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Efficient Modeling, Control and Optimization of Hybrid Renewable-Conventional Energy Systems

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Abstract- In this paper, a generic and an efficient model for hybrid renewable-conventional electrical energy systems is presented. This simulation model is successfully validated by means of HOMER. Moreover, two control strategies for electrical power dispatch are described. Furthermore, an optimization problem is formulated and solved, using Genetic algorithm technique, for optimizing the size of system components where the overall cost of the system is minimized. Four case studies are investigated. The results show a dependence of the size of the system components on the meteorological characteristics of the area under consideration, which validate the proposed methodology.

Keywords: Hybrid energy systems, renewable sources, simulation modeling, optimization problem

1. Introduction

Hybrid renewable-conventional electrical energy systems have been attracted a considerable attention from electric utilities and scientific community in the world. These hybrid systems are widely used to provide electricity to rural or remote areas where the electrical grid is not available. This type of plants is called ‘stand-alone’ power plants. In order to achieve the optimal performance of these hybrid energy systems, they need to be properly designed [1, 2]. Therefore, in this paper, we aim at designing the hybrid energy systems in such a way to enhance the system reliability, robustness and efficiency while minimizing the total cost.

During this research work, a simulation model of the hybrid renewable-conventional energy system has been developed. The hybrid system considers all components of the hybrid solar/wind/diesel power plant. Literature review of the research topic is given in section 2. Then, the simulation model is presented in section 3.

Moreover, we aim at controlling the considered hybrid system using different control strategies. In fact, two different control strategies are implemented, i.e. a *load following strategy* and a *cycle charge strategy*. These control strategies are described in section 4. Furthermore, an optimization problem is solved in order to optimize the current hybrid energy system. The optimization procedure utilizes the *Genetic Algorithm* to optimize the size of each element and to minimize the total cost. In addition, the proposed procedure is able to select the best control strategy. The optimization problem is formulated and introduced in section 5.

As real applications, four different case studies are tested. The results of these case studies are given and discussed in section 6. Comparative study among all case studies is outlined in section 7. Finally, the conclusions are drawn in section 8.

This section gives some background information about renewable-conventional energy systems according to previous research works.

Solar photovoltaic energy could harness the sun energy to provide environmental friendly electrical energy. Solar energy is one of the cleanest energy sources that do not contribute to global warming. However, some important barriers are limiting the development of solar energy technologies, such as, the poor efficiency of Photovoltaic (PV) panels, i.e. 4-12% for thin film and 22% for crystalline panels in the current market. Another barrier is the high initial cost and lack of easy financing options.

Existing studies expect that solar energy will play, in near future, a crucial role in meeting future energy demands [3, 4]. The present and expected development and installation of solar photovoltaic power plants are mentioned in table 1.

Table 1. The present and expected development, in [MW], of solar PV power plants [3].

Year	USA	Europe	Japan	Worldwide
2010	3,000	3,000	5,000	14,000
2020	15,000	15,000	30,000	70,000
2030	25,000	30,000	72,000	140,000

On the other hand, wind energy can be considered a common renewable energy source. Although wind energy is the fastest growing renewable energy source that has been in use for centuries in Europe [5], the common social acceptance of wind energy is still low. The main problem is that wind turbines produce noise, vibrations and drop shadow around the wind turbine. Furthermore, wind facilities have potential negative impact on birds and cetaceans, and landscapes. However, the general negative impacts of the wind energy are much lower than the ones produced by conventional sources [6].

Because of the growing importance of global warming effects and government pressure to reduce the emission of greenhouse gases (CO_2, CH_4, N_2O, etc.), the significance of renewable energy sources can not be ignored in the future.

Delivering electrical power to remote areas is still a problem for public and private organizations, particularly, when transportation costs are not negligible and the distance from fossil fuels is long. Another advantage of the renewable energy is the less need for the transportation. The simulation results, stated in [7], confirm that the hybrid configuration is truly feasible.

It is expected that different components of hybrid energy systems are getting cheaper according to their performances which result in more output power with an efficient financial consuming because on one hand the increase in efficiency and on the other hand the reduction of production cost. This effect gives a bright future for these hybrid systems.

Various renewable and conventional energy sources are available, and as a result, many hybrid energy system configurations can be constructed. Kellogg *et. al.* investigated the utilization of hybrid renewable energy systems at the residential customer level [8]. Gupta *et. al.* [9] studied a stand-alone hybrid energy system with a PV installation, a micro hydro generator, a biogas generator and a biomass generator as renewable energy sources, and a diesel generator as conventional energy source. Their aim was to develop a model to simulate and optimize this kind of hybrid energy system.

