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Rapid Sizing of Renewable Energy Power Components in Hybrid Power Plants for Reverse Osmosis Desalination Process

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Abstract: The cogeneration of water and electricity through the exploitation of Renewable Energy Sources is becoming an increasingly promising option, especially for arid and remote areas, where alternative energy supply is either unavailable or too costly to develop. This paper presents a new methodological approach for the preliminary design of a Renewable Energy (RE) power plant, primarily aimed at meeting the energy requirements of a Reverse Osmosis desalination unit. The design of the power plant's components involves the calculation of the installed capacity of each RE component (Photovoltaics and Wind Energy Conversion Systems), the size of the energy storage system (Battery), and required auxiliary energy sources (Diesel Consumption). The sizing of the two RE components and the calculation of the corresponding energy production is performed using a simplified mathematical model for the diurnal variation of wind speed and solar radiation. The overall approach is applied for the rapid sizing of components and the estimation of auxiliary energy supply needed for a medium-sized desalination unit in Tunisia, and is complemented with a preliminary economic assessment of the power plant costs.

Keywords: Renewable Energy Sources; Reverse Osmosis; Wind Power; Photovoltaics; Desalination

1. INTRODUCTION

The co-generation of electrical power and desalinated water from renewable energy sources (RES) is a very promising option [Koroneos et al., 2007], especially in arid and isolated from the grid regions, where the use of conventional energy is costly or unavailable [Elhadidy et al., 2000]. The energy and water requirements in such regions can be satisfied through a combination of RE components, conventional diesel generators and energy storage systems [Houcine et al., 1999; CRES, 1998]. The design of such a hybrid power system would require an overall system engineering approach, which can be further integrated into a Decision Support System (DSS) to address the problem of decision making in a generic way. The decision-making process involves three steps. The first step comprises the sizing of the power system, based on a minimum set of data and guided by specific design goals; the output of this step is a number of alternative configurations (scenarios). The second step involves the assessment of different indicators for each scenario, based on simulation techniques using detailed data. The final step is the evaluation of the scenarios on the basis of the selected indicators, following a multi-criteria decision analysis approach.

The work presented in this paper focuses on detailing the methodology for the first step of the decision making process, where alternative component sizing configurations are defined. In previous works, the definition of the required battery size and diesel usage is performed on the basis of simulation results, using general rules of thumb. For example, a rule of thumb proposes that battery power supply for three days reduces diesel consumption by 45% [Elhadidy et al., 2000]. Such rules of thumb cannot give accurate results, because they do not take into account the combined energy production from the two renewable energy subsystems. The proposed methodology takes into account diurnal fluctuations in wind speed and solar radiation, and transforms the corresponding mean monthly meteorological data into daily profiles of renewable power production, without the use of simulation.

Often, the design of a RES-powered desalination plant needs to address conflicting goals, rules and constraints. These can be overcome using a scenario-based approach, where a set of alternative configurations (scenarios) for the size of the different system components is defined. These scenarios can then be fed into a Decision Support System for more detailed simulation and design, and, subject to economic evaluation and performance assessment, can be used to define the final structure of the power plant.

Section 2 of this paper provides an overview of the methodology for preliminary design, including a description of the power plant and the specific sizing and modeling algorithms. Section 3 presents the application of this approach for the sizing of a RES-powered plant used to supply a brackish water reverse osmosis plant in Tunisia (capacity of 50 m^3/d). Section 4 presents the main outcomes of the analysis undertaken and outlines orientations for further research.

2. METHODOLOGY

2.1. Power Plant Description

The energy subsystem of the Renewable Osmosis (RO) power plant combines different renewable energy sources, backed up by conventional ones (e.g. Diesel Generator). A configuration representative of this subsystem is presented in Figure 1.

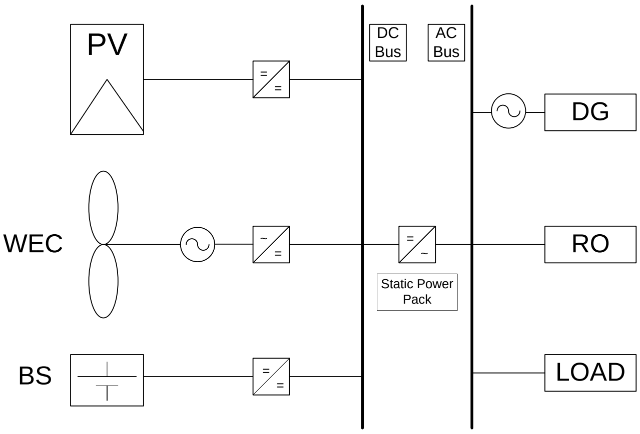


Figure 1. The hybrid energy configuration.

The main parts of the system are the: (a) Wind Energy Conversion system (WEC); (b) Photovoltaic system (PV); (c) Diesel Generator (DG); (d) Battery Storage system (BS); (e) Reverse Osmosis plant (RO); and (f) other power loads (LOAD), if the system is designed to supply energy to additional units at the installation area.

In such hybrid systems, and under adequate solar radiation and/or wind speed conditions, the WEC and PV feed the load demand (RO plant and additional power loads). The excess energy (i.e. the energy above this demand) from the WEC and PV is stored in the battery until full storage capacity is reached. If output from the WEC and PV exceeds the load demand and the battery is fully charged, then excess energy is drained away (undelivered energy) or fed back into a utility grid (if the system is connected). The diesel back-up is used to support the system in meeting the load demand should the WEC and PV systems fail to manage the load and battery storage be depleted.

2.2. Design Goals and Operational Constraints

The system design is based on the following set of goals:

- The local Wind and Solar Energy Potential are exploited to the maximum possible extent (MAX-RES goal).
- The undelivered excess energy (the energy drained away from the system) is minimal (MIN-UNDELIVER goal).
- The capital cost for infrastructure investment is minimal (MIN-CAP goal).
- The operational cost is minimal (MIN-OP goal).
- Environmental impacts (i.e. CO_2 emissions) are minimal (MIN-ENV goal).

At the operational level, there are two important constraints to guarantee the continuous and stable operation of the reverse osmosis unit. The first outlines that there should always be energy available for water production (Continuous Operation constraint) and the second that the power supplied to the RO high-pressure pumps should be stable (Stable Operation constraint).

The above goals and constraints are used in the design phase, to derive a number of rules that allow the sizing of the system (design rules). If a design parameter influences various goals in a conflicting manner (trade-offs) then it is treated as a decision variable and alternative values are examined. This corresponds to a "scenario-based" approach, defining the maximum, minimum and intermediate sizes for system components installed power.

2.3. Design Stages and Design Rules

The design process is structured in three sequential stages:

Stage 1 addresses the estimation of the energy and power requirements of the RO unit during the design period. This is a preliminary stage that addresses the energy requirements of the RO plant, which depend on water demand and the salinity of the feed water. The power demand is taken as constant and the additional electric load (as shown in Figure 1) is assumed to be zero.

Stage 2 involves the sizing of the renewable energy components (PV, WEC or both). This stage addresses the estimation of the size of the renewable energy components (PV and WEC) that will achieve, where possible, the design goals and satisfy the operational constraints of Section 2.2. The design variables are the photovoltaic installed power and the total rated power of the WEC system. All the above factors greatly influence the capital cost of the power system. The design rule that allows the estimation of the RE components size is summarized as:

- "The renewable energy delivered during the design period (year or month) is equal to the energy required by the RO plant during the same period."

This rule is in agreement with the "MAX-RES" and "MIN-UNDELIVER" design goals and meets the "Continuous Operation" constraint. However, the above design rule can lead to alternative configurations of the hybrid system, because the same amount of energy can be produced by different combinations of RE components. Therefore, an extra decision variable is required in order to define the hybrid system, which is the contribution of each one of the components (PV and WEC) to the total energy produced. The decision variable needed is the ratio of energy produced from PV to the total energy produced from renewable sources denoted by "α" (PV contribution). Figure 2 and Figure 3 present the complete algorithms for sizing the PV and WEC respectively. The calculation for the WEC components uses the well known Weibull equation.

Stage 3 comprises the sizing of auxiliary energy components (BS and DG). The design variables for the auxiliary components are the battery capacity of the battery system (in Ah) and the annual diesel usage (in kWh). The capacity of the battery system (and consequently the number of batteries for a given battery type) mainly influences the capital cost of the power system. Diesel generators are relatively inexpensive to purchase but the energy they supply determines the operational cost and environmental impacts [Patel, 1999; Elhadidy et al., 2000]. The design rules that allow the sizing of the auxiliary components are:

- The installed power of the diesel generator is equal to the power demanded by the RO plant.
- The unmet (by RE components) energy demand is fully satisfied first by the excess energy stored in the battery, and then by the energy supplied from diesel engine.

Both rules are derived based on the “Stable Operation” constraint. The first rule is required in order to ensure stable operation during the time periods where renewable energy sources are unable to provide power. The second rule is in agreement with the “MIN-UNDELIVER” goal. Here too the above design rules can lead to alternative configurations, as the unmet demand can be satisfied by different configuration of auxiliary components. A new decision variable is required to define the system, the utilization of the diesel engine. This variable influences the “MIN-CAP”, “MIN-OP” and “MIN-ENV” goals in a conflicting manner and thus two extreme cases are considered, as follows:

- The “Diesel-Min” case addresses the minimization of the plant operational cost and the environmental impacts by minimizing the energy supplied from the diesel generator (maximization of energy supplied from RES);
- The “Diesel-Max” case addresses the minimization of the plant capital cost, by minimizing the required battery capacity and the installed power of RE components.

2.4. Sizing Process and Modeling

The PV and WEC component sizing is undertaken under the primary design rule described in design step 2. The output from this process is the rated installed power of the photovoltaic panels and the nominal installed power of the WEC system, and the algorithms are shown in the figures below

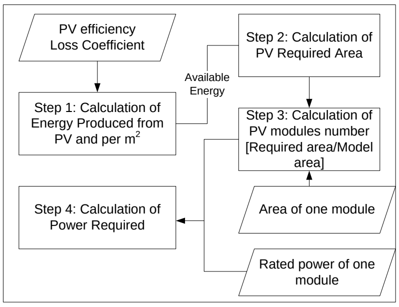


Figure 2. The PV sizing algorithm

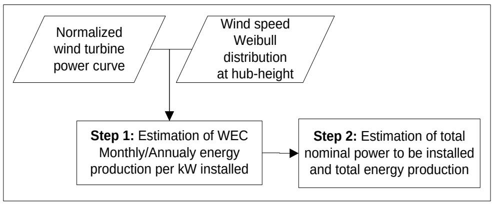


Figure 3. The WEC system algorithm

The design of the auxiliaries is based on the system performance over the whole design period, taking into account the variation of the renewable sources over a day, on the performance of the system over the whole design period. The approach is described in the following paragraph.

Firstly, a daily distribution of the renewable energy sources (solar radiation and wind speed) is assumed. This distribution is transformed into a model distribution of the renewable power produced over the day, so that the energy produced over the design period is equal to the renewable energy estimated in the design stage (for both Diesel-Min and Diesel-Max scenarios). This model distribution enables the estimation of the unmet energy demand (energy demand that cannot be directly satisfied by renewable sources) and the excess renewable energy (renewable energy produced in excess of demand for all the months of the year). The above energy quantities, combined with the design application of design rule 2, are used for sizing the battery and estimating the energy required by the diesel engine.

In general, the power distribution by photovoltaics (P_{PV}) is produced by a solar distribution in the shape of a triangle with its summit at the solar midday (12:00 PM). The power distribution by WEC (P_{WEC}) is produced by a cosine curve that represents the diurnal variations of the wind speed [Manwell et al., 2006]. Figure 4 presents the distribution of renewable power produced (P_{RES}) over a day, and its relation to the load demand (P_d), where three different areas (which represent different energy quantities) are formed. The P_{RES} distribution is the sum (per time) of the P_{PV} and P_{WEC} distributions:

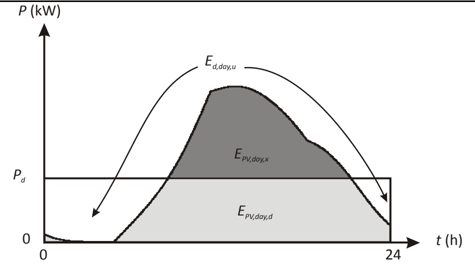


Figure 4. Distribution of renewable power and its relation to the load demand.

- $E_{RES,d}$ is the renewable energy produced and delivered directly to demand.
- $E_{RES,x}$ is the excess renewable energy
- $E_{d,u}$ is the unmet energy demand.

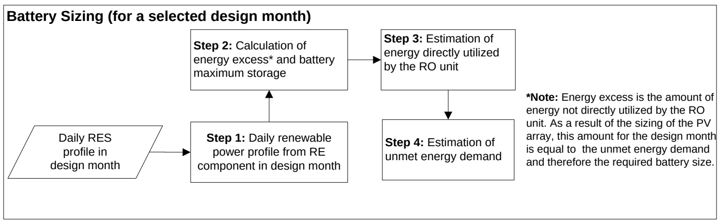
The sizing of the battery system and the diesel engine depends on the relation between the unmet energy demand and the excess renewable energy, where three cases are foreseen:

- $E_{RES,x} = E_{d,u}$ (the excess energy is equal to the unmet demand). All excess renewable energy will be stored in the battery system and will satisfy all unmet energy demand. The capacity of the battery system is equal to the excess renewable energy (or the unmet energy demand) and no diesel engine is required.
- $E_{RES,x} > E_{d,u}$ (the excess energy is greater than the unmet demand). Part of the excess renewable energy will be stored in the battery system and will satisfy all unmet energy demand. The capacity of the battery system is equal to the unmet energy demand and no diesel engine is required.
- $E_{RES,x} < E_{d,u}$ (the excess energy is less than the unmet demand). All excess renewable energy will be stored in the battery and will satisfy part of the unmet energy demand. The rest of the unmet demand will be satisfied by the diesel engine. The capacity of the battery system is equal to the excess renewable energy, and the energy required by the diesel engine is equal to the difference between unmet demand and excess renewable energy ($E_{d,u}$–$E_{RES,x}$) summed for all days of the period. The complete algorithm for the battery sizing and the estimation of the diesel usage is depicted in Figure 5.

The modelling approach is being applied to all examined system configurations. In order to define the two alternative extreme cases for auxiliary energy supply, design of the system is repeated for two months:

The month when the renewable source (solar radiation or wind speed) is at minimum (Worst month-based design). This case leads to the estimation of the size for the RE components that would maximize RE utilization and the energy required from auxiliary energy sources (Diesel-Min scenario). In this case, the defined battery size is larger than required, as the unmet energy requirements of the RO unit will be lower during the rest of the year, and the energy stored will never be fully supplied to the desalination plant.

The month when the renewable source is at maximum (Best month-based design). This case leads to the estimation of a minimum size for the RE components, but also to the maximization of the energy required from other auxiliary sources (Diesel-Max scenario). The estimated battery storage is again larger than that required, in the sense that the battery will never be fully charged during the rest of the year.



***Note:** Energy excess is the amount of energy not directly utilized by the RO unit. As a result of the sizing of the PV array, this amount for the design month is equal to the unmet energy demand and therefore the required battery size.

Figure 5. Algorithm for the sizing of the battery

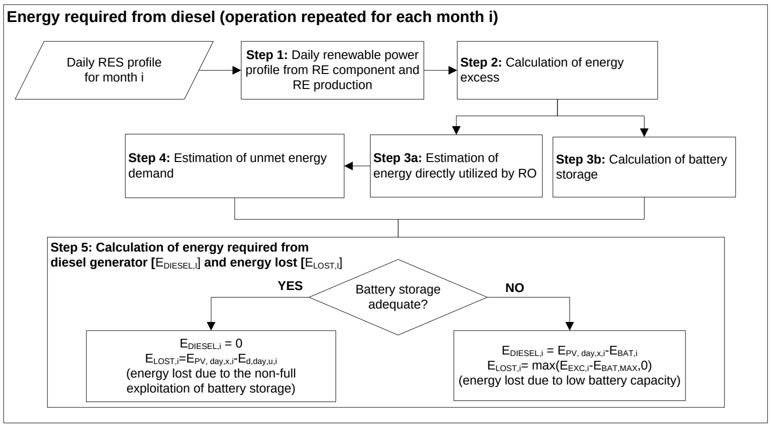


Figure 6. Algorithm for the estimation of diesel usage.

3. CASE STUDY

3.1. Implementation

The above methodology was implemented in a test site in Tunisia, where water demand is 50 m^3 per day and its specific energy for desalination is 2 kWh/m^3 (Brackish water) [CRES, 1998]. Wind and solar data can be acquired from public databases such us the NASA/RetScreen Database (eosweb.larc.nasa.gov) for wind data and METEONORM 6 demo application. The PV efficiency used for these calculations is 11.9%, with a module area of 1.26 m^2 and rated power of 0.15 kWp per module. The wind generator characteristic power curve is modeled by a (normalized) polynomial with appropriate coefficients. Additional data are the latitude (36.2^o) of the area, the time of the day that the maximum wind speed occurs (15:00 PM) and the DC bus voltage (48V). The mean monthly solar radiation per day ranges from 3.97kWh/m^2 for January to 7.32kWh/m^2 for July for the Latitude tilt. The mean wind speed ranges from 4.08m/s for July to 5.67m/s for February.

3.2. Results

The proposed installed power for both the PV and WEC system for the Diesel-Max and Diesel-Min is a linear function of the PV contribution (α). For PV contribution 50% the proposed installed power for PV is 17.5kWp for Diesel-Min and 9.5kWp for Diesel-Max and the installed power for the WEC is 21.8kW for Diesel-Min and 8.3kW for Diesel-Max. Figure 7 and Figure 8 show the battery capacity and the expected diesel consumption for the Diesel-Max case respectively.

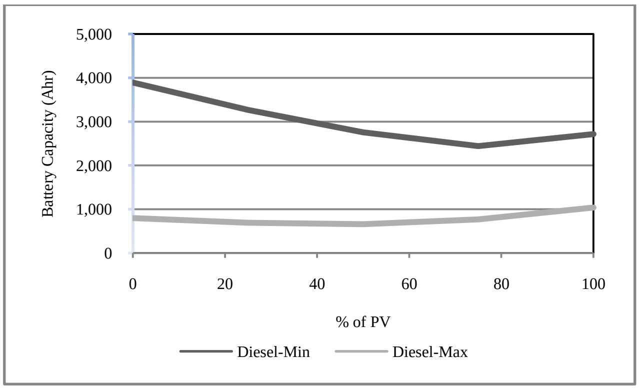


Figure 7. Battery system capacity as a function of the percentage of energy produced by PV

Figure 9 displays the basic energy indicators describing the utilization of the renewable and conventional energy for each scenario. The two extreme scenarios of Diesel-Min and

Diesel-Max indicate the minimum and maximum limits for the installed power of the power plant components, for use with reverse osmosis desalination. The acceptable diesel usage consumption, or other parameters such as environmental pollution, can be used to define the optimal size of the power components.

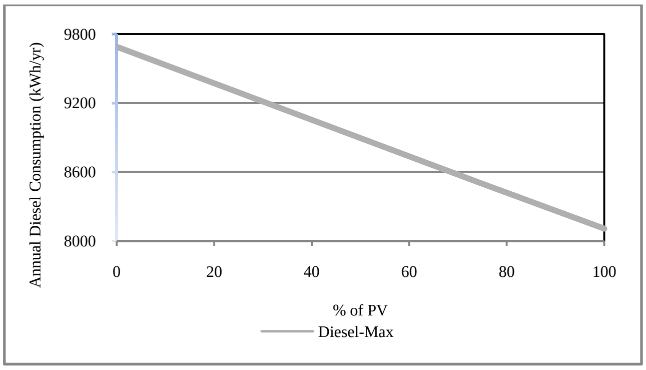


Figure 8. Annual diesel consumption as a function of the percentage of energy produced by PV

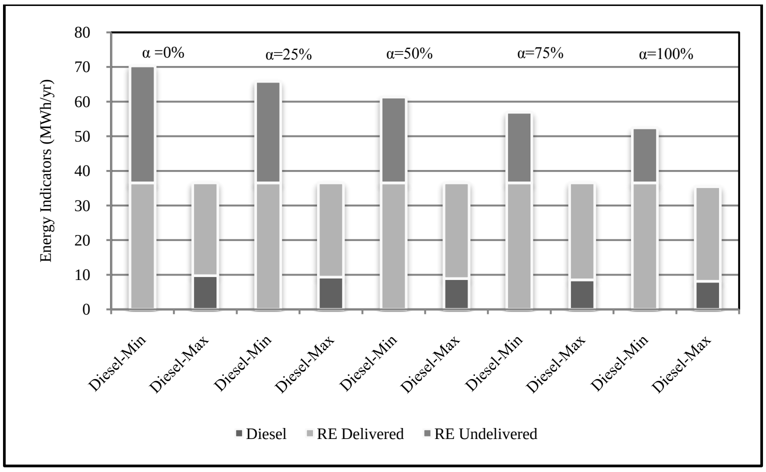


Figure 9. The main energy indicators for selected values of the percentage of energy produced by PV

Capital and operational costs are critical (but not the only) parameters for the final selection scenario (Diesel-Min and Diesel-Max). The design parameters calculated for these two scenarios are analyzed for their financial performance. The cost equations for each component can be found in Appendix A of Kaldellis et al. [2007]. The diesel price is set at 0.8 €/l, the battery life is set at 5 years and the life of the plant is set at 20 years. The results are shown in Figure 10.

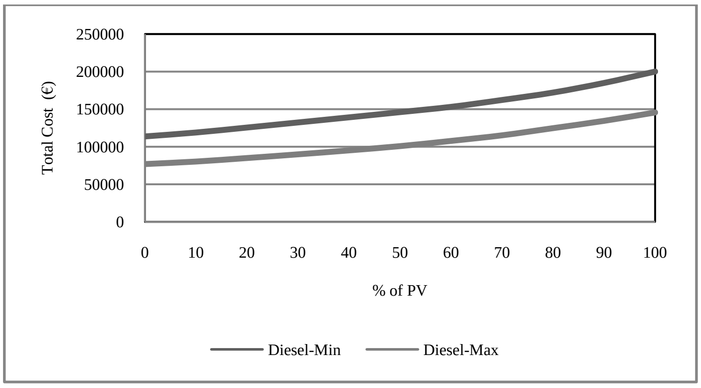


Figure 10. The total cost of the power plant for each extreme scenario and as a function of the percentage of energy produced by PV.

3.3. Discussion

It is evident from the indicators in Figures 10 and 11 that incorporating more photovoltaics into the renewable mixture (% of PV→100%) enables better exploitation of the energy sources for the area of the case study. Furthermore, the diesel usage in the Diesel-Max scenario decreases considerably. (It should be impossible to design a power plant that will operate in steady state and continuously only with the use of RES, and thus the diesel consumption should be greater than zero in the Diesel-Min scenario; however the proposed scenario is an extreme approach). When more WEC are introduced into the system (% of PV→0) the renewable energy undelivered is greater than the renewable energy delivered due to the great fluctuation of the wind speed. On the other hand, Figure 10 clearly indicates that the overall cost is less when more WEC are incorporated into the system. Figure 7 shows that the battery capacity has a minimum value when % of PV~80% at the Diesel-Min case and a minimum value when % of PV~50% at Diesel-Max case.

4. CONCLUSIONS AND SUGGESTION FOR FURTHER RESEARCH

A method for estimating the size of a renewable energy power plant was presented in this paper. The method is based on a rapid sizing algorithm which can be used to calculate alternative scenarios for the power plant of a reverse osmosis desalination unit driven by renewable energy sources. The calculations can be achieved under minimal set of monthly mean meteorological data. The effect of the variations of renewable resources on the size of the auxiliary components is estimated using proper diurnal profiles. The proposed rapid sizing algorithm was applied in a test site in Tunisia. Several alternative configuration scenarios can be designed easily showing that such rapid algorithms are important components of a decision support system due to the number of indicators that can be derived from this method.

The presented sizing method is only the first step of a decision support system for engineering design of a hybrid power system. The next steps involve the estimation of different indicators through simulation techniques and the evaluation of scenarios following a multi criteria decision analysis approach. As part of the decision support system can be also the sensitivity analysis for battery and diesel price and for battery life.

ACKNOWLEDGEMENTS

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