.2.3*. Using *equation (35)*, the fitness of these vectors is evaluated. The vectors with fitness values closest to one have the greatest probability of reproducing themselves, thus carrying over the good parameter choices. As per GA definition, mutation of genes (introduction of other components not in the original vector group) must take place in the next step, ensuring that global minima may be determined. The resulting individuals that have been obtained during the first iteration, and that have completed the reproduction and mutation phases, are evaluated, and made available for the next generation (loop iteration). The results of the tertiary algorithm are now added to the vectors, completing a valid system configuration.

With the above (in-loop) process complete, N_m vectors (solutions) should have been produced. We now need to determine the fitness parameters for these vectors and sort them accordingly. As in the secondary algorithm application, GA mutation and reproduction now takes place, putting forth new combinations that are used in proceeding generations. When the maximum main algorithm vectors have been determined, the lowest value for C_{tot} is found, with the corresponding permutation selected as the best solution. This solution describes both a how the ratio between wind energy generation and solar energy generation is defined, and the component configuration which satisfies this ratio. The generic GA parameters (cross-over rates and mutation rates) are inputted as default values using a method described in [49]

4.4 CHAPTER REVIEW

This chapter provided the complete theoretical foundation upon which the modules of the ESM were constructed. A systematic approach was taken with the development of the different sizing techniques, starting with the sizing techniques for the renewable energy sources. This was followed with sizing comments on the other constituents of an REHS-based plant.

In order to extract an optimal solution from the database of components, an optimisation technique based on a genetic algorithm approach was discussed. This provides a much faster path to obtaining the most cost-efficient plant configuration than a normal linear sizing process, as the amount of components that can be included in the plant configuration is very large, and even the addition of one component may lengthen the sizing process considerably. In the proceeding chapter, the discussed ESM modules are tested and illustrated, showing the functionality of the techniques derived here in greater detail.