Manwell [10] describes the effect of components used in hybrid energy systems. The effect of no grid connection, a weak connection or a strong one was also studied. The effect of various energy consuming devices, renewable energy sources, fossil fuel generators and energy storage facilities on hybrid energy systems was investigated. The latter ones, energy storage facilities, were divided into convertible storage and end usage storage. They described as convertible storage the battery, pumped hydro, flywheel, compressed air and hydrogen storage facility. Khatib *et. al.* [11] described an optimization procedure for building integrated hybrid PV/diesel generator system for zero load rejection in Malaysia. The optimization was performed with a loss of load probability of 0.01%. Geem [12] optimized a hybrid PV-wind system while providing all input data needed to reproduce the optimization process. Glavin *et. al.* [13] used ultra capacitors to increase the power density of the overall system and optimized the system.

The considered hybrid electrical energy system consists of a combination between a renewable energy system (photovoltaic solar panels, wind turbines) and a conventional system (a diesel generator) as well as a battery bank. Power converters, *e.g.* set of inverter/rectifier units, are also modeled. The schematic diagram of the considered hybrid energy system is shown in figure 1.

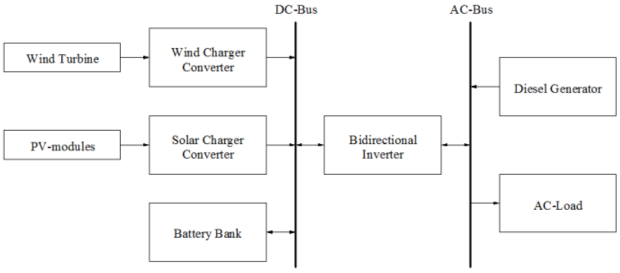

Fig. 1. Schematic diagram of the considered hybrid energy system.

In order to simplify and generalize the model, the following assumptions are made [9]:

- The system is considered in a steady-state regime within every time step.
- The steady-state power, efficiency and energy is considered, no other values are used for the system description.
- The model incorporates conservation laws, e.g. conservation of the power flow.
- Equipment breakdowns or planned maintenance are not considered.
- Costs are additive, and there are no perceptional changes in the plant capacity, unit cost of energy sources and the configuration of the system during the simulation.
- A time step of one hour is used.
- The renewable sources, as well as the electrical loads, are constant within each time step.

The developed mathematical model can be divided into several parts; each part is devoted to a certain component.

3.1. Modeling of Solar Energy

The hourly solar radiation is calculated by checking the hourly relative position of the sun to the earth. Then, an hourly clearness index is generated according to a predefined probability function which depends on the monthly mean clearness index.

These calculations allow generating the diffuse, beam and reflection part of the solar radiation which can be used in the HDKR (Hay-Davies-Klucher-Reindl) model to generate the total hourly solar radiation on a tilted surface [14]. This advanced anisotropic model takes into account the circumsolar diffuse and horizon brightening components on a tilted surface.

The model for the solar panel, i.e. Photovoltaic (PV) panels, is made according to [7]. The PV power produced is estimated by the following equation:

$$P_{pv} = P_1 \frac{G}{G_{ref}} .(1 + \mu_p .(T_c - T_{ref})).P_{pv,r} \qquad (1)$$

with P_1 being the coefficient depending on cleanliness of the PV-cells, Joule effect and instability of the system characteristics, while μ_P is the temperature coefficient $\left(c^{\circ}\right)^{-1}$. G is the solar irradiance on a tilted surface and T_c is the working temperature of the PV panels. G_{ref} and T_{ref} are the reference values of the flux radiation and ambient temperature, respectively, *i.e.* 1000 $W.m^{-2}$ and $25\,c^{\circ}$. $P_{PV,r}$ is the rated power of PV panel under standard test conditions [7].

3.2. Modeling of Wind Energy

Based on the mean monthly wind speed ($\overline{V}_{ref}$), hourly wind speed values (V_h) are generated taking into account a Weibull distribution function:

$$f(v) = \frac{k}{c}(\frac{V_h}{c})^{k-1} \exp[-(\frac{V_h}{c})^k] \qquad (2)$$

with a specific shape factor (*k*), scale factor (*c*) and the mean value ($\overline{V}_{ref}$). The hourly wind speed time series have some autocorrelation and daily pattern implemented according to [15].

Further on, the hourly wind speed values need to be transformed into hourly energy values generated from the wind turbines. This can be done by the following formula [16]:

$$P_w = \begin{cases} 0 & V_h < V_c \\ a{V_h}^3 - bP_{w,r} & V_c \le V_h \le V_r \\ P_{w,r} & V_r \le V_h \le V_f \\ 0 & V_f \le V_h \end{cases} \qquad (3)$$

where *a* and *b* are given by:

$$a = \frac{P_{w,r}}{V_r^3 - V_c^3}, \qquad b = \frac{V_c^3}{V_r^3 - V_c^3} \qquad (4)$$

where V_c, V_r, V_f, and V_h are cut in, rated, cut out (or furling) and hourly wind speeds, respectively. P_w and $P_{w,r}$ are the hourly output power and the rated output power of the current wind turbine, respectively.

3.3. Modeling of the Diesel Generator

The diesel generator is utilized for compensating the power shortage when the power demand is higher than the power produced by renewable energy sources and the battery bank. The model [7] uses the following formula to calculate the fuel consumption:

$$F_{DEG}(t) = F_s .P_{DEG}(t) + F_i .P_{DEG,r}, \forall t \in T \qquad (5)$$

where the fuel consumption F_{DEG} is determined by the *idle fuel consumption* F_i which is the fuel consumption at zero load, and the specific fuel consumption F_s of a particular diesel generator. P_{DEG} and $P_{DEG,r}$ are the output power of the diesel generator and its corresponding rated value, respectively. T is the set of all simulation time steps.

3.4. Modeling of the battery bank

The battery bank is used as a storage unit to store the energy when the generated power becomes higher than the required load. The battery starts to discharge the stored energy according to a certain control strategy. The state of charge of the battery (SOC) must stay between the minimum and maximum state of charge, $SOC_{\mathbf{min}}$ and $SOC_{\mathbf{max}}$, respectively:

$$SOC_{min} \text{ £ } SOC \text{ £ } SOC_{max} \qquad (6)$$

All components used in the simulation model are compared and validated with HOMER. Figure 2 shows validation results for the produced solar, wind and diesel energy for every month under the load following strategy. The simulations results are in good correspondence with HOMER results. The cycle charge control strategy has a slightly different implementation than the HOMER implementation.

3.5. Model validation

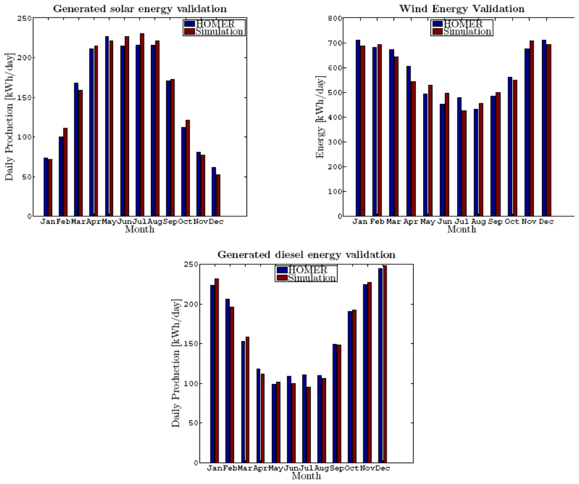

Fig. 2. Validation results using HOMER.

In order to manage the power distribution between the different components of the hybrid power plant, the system needs a controller. The main target of the controller is to ensure the continuity of delivering the power supply to the loads by controlling the battery state of charge and the diesel generator, based on the generated power from renewable energy sources. Many different control strategies can be used for dispatching the electrical power. However, there are two strategies that are commonly used in hybrid energy systems [9], i.e. the *load following strategy* and the *cycle charge strategy*, which are explained in this section. These two strategies are implemented in such a way that they always use the cheapest energy sources first, which are of course the renewable energy sources, when available. Then, depending on the chosen strategy, the diesel generator is started or the battery is discharged.

4.1. *Load Following Strategy*

The load following strategy starts by reading the input parameters. Then, the renewable energy is sent to the primary load which is limited by the rated power of the inverter. The remaining renewable power will be sent to the battery bank if the battery bank is not already fully loaded. If the primary load is fulfilled with renewable energy, the diesel generator will not start and the model calculates the dumped power. On the other hand, when the primary load is not yet fulfilled, the model tries to unload the battery bank. When this is not possible, the diesel generator will start tying to fulfil the load. Finally, the dumped power and the power shortage will be calculated.

4.2. *Cycle Charge Strategy*

The cycle charge strategy starts by reading all input parameters. Hereafter, it checks if the diesel generator is running. When this is the case, the diesel generator will be stopped when the battery is loaded above its SOC set point and the diesel is running longer than its minimum running time. The diesel will start when the primary load cannot be met with the renewable power energy, directly dispatched from the renewable sources or in the second priority from the battery bank. When the state of the diesel generator is determined, the diesel generator state will be checked. If the diesel generator is running, the model will check the battery state. When the battery is fully loaded, the excess renewable energy will be dispatch to the load before loading the batteries. After this procedure, the diesel generator power will be used to fulfil the remaining primary load.

If the primary load is not yet fulfilled, the remaining renewable power will be used to meet the primary load. When there is renewable power energy left at this stage, it will be sent to the battery bank if not completely full. In a last stage, the remaining diesel generator capacity will be used to load the battery bank. The second scenario will be started when the diesel generator is not running. This procedure uses the renewable power to supply the load or charge the batteries. The primary load can discharge the batteries when the renewable power is not sufficient.

In this section, the optimization procedure used to optimize a hybrid energy system is presented. In this study, we use genetic algorithm technique, which is explained in details in the next section followed by the description of objective function formulation.

5.1. *Genetic Algorithm*

Genetic algorithm (GA), as its name already reveals, is based on a genetic process of biological organisms. The concept of GA was first introduced by Holland in 1975 [17]. In last three decades, GA has been widely utilized in several engineering applications; electrical [18], electromagnetic [19], mechanical [20], biomedical [21], etc.

In particular, GA has been successfully applied in the optimization of hybrid energy systems [2]. The most significant advantage of using GA in the optimization of hybrid energy systems is the efficient capability to find the global optimum values; however, its huge computational time is the main disadvantage. This disadvantage becomes much more troublesome when the forward model is computationally burden, due to the iterative nature of the optimization procedure.

In the following, the GA applied for the optimization of the hybrid system is described. The GA procedure is summarized in figure 3. For more detail about the GA, see [22].

Starting with the input data passed to GA, the fitness function and GA parameters need to be defined. The fitness function represents the objective cost function of the hybrid system to be minimized. The GA parameters define recombination and mutation function, as well as, the sought-after parameters of the hybrid system, *i.e.* the parameters that need to be optimized. Moreover, the constraints of the optimization problem are defined, such as the lower and upper bounds of the controlled parameters, *i.e.* the parameters to be optimized, of the hybrid system, *e.g.* the maximum installed power of wind turbine. The parameters of termination criteria, such as minimum allowable error of the objective function, the maximum number of generations or the maximum amount of time spent on the optimization process, are explicitly included in the GA.

Finally, the last data input, necessary to start the optimization process, are the geographical, meteorological and economical conditions of a specified location where the hybrid power plant needs to be installed.

When all input data are available, the optimization process starts with creating the initial populations and hence evaluating the fitness for each individual. Notice that, every individual is a forward model of the hybrid system with parameters specified by the optimization algorithm. When the fitness of each individual is determined, the selection, crossover and mutation algorithms are recalled. The selection algorithm selects a percentage of the initial populations due to their fitness value. Utilizing these solutions, the crossover algorithm provides new possible solutions with the aim to provide better fitness values. Thereafter, the mutation algorithm is applied to prevent getting stuck at a local minimum, and to ensure obtaining the global minimum. The complete procedure is 'iteratively' updated until the predefined stopping criteria are met.

In fact, some 'internal' key parameters of the optimization process, *e.g.* the number of subpopulations and the number of individuals for each subpopulation, are largely influence the obtained results of GA. Therefore, their optimal settings are required.

Specifically, for the optimization of a complex photovoltaic-wind-diesel-batteries-hydrogen system, the following parameters have been considered [22]: the size of the population, the number of generations, the ratio of crossing and mutation, as well as the type of mutation. According to [22], it is recommended to set the following values to assure the highest probability of obtaining the global optimal design using the GA:

- Size of population ≥ 0.003% of all possible solutions.
- Generations ≥ 15.
- Crossing rate equal to 90%.
- Mutation rate equal to 1%.
- Uniform mutation

Using these parameters, the necessary computational time will be approximately 0.045% of the time consumed by the enumerative method, with the highest probability to obