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A new visual library for modeling and simulation of renewable energy desalination systems (REDS)

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ABSTRACT

The recourse to renewable energy systems in general has become a reality. Thus, it has become very important for engineers to design and simulate such systems that serve the renewable desalination plants. A computer software package has been developed by the authors for design and simulation of renewable energy desalination systems (REDS). This was motivated by unavailability of such packages in the literature or on a commercial scale. Solar desalination systems, wind desalination systems, and geothermal desalination systems software libraries became affirmative parts of the main REDS software library. This library enables the user to construct different configurations by clicking the mouse over the required units (blocks). The interface aids designers, scientists, and operators to perform different analyses and calculations such as energy, exergy, cost, and thermoeconomics. Typical desalination processes such as a multi-stage flash, multi-effect distillation, and reverse osmosis are numerically modeled and embedded within the main library of the developed software. REDS shows a wide scope of validity, reliability, and capability to model and simulate renewable desalination systems.

Keywords: Solar desalination; Wind energy; Geothermal power

1. Introduction

The renewable energy sources (solar, wind, geothermal, etc.) are attracting more attention as an alternative energy. The application of renewable energies such as solar and/or wind energies to produce fresh water is receiving increased interest due to the need for solving the water shortage problems in various areas of the world and at the same time as conventional energy sources used for obtaining water in different scenarios becoming depleted. The use of renewable energy sources in water desalination is of interest, especially for remote areas where a conventional energy supply is not easily available [1]. On the other side (the load side), water desalination (seawater/brackish) is distinguished by operations as thermal distillation processes (vapor compression, multi-stage flash, solar still, and multi-effect distillation) and membrane processes (reverse osmosis (RO), forward osmosis, ion exchange, and electrodialysis).

Solar energy as an example of renewable energy can power these different techniques by providing the required electricity via photovoltaic (PV) and/or concentrating solar power (CSP). At the same time,

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renewable desalination processes consist of a number of complicated interactive units such as heat exchangers, solar collectors, wind turbines, storages, pumps, pipes, etc. Using these units in a wide range of process configurations and types can be obtained. To understand the behavior of these processes under different operating conditions, different analyses, and different techniques, a flexible computer program is really needed. Using such software program, a large number of flow sheeting problems can be manipulated [2,3].

The available software packages in such research field (renewable desalination systems) are distinguished by some criteria like, the technique of modeling, the generality, and the dimensions of the software package itself. Habib et al. [4] presented a computer program developed for sizing and simulating a solar-powered desalination station using the Solar Multiple Condensation Evaporation Cycle principle. Habib's work was established based on one dimension analysis (energy), and is visualized only for solar thermal desalination applications. Uche et al. [5] presented an outline a development-oriented object program having a userfriendly software in the form of building blocks for design of either individual or integrated systems for energy and water.

Uche's work was very promising; however, exergy and thermo-economic analyses were absent. Moreover, the renewable energy systems also were absent from Uche work. Hamad and Alsaad [6] presented a computer software application to simulate hourly energy flow of a grid connected PV system. The software enables conducting an operational evaluation of a studied PV system in terms of energy exchange with the electrical grid. Hamad and Alsaad's [6] work was established for only PV application without any assistance of desalination parts or units. Another visual software package was presented by [7,8]; however, it was concerned about only water desalination without any existence to solar, wind, or/and geothermal technologies.

For solar electrical energy units such as PV systems, most of literatures are focused on the cell performance, temperature distribution, cell physical, sizing, and some applications for existing techniques. Most of these models were implemented according to performance technique and not for the design technique. For cell characteristics modeling example, some literatures [9–14] were implemented for that purpose. The performance issues examples of the PV based on the I-V relation that were presented according to references [15–19]. At the same time, wind turbine models [20–24] focused on the performance and optimization matters without any interference from the desalination technologies.

It is obvious from the literature that the modeling software packages are presented to solve a special case where some of it is focused on renewable and the rest are focused on only desalination without any combination between the two technologies. Moreover, most of it has no more than one or two modeling dimensions i.e. one part focused on performance and other focused on cost not thermo-economic and/or energy not exergy. Therefore, the need for a general, flexible, accurate, and visualized software package for renewable desalination systems has become an urgent need. In this work, a new software package for renewable energy desalination systems (REDS) is presented. The technique of modeling, the process description, the modeling dimension, the software features and capabilities, and the interface explanation are also presented.

2. The process modeling dimensions

Engineering processes (especially renewable energy combined with desalination processes) consist of a number of interactive units. Using these units in a wide range of process, configurations and types can be obtained. Generally, to understand the behavior of these processes under different operating conditions, a flexible computer program is really needed. Using such program, large number of flow sheeting problems can be manipulated [2,3]. To achieve generality for any successive software program, the process modeling technique should have some requisites such as the dimension of the technique utilized. The main modeling dimensions are:

- The mathematical technique environment (MTE).
- The simulation type.
- The data analysis type.

The MTE is normally decided by the programmer from the beginning by choosing the program language or technique. The MTE is also divided into three main categories: the first called (a) special purpose program (sequential or simultaneous marching), the second is (b) general purpose program (sequential or simultaneous modular approaches), and (c) new visual system program (subsystems are broken to physical, functional, or both concepts). The simulation type is considered a very important dimension because it can decide the direction of the program. This simulation type can be generally divided into three classes: (a) performance, (b) design, and (c) optimization. In the performance type, the variables associated with the feed streams to a process unit and all design parameters (such as PV module area, PV panel's dimensions, etc.) are assumed to be known. The variables associated the internal and output streams are the unknowns. In the design problem (the current work matter), some design parameters (areas, dimensions, voltage, current, number of cells, unit cost, etc.) and/or feed variables are left unspecified and become unknown. The known streams are the broader streams of the process such as the power of the PV module or the system productive. The optimization problem differs from the design problem in that the number of equality constraints is smaller than that of the variables left unspecified. The unspecified variables are now calculated so as to minimize an objective function (usually the cost or specific power consumption), normally of economic nature. The data analysis dimension depends on the programmer choice. More analyses mean more generality and more capabilities added to the software. For this work (REDS), the available analyses are; (a) energy, (b) exergy, (c) cost, and (d) thermo-economic. The programmer has to decide his methodology from the beginning i.e. building the numerical model according to the dimension. For example, solar radiation model [25] is considered one-dimensional model because it calculates the solar radiation as an output based on parameters input. Solar radiation model [25] was not performed for performance or design matters. Therefore, a new visual system program by the use of SimuLink [26] is built to solve design type of simulation and to run out all possible types of output data analyses such as energy, exergy, cost, and thermoeconomic. The developed software code has some features such as a generality, flexibility, accuracy, availability, and friendly interface. Fig. 1 shows the schematic diagram of the main pillars of modeling dimensions that been considered as an ideal structure for the REDS program. The REDS contain very interested libraries such as solar desalination systems (SDS) library, wind desalination systems (WDS) library, and geothermal desalination systems (GDS) library. The main libraries also contain many individual units like tanks, tubes, storages, solar collectors, boilers, turbine, pumps, wind turbines, PV systems, heat-exchangers air coolers, diesel generators, gas turbine cycle, etc. User can easily gather the units and connect it from the library to construct the desired system.

3. The REDS visual library

For modeling, SimuLink provides a suitable graphical user-interface (GUI) for building models as block diagrams, using click-and-drag mouse operations. The ordinary models used to make stream elimination to overcome modeling instability or error bugs. However, SimuLink overcomes this problem permitting ultimate stream allowance between the units through the model environment. Therefore, SimuLink [26] is utilized as a suitable code and the interface for the building operation of the REDS program. The REDS interface is created and customized by the use of "User defined function block" block. Fig. 2 shows a flow chart of the REDS libraries.

3.1. SDS library

SDS are a library part of the REDS software package that developed by Sharaf et al. [3]. SDS library contains two main categories: (a) Solar thermal power and (b) Solar electrical power. For thermal section, the library contains different types of solar collectors such as Parabolic trough concentrator (PTC), compound parabolic concentrator, and flat plate collector. Also, it contains pumps, storages, and heat exchangers. Also solar organic Rankine cycle (SORC) takes an important part through the thermal section. Therefore, condensers, boiler heat exchangers, pumps, and expanders are modeled and simulated. Thermal

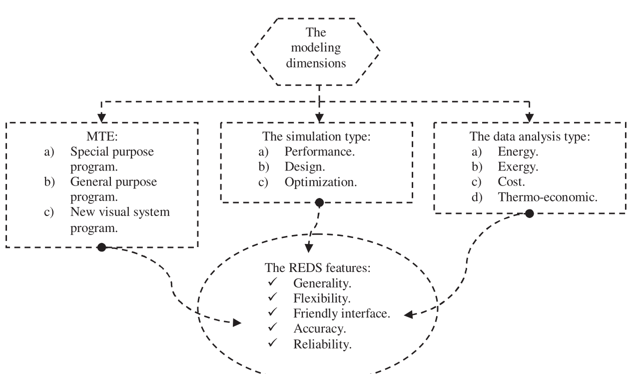

Fig. 1. Schematic diagram of the REDS modeling dimensions.

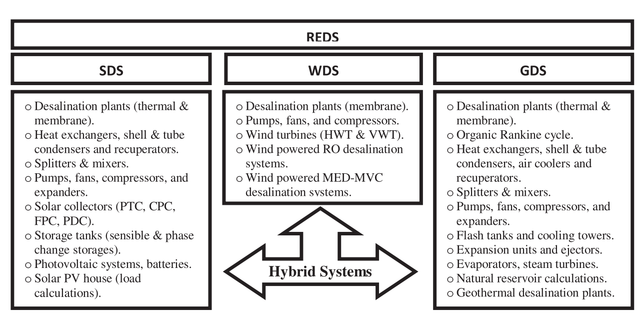

Fig. 2. The main flow chart of the REDS software libraries.

section of the SDS library is approved for many configurations as introduced by Sharaf et al. [3,27–30]. Moreover, the solar field is modeled for many configurations such as direct and indirect vapor generations with the utilization of many of working fluids (Toluene, molten salt, steam, oils, Freon's, etc.). For solar electrical section, a PV system is modeled and introduced. It is proposed that by identifying the output power from the system application (example of RO desalination plant), the design limits would be calculated. The PV application is modeled for membrane RO and the calculations of solar building loads. Fig. 3 shows a photograph of a part of the SDS. The library is embedded in the SimuLink/MatLab tool box. User can easily open a new model browser window, drag and drop the selected unit, then double clicking on the unit in order to specify some input parameters (related to design a type of simulation). Also, the designer or the user has the ability to construct any proposed system by dragging the needed units thence; using the ultimate stream allowance by the SimuLink to connect all units together. The user has the ability to run out all physical properties (temperatures, pressures, enthalpies, entropies, etc.) and all data types such as energy, exergy, cost, and thermoeconomic. SDS library has some features such as:

- Containing a lot of thermal units used for CSP power generation.
- Thermal desalination plants are thermo-economically modeled and stored as a ready model for any designer to use with friendly interface.
- The PV power system is modeled for membrane RO desalination plants.

3.2. WDS library

Wind energy plays a vital role in the quest for renewable and sustainable energy as well as in reducing carbon emission. Moreover, wind turbines have demonstrated their viability. It is estimated that their indirect carbon dioxide emissions (through their material fabrication) are paid back within nine months of operation for offshore turbines. They are, essentially, grouped into two configurations based on their rotational rotor axis with respect to the ground: (i) the older generation, lower–power vertical axis vertical wind turbines (VWT) and (ii) the higher power, horizontal-axis horizontal wind turbines (HWT) at wide commercial deployment. In this work, design and simulation of different types of wind turbines are performed and analyzed based on design method of modeling. The developed power of the load on turbine unit is assigned in order to calculate the rest of design parameters such as minimum wind speed, average wind speed, rotor diameter, hub height, rotor speed, and the unit cost.

Artificial neural network (ANN) algorithm is used to simulate the turbines and to compare the results with the correlations and the test data from the manufacture manual. The WDS library is constructed for different types of wind turbines. The MatLab/SimuLink (GUI) and ANN are utilized for the simulation procedure. The wind turbines are modeled within the range of operating conditions (0.5–7500 kW for HWT & 0.3–10 kW for VWT). This modular program has great capabilities to overcome previous programming problems and limitations such as the recycle streams. The units are modeled to present a good example of the proposed modular program. Moreover, the new code

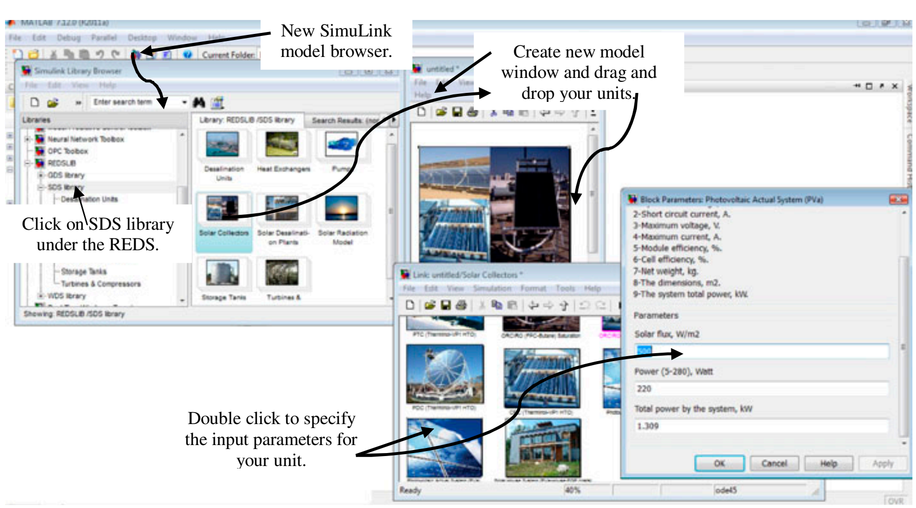

Fig. 3. A photograph part of the SDS library.

may help the user or the designer to select a suitable turbine unit based on the demanded electrical power from the desalination load. User can easily combine the RO membrane desalination with different types of wind turbines as a general system to study (energy, exergy, cost, and thermoeconomic). Fig. 4 shows a photograph of the WDS library.

In order to simulate and predict the characteristics of different types of wind turbines, a lot of real data are taken from the manufacture manual of each type. It is proposed that by identifying the output power from the turbine unit, the design limits would be calculated. Moreover, the designer has a great ability to assign the number of wind turbines that could be used in the wind farm based on the unifying power and the total power. The developed code of the WDS library calculates the following design limits for wind turbines:

- Starting wind speed (cut-in speed), m/s.
- Average wind speed, m/s.
- Hub height, m (HWT) and fin length, m (VWT).
- Rotor diameter, m.
- The rotor speed, RPM.
- The unit cost, $.
- Number of blades in case of vertical type.
- Wind farm design (number of required wind turbines, area and dimensions).

3.3. GDS library

Desalination by means of renewable energy sources is thus a suitable solution for providing fresh water. Geothermal wells deeper than 100 m can be employed to power desalination plants. The geothermal energy is used to heat the saline water and it could be used to generate electricity for operating RO units. Furthermore, with the recent progress thermal distillation technology, the utilization of geothermal brine with temperature up to 60˚C has become a promising option. Therefore, GDS library contains most of types and configurations of thermal and membrane desalination processes combined with geothermal technologies. Also, steam and organic Rankine cycles are considered in the same library. Fig. 5 shows a photograph of the GDS library under SimuLink browser.

The user has the ability to run out some important parameters related to the geothermal reservoir such as:

- Well bore.
- Well depth.
- Rock temperature.
- Field data (mass flow rates, pressure, enthalpy, area, etc.).
- Pumps power.
- The driller dimensions.
- Drilling, field, and plant costs.

Moreover, the user can select the method of thermal power utilization and the combination type with the power plant or the direct vapor generation with thermal desalination type. For direct combinations, flash tanks and heat exchangers are used with multi-stage flash, multi-effect distillation (thermal and mechanical vapor compressions). For indirect combinations, steam or organic Rankine cycles are utilized

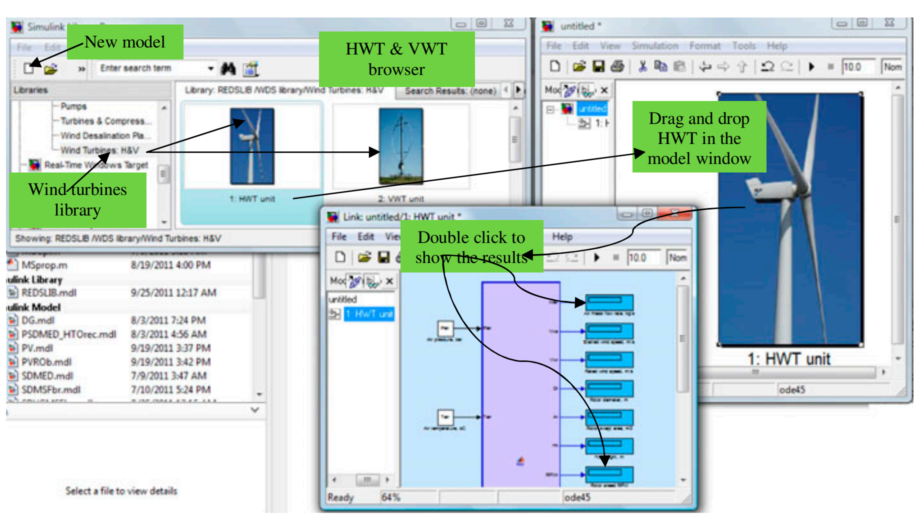

Fig. 4. Wind turbines library browser under MatLab/SimuLink platform as a part of REDS.

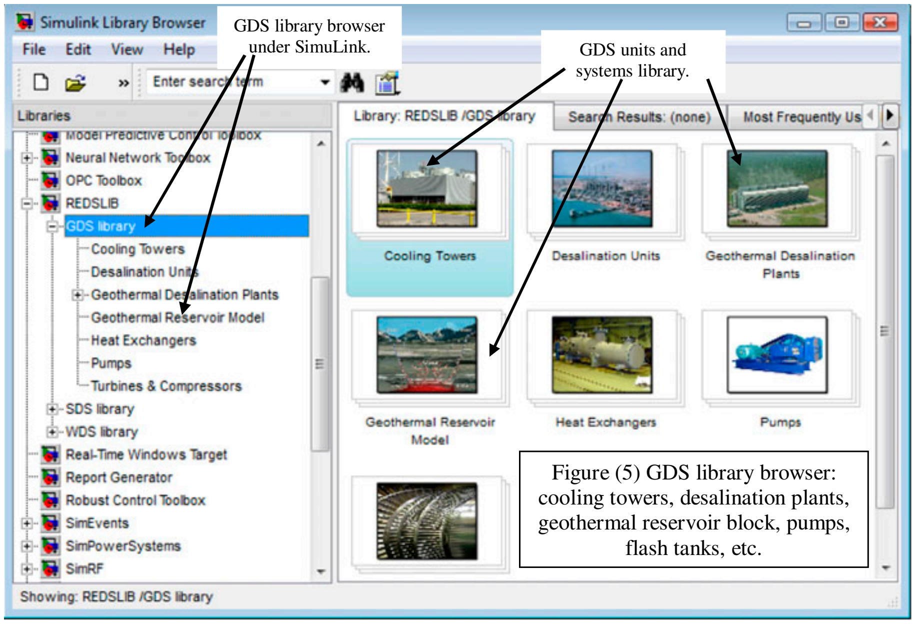

Fig. 5. GDS library browser: cooling towers, desalination plants, geothermal reservoir block, pumps, flash tanks, etc.

for RO membranes and multi-effect distillation with mechanical vapor compression (MED-MVC).

4. The calculation methodology

REDS are built according to design calculation method. As indicated earlier, the system border streams (outlet temperature, ambient temperature, inlet cooling water temperature, etc.) are assigned by the user than the entire design data (area, length, volume, mass flow rate, etc.) will then be calculated. Therefore, a user would assign the amount of needed fresh water from the desalination plant them all possible or required data for all the system units would be calculated in sequence.

Assigning the system productivity would calculate the required thermal load (in case of Multi-Stage Flash (MSF)) or the electrical load on the high pressure pump in case of RO. Also, the required design limits and performance calculations would be run out instantaneously. For thermal configuration, the thermal load would calculate the mass flow rate and the considered physical properties thence; to calculate the power from the S-ORC turbine, in case of indirect connection with the ORC, or the area and thermal power for the heat exchange in case of direct vapor connection type.

Thence, the thermal load related to the S-ORC would decide the load on the solar field and the storage volume in case of storage tanks. The thermal load on the solar field would then calculate the design limits of the solar field such as pressure drops, mass flow rate, field area, number of loops, loop length, etc. Moreover, all physical properties, energy, exergy, cost, and thermoeconomic streams are calculated in the entire code generation behind the blocks of the system units. In case of geothermal power source, the thermal load and the heat exchanger rejected power would calculate the design limits of the wall such as well depth, bore, mass flow rate, and so on.

For electrical power utilization, the demanded fresh water would calculate the electrical load on RO in case of high pressure pump operation or load on the MED-MVC in the case of the mechanical vapor compressor. The calculated electrical power would decide the mass flow rate and the required solar field area in the case of S-ORC, or the well design limits and dimensions in the case of geothermal operation, or the wind farm design for HWT operation or the PV solar field characteristics for use of PV solar filed. Fig. 6 shows a flow chart of the calculation methodology of the developed REDS program.

5. Validation and case studies

5.1. REDS for international projects

The first important step for building the REDS library is putting into consideration the validation process for the REDS. Each unit that has been

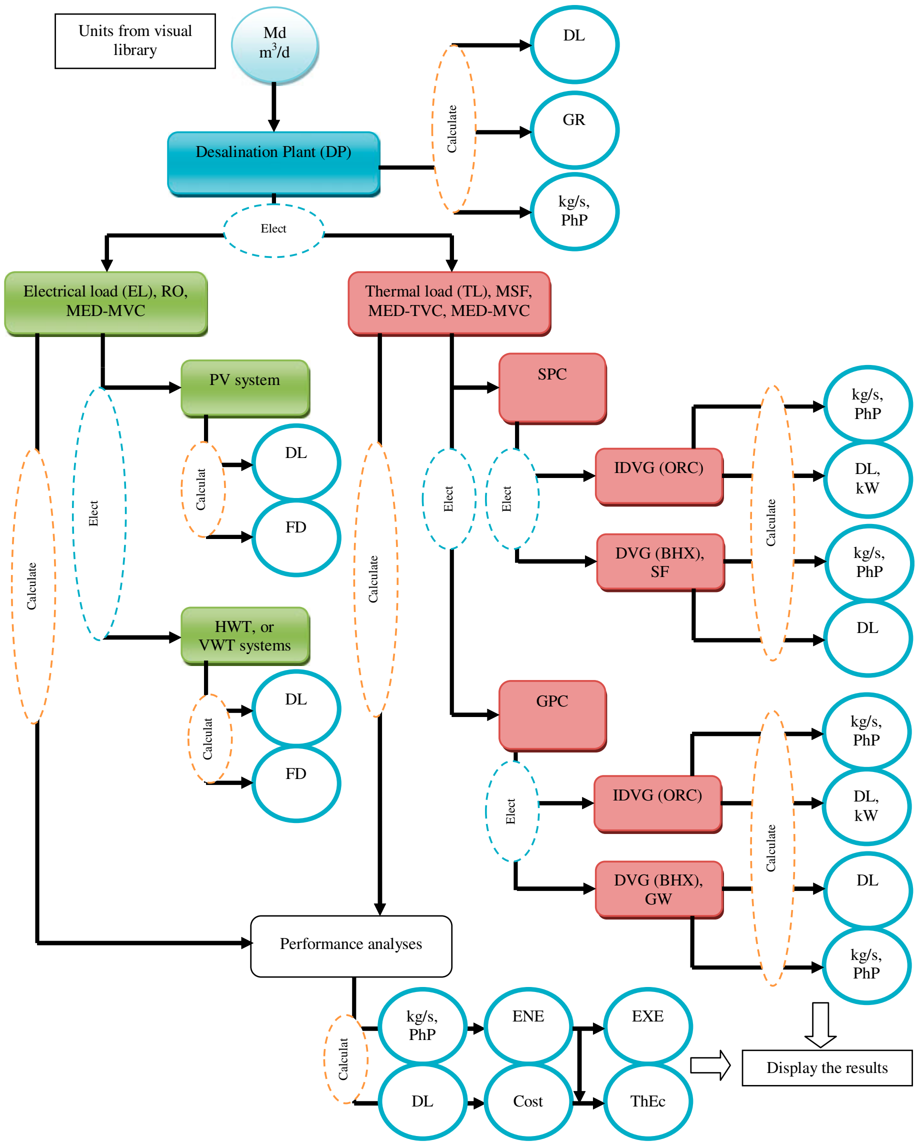

Fig. 6. The REDS calculation methodology. Md: productivity, DL: design limits, kg/s: mass flow rates, TL: thermal load, EL: electrical load, GR: gain ratio, PhP: physical properties, SPC: solar power cycle, GPC: geothermal power cycle, IDVG: indirect vapor generation, DVG: direct vapor generation, FD: farm dimensions, ENE: energy, EXE: exergy, ThEc: thermo-economic.

built was checked and validated. The development library was used, and utilized in many international and local projects. For an international example, REDS is used as a simulator and modeling process program for the POWERSOL project (FP6: 2007–2010) [34]. POWERSOL project is supported by the European Commission under the specific program for research, technological development. The proposal focuses on the technological development of a solar thermal-driven mechanical power generation based on a solar-heated thermodynamic cycle (POWERSOL system).

SORC (based on POWERSOL concept) is utilized to power on a RO desalination plant by the use of 100 ∼ 500kWe. Multipurpose Applications by Thermodynamic Solar (MATS) project (FP7: 2011–2014) [35] used the REDS as a simulator for the all system units. MATS project is performed to produce an amount of 250 m^3/day of distillate water by the use of the MED desalination process. The main thermal power is extracted from the solar Rankine cycle via the turbine unit. Molten salt working fluid is used through the PTC field and the water steam working fluid is used for the Rankine cycle. Fig. 7 shows the MATS concept

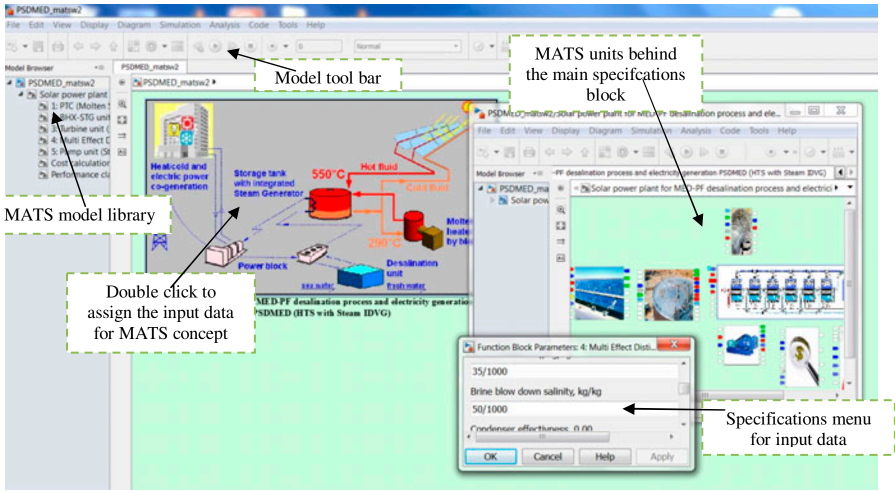

Fig. 7. REDS modeled for MATS project (FP7: 2011–2014 [35]) concept.

that has been modeled and simulated with the aid of REDS library.

5.2. REDS: units example

In this section, some of REDS units are introduced as a validation example. Based on the horizontal wind turbine, users can easily browse in the WDS library and elect between the HWT and VWT according to the user case study. In case of HWT, users can drag and drop the HWT block in a new model window. Double clicking on the model block can help to specify the air temperature, air pressure, and module power category. Behind the block, the user can demonstrate the results such as a cut in wind speed, average wind speed, air mass flow rate, axial force, torque, rotor diameter, hub height, turbine unit cost, total cost, power coefficient, number of required wind turbines, and the farm dimensions. The manufacture data manual of more than 50 famous companies of wind power generation are stored in a lookup table block and modeled by the aid of Neural Network modeling technique. Fig. 8 shows a part of the WDS library: validation example of the HWT unit.

As a case study of wind farm **Zafarana-5** [31], the demanded total power was in the range of 85 MW. The number of wind turbines was about 100 times of 850 kWe per unit. By the use of the developed models in this work, it becomes very easy to assign the input (Power = 850 kWe) in order to obtain the important specifications of the turbine unit. Therefore, the designers would become able to put in mind the wind farm dimensions before the establishment operations. The calculated spacing would become 606.3 m in wind

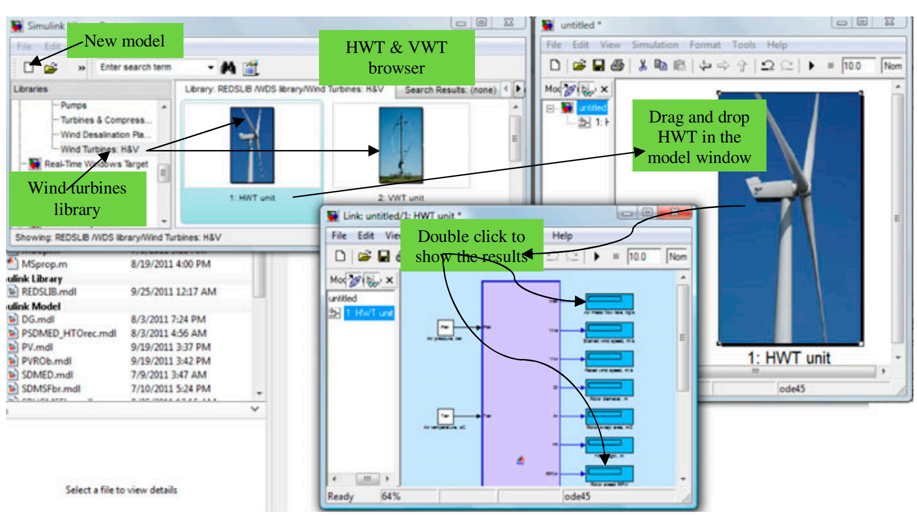

Fig. 8. WDS submenus for horizontal and vertical wind turbines.

direction and 151.6 m crosswind direction. Thence, the area of 100 turbines would become 3.8km^2. The turbine cost is calculated about 8.5e5$ and the farm direct total costs are about 8e7$. The following table shows a data results comparison of the developed model in this work and the data obtained from **Zafarana-5** [31] wind farm. The related table shows that there is a very good matching between the simulated data and the real data from **Zafarana-5** (see Table 1).

Fig. 9 shows a schematic diagram for the single effect evaporation unit (SEE). The main components of the process are the evaporator and the feed preheater condenser. Table 2 demonstrates the obtained results by the present REDS-SDS program and by Dessouky and Ettouney [8]. Also, results for a single effect thermal and mechanical vapor compression are illustrated in Table 2. Results from the developed REDS-SDS program compared with the experimental results of Dessouky [8] and [7] shows a good agreement under the same range of operating conditions.

Table 1
Data results from **Zafarana** wind turbine model.

Zafarana-5 (GAMESA G52)	The developed model (WDS)
Rotor	Rotor
Diameter 52 m	Diameter 51.52 m
Swept area 2,214 m^2	Swept area 2,085 m^2
Rotational speed 30.8 rpm	Rotational speed 31.95 rpm
Blades	Blades
Number of blades 3	Number of blades 3
Tower	Tower
Type modular height 53 m	Type modular height 50 m
Model results:	
Mass flow rate, kg/s	4.466e + 004
Start wind speed, m/s	5
Rated wind speed, m/s	18.24
Axial force on the turbine wheel, kN	362
Power coefficient	0.1144

5.3. REDS: case study

The tourism sector in Sinai, Egypt demanded more sustainable source of fresh water to serve the sector requirements. To supply the needed fresh water to Sinai resorts, the government constructed many of the RO desalination plants to recover the water shortage. Securing a suitable source of power is considered one of the great challenges to these plants. Charming Sharm-Sharm El Sheikh, Egypt is an RO desalination plant that demanded to use renewable energy source (PV solar field) instead of conventional energy due to environmental constraints in this resort area. REDS program is utilized to calculate the plant requirements such as: landscape area in case of PV solar field, number of modules, storage capacity, the price of m^3/day, and a lot of other design limits that the REDS can calculate. As investigated, the proposed system to study contains RO for 3500 m^3/d of fresh water (good source), control room unit, and PV solar field. The design limits and the calculated parameters of the proposed units are illustrated in Table 3.

The proposed configurations are shown in Fig. 10. The proposed system is modeled by the aid of the REDS software browser. The model configuration contains the following; PV system, the HWT for power generation, inverter unit, battery bank as a storage unit, a control room for power switching between PV and HWT and RO system. The model system has the ability to be operated by only PV or by only HWT or by hybrid power sources (PV + HWT). User can switch

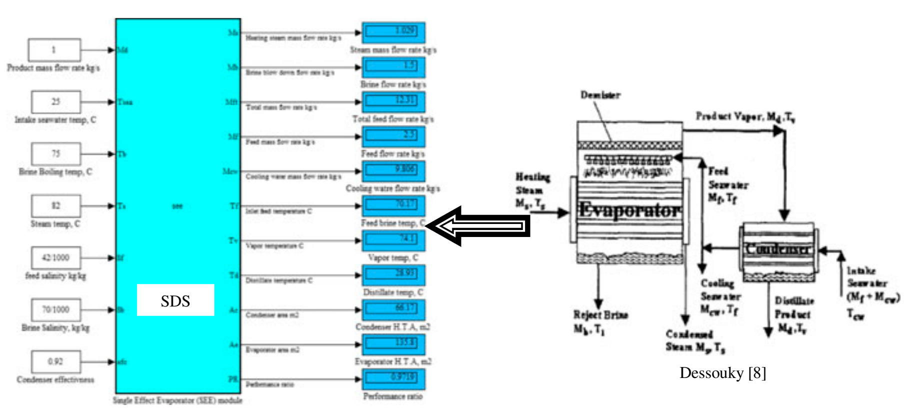

Fig. 9. Schematic display of SEE under MatLab-SimuLink software environment.

Table 2
The REDS-SDS and Dessouky [8] results comparison for SEE model

Variables	Dessouky [8]	SDS
SEE		
Steam mass flow rate kg/s	1.03	1.029
Brine mass flow rate kg/s	1.5	1.5
Total feed mass flow rate kg/s	12.3	12.31
Feed mass flow rate kg/s	2.5	2.5
Cooling water mass flow rate kg/s	9.8	9.806
Feed temperature ℃	70	70.17
Vapor temperature ℃	74.097	74.1
Distillate temperature ℃	28	28.93
Condenser area m^2	65.5	66.17
Evaporator area m^2	135.9	135.8
Performance ratio	0.97	0.9719
*Product mass flow rate kg/s	1	1
*Seawater temperature	25	25
*Condenser effectiveness	–	0.92
*Feed salinity ppm	42,000	42,000
*Steam temperature ℃	82	82
*Brine temperature ℃	75	75
*Brine salinity ppm	70,000	70,000
Single effect thermal vapor compression		
Steam mass flow rate kg/s	1.03	1.029
Brine mass flow rate kg/s	1.5	1.5
Total feed mass flow rate kg/s	12.3	12.31
Feed mass flow rate kg/s	2.5	2.5
Cooling water mass flow rate kg/s	9.8	9.806
Preheated feed temperature ℃	70	69.2
Vapor temperature ℃	74.097	74.1
Entrained vapor mass flow rate kg/s	0.37	0.373
Motive steam flow rate kg/s	0.678	0.68
*Product mass flow rate kg/s	1	1
*Seawater temperature	25	25
*Condenser effectiveness	0.9	0.9
*Steam temperature ℃	82	82
*Brine temperature ℃	75	75
*Brine salinity ppm	70,000	70,000
*Feed salinity ppm	42,000	42,000
*Motive steam pressure kPa	750	750
*Compression ratio	2.5	2.5
Evaporator area m^2	39.8	41
Single effect mechanical vapor compression		
*Product mass flow rate kg/s	17.36	17.36
Steam mass flow rate kg/s	17.36	17.36
Brine mass flow rate kg/s	31.25	31.25

(*Continued*)

Table 2 (*continued*)

Variables	Dessouky [8]	SDS
Total feed mass flow rate kg/s	48.61	48.61
*Brine salinity ppm	70,000	70,000
*Feed salinity ppm	45,000	45,000
*Seawater temperature	27	27
Vapor temperature ℃	60	60
Feed temperature ℃	57.93	57.04
Steam temperature ℃	96.2	96.17
Distillate blow down temperature ℃	32.51	32.93
Brine blow down temperature ℃	37.72	37.7
Inlet compressor pressure kPa	20.03	19.84
Outlet compressor pressure kPa	27.047	26.8
Compressor power kW	1,081	1,076
Specific power consumption kWh/m^3	17.291	17.2

Note: *Specified variables.

between the two fields (wind or PV) while supporting the RO load. In this case, PV powered the RO plant without any operation of the HWT farm. User can easily open the REDS library, elective the considered units, connecting all units by the aid of SimuLink browser, and then run the model.

Table 3 shows the data results of the PV-RO system to produce the same amount of fresh water (3,500 m^3/d). It is anticipated to generate the power load (1,131 kWe) for the RO plant. A value of 220 Watt module is chosen for the PV site. Also, 350 W/m^2 of solar radiation is chosen as a minimum solar radiation as a known input parameter in order to calculate the PV site area based on the worst winter conditions. Minimum operating conditions can secure a safe area to generate a sufficient electric power for the RO. The value of 350 W/m^2 is a typical average winter value in the Suez Gulf region [28]. The excess power in summer is stored in some other facilities such as the control room cabinet or lighting issues in the plant. The specific power consumption is about 7.68 kWh/m^3 and that is considered high. Energy recovers unit should be operated to lower this value to reach 3 ~ 2.5 kWh/m^3. The salinity of the produced fresh water is calculated as 250 ppm downs since 45,000 ppm.

The PV site specifications are listed in Table 4 shows that the PV consumed about 5,135 modules with about 0.02 km^2 to generate about 1.131 MWe. The direct capital cost of the PV site is about 7.912e5$, and is required to become 3.5e6$ for the RO plant. The PV-RO results reveal that the unit product cost (UPC, $/$m^3$) is calculated as 0.53$/m^3. It is obvious

Table 3
The specified parameters based on the design technique of modeling concept

Specified	Calculated
RO model	
Fresh water productivity, $m^3/d = 3{,}500$	Feed and brine mass flow rates, kg/s
Seawater temperature, ℃ = 25	Pressure on the HPP, bar
Well salinity, ppm = 45	Average pressure, bar
HPP efficiency, % = 80	Product and brine salinities, ppm
Membrane fouling factor, % = 85	HPP power, kW
Number of elements/number of pressures vessels = 7/42	SPC, kWh/m^3
Element area, $m^2 = 34.5$	Unit product cost, $\$/m^3$
Recovery ratio, % = 30	Salt rejection percentage, %
PV module	
Solar radiation, $W/m^2 = 400$ (daily average-winter)	The open circuit voltage, *V* and the short circuit current, *A*
Power/panel, Watt = calculated based on the HPP load	The maximum voltage and current
Total system power, kW = calculated based on the HPP load	The cell and module efficiencies, %
	The number of cells and modules of the system
	The module and system weights, kg, and areas, m^2
	The battery bank capacity, *A*

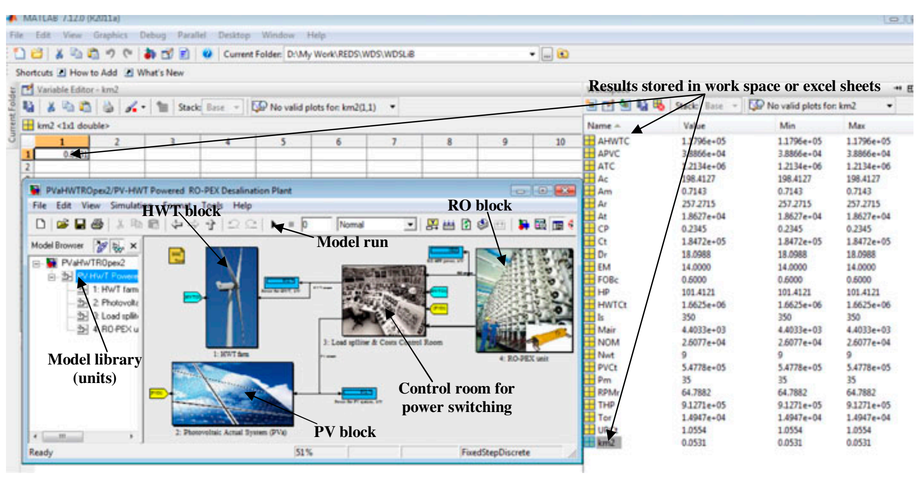

Fig. 10. The proposed system model browser of (PV–HWT–RO). The system contains: (a) HWT; (b) PV system; (c) control room unit; and (d) RO desalination plant block.

that the REDS program is a helpful tool to simulate and design renewable energy models that are combined with the desired desalination systems. More information about some REDS models are listed in the Appendix.

6. Conclusion

The modeling method is a useful tool for designers who need a simple, fast, accurate, and easy-to-use for using in simulations of renewable desalination systems. REDS is a new development visual software package that differs from the traditional techniques of modeling. This modular program has great capabilities to overcome previous programming problems and limitations such as the recycle streams. The REDS is built to accommodate all possible dimensions of modeling such as the mathematical environment, the simulation type, and the analysis type related to renewable desalination systems. Moreover, it enables

Table 4
Preliminary data Results for PV-RO system for 3,500 m^3/d

Environmental conditions	
Ambient temperature, ℃	15 (winter)
Solar flux, W/m^2	350 ~ 400 (winter) [28]
Air pressure, bar	1.01
Seawater temperature, ℃	25
RO plant results	
Specific power consumption, kWh/m^3	7.68
Power, kW	1,131
Feed mass flow rate, m^3/h	485.9
Production flow rate, m^3/h	145.83
Brine flow rate, m^3/h	340.1
Brine salinity, ppm	64,180
Fresh water salinity, ppm	250
Salt rejection value	0.9944
RO high pressure, kPa	6,850
PV site results	
Open circuit voltage/short circuit current, V/A	58.6/8.49
Maximum voltage/maximum current, V/A	47.4/4.641
Module efficiency/cell efficiency, %/%	15.45/17.5
No. of cells per module/No. of total modules	96/5,135
Module dimensions/width, m^3/mm	0.095/45
Net weight per module, kg	21.5
Cell area/module area, cm^2/m^2	423.8/4.06
Total system area, km^2	0.02089
Battery storage, Wh	3.766e6
Battery capacities, Ah	7.945e4
No. of batteries-12 volt system	4
Cost results	
Plant life time/interest rate	25/%5
Direct capital costs of PV, $	7.912e5
Direct capital costs of RO plant, $	3.5e6
Annual total costs, $/yr	6.099e5
Unit product costs, $/$m^3$	**0.5305**

the user to pose a question about a system, model the system, and see what happens. The high rate of accuracy of the developed REDS enables it to be utilized for many international projects such as POWER-SOL and MATS project. The developed program (REDS) overcomes the problem that appears in other techniques of simulation such as sequential approach, and matrix manipulation technique. It becomes very easy to solve real problems in a variety of industries, including:

- Concentrated Solar Power Plants (CSP) and PV.
- Solar steam or organic Rankine cycles.
- Solar gas turbine cycle.
- Different types and configurations of desalination processes.
  - RO (basic, Pelton Wheel, Pressure Exchanger).
  - MSF (once through, brine mixing, brine recycle).
  - MED (forward feed, backward feed; forward feed with feed heaters, parallel feed, thermal and mechanical vapor compression).
- Different techniques of REDS.
  - Direct vapor generation (DVG).
  - Indirect vapor generation (IDVG).
- Different thermal and turbo-machinery units.
- Wind turbines.
  - HWT.
  - VWT.
- Geothermal power systems.
- Biomass-Biofuel library is considered for the future work and to be added to the main library of the REDS.

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Appendix

A. Multi-stage flash brine recycle model (MSF-BR) (Desalination Example)

Different configurations (once through, brine mixing, and brine recycle) of the Multi-stage desalination processes are modeled and stored in the REDS library browser. This section highlights on the MSF-BR configuration as an example of the REDS library. To assign the plant productivity m^3/day, ambient temperature, ° C and solar radiation data, the user have to click on the model explorer icon then double clicking on the main block. The block parameters menu will open and the user can easily assign the main input data. Also it is very easy to assign the input data of the location such as longitude, latitude, and the day number of the year. Figs. A.1–A.3 shows the example of MSF-BR under REDS model browser.

In the sub menu, user can easily find out the units and the subunits that represent the proposed process. In the following figure, the process units are PTC solar field, boiler heat exchanger unit, pump, brine heater, and MSF-BR desalination plant. By double clicking on the blocks, user can easily specify the operating conditions and the permitted design consideration for each unit individually. The user also has the ability to use the capabilities of the MatLab/SimuLink that included in the software tools. The tools are concluded in to the following items:

- Users can easily copying the units and duplicate and pasting them.
- User can delete the unwanted units.
- The user can take copies to clipboard with high permeation to edit and reform.
- Also printing the models and their sub models are easily available.
- User can redo his work for instant accident such as removing or deleting any parameter or unit.
- User can drive out his results through different ways such as "mat" files, Matlab "workspace", or/and display block.
- Also, it is becoming easier for the user to handle the "mat" to an "excel sheet" or construct a new figure.

Consider an example of MSF-BR desalination plant with a capacity of 32728 m^3/day. The input parameters and specifications are illustrated in the following table. The process validity of the MSF-BR example is examined with Dessouky (Fundamental of salt water

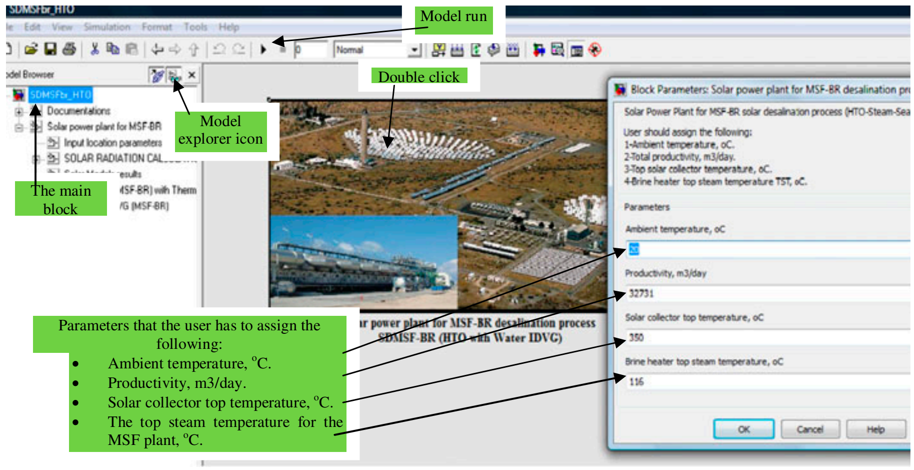

Fig. A.1. The main model menu: double click to demonstrate the input and specifications menus.

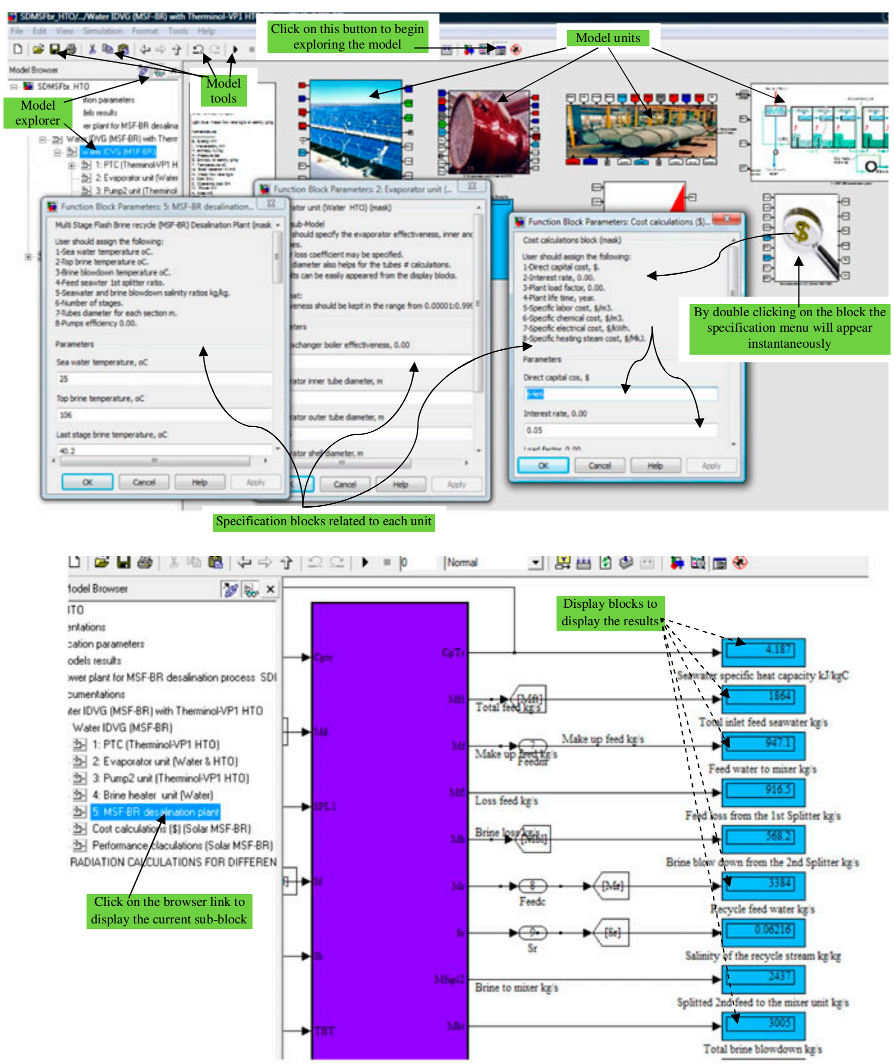

Fig. A.2. The submenus show the blocks represent the units of the proposed plant. User can easily illustrate the data results via display blocks.

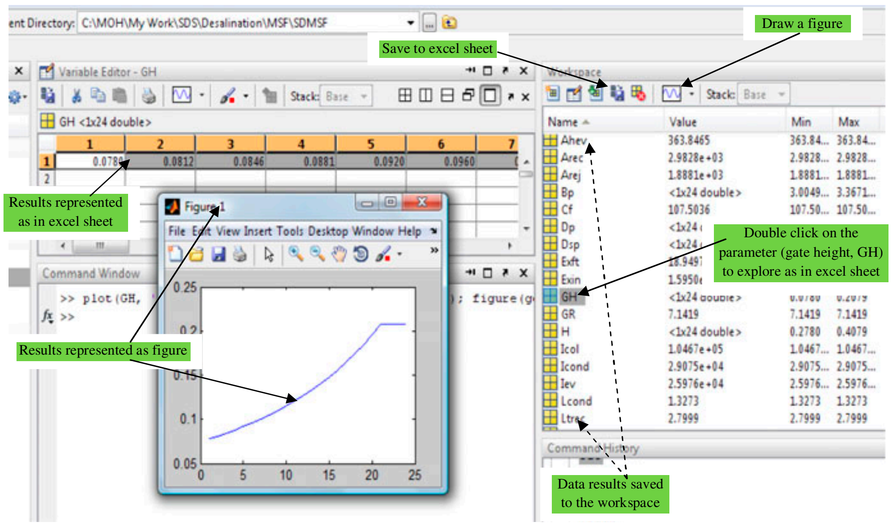

Fig. A.3. Data results can be easily shown via excel sheets. User can save the data in mat files.

Table A.1
The data results for the solar MSF desalination plant

32728m^3/day MSF-BR		
Top brine temperature (TBT), ℃		106
Brine blow down temperature, ℃		40.2
Feed seawater temperature, ℃		25
Cooling water splitter ratio		0.5082
Sea water salinity, ppm		42,000
Brine blow down salinity, ppm		70,000
No. of stages		24 (21/3)
Chamber load, kg/s m		180
Vapor velocity, m/s		12
Weir coefficient		0.5
Design point results:	Dessouky [8]	SDS-REDS
Total feed, kg/s	1861	1862
Distillate flow rate, kg/s	378.8	378.8
Make up, kg/s	947	947
Brine recycles flow rate, kg/s	3,384	3,384
Brine blow-down flow rate, kg/s	568.2	568.2
Steam mass flow rate, kg/s	52.52	53.04
Top vapor temperature, ℃	101.2	101.98
Top feed temperature, ℃	97.75	97.78
Recycle blow down temperature, ℃	48.25	48.42
Vapor temperature at last stage, ℃	–	38.2
Recycle stream salinity, ppm	62,170	62,163
Stage length, m	2.56	2.58
Performance ratio	7.21	7.14

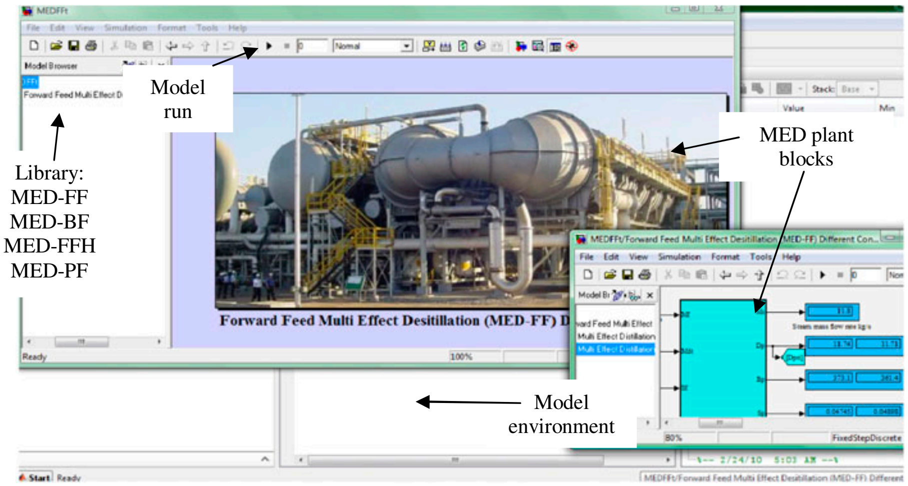

Fig. B.1. MED model environment designed using SDS package.

Table B.1
Data validation between REDS-SDS and Darwish [33] for MED model

Effect #	T brine ℃		T feed ℃		M brine kg/s		M distillate kg/s		S brine g/kg	
	SDS	Ref. [33]	SDS	Ref. [33]	SDS	Ref. [33]	SDS	Ref. [33]	SDS	Ref. [33]
1	65	65	62	62	373.09	373.18	11.74	11.85	47.44	47.46
2	62.54	62.55	59.54	59.55	361.41	361.37	11.71	11.8	48.98	49.01
3	60.09	60.09	57.09	57.09	349.79	349.62	11.68	11.75	50.6	50.66
4	57.63	57.64	54.63	54.64	338.22	337.91	11.65	11.71	52.33	52.41
5	55.18	55.18	52.18	52.18	326.72	326.26	11.62	11.66	54.18	54.29
6	52.72	52.37	49.73	49.73	315.27	314.65	11.59	11.61	56.14	56.29
7	50.27	50.27	47.27	47.27	303.88	303.09	11.56	11.56	58.25	58.44
8	47.81	47.82	44.82	44.82	292.55	291.58	11.53	11.51	60.51	60.74
9	45.36	45.36	42.36	42.36	281.27	280.12	11.5	11.46	62.93	63.23
10	42.9	42.91	39.91	39.91	270	268.71	11.47	11.41	65.55	65.91
11	40.45	40.45	37.45	37.45	258.87	257.34	11.45	11.36	68.38	68.82
12	38	38	35	35	247.76	246.03	11.42	11.32	71.45	71.99

desalination, Book [8]) and also illustrated in Table below. The data results show a good agreement of the developed program (SDS) with Dessouky [8] results. See Table A.1.

B. Multi-effect distillation models

Different MED configurations and types are simulated and designed using REDS-SDS package. The results show a very good agreement with some existing plants. Fig. B.1 shows a display of the MED under SDS package. Also Table B.1 shows the data results comparisons between SDS and Darwish [32,33]. Data comparison with reference [33] is implemented according to Sidem 12-effect units and 11 feed heaters. The unit given data are: n (number of effects) = 12, output Md = 500 ton/h (139 kg/s), Top brine temperature, TBT = 65℃, last stage brine temperature, T_b = 38℃, inlet feed temperature, T_f = 28°C, feed temperature at condenser exit = 35℃, feed salinity S_f = 46 g/kg, and maximum salinity S_b = 72 g/kg where f and b related to feed and brine, respectively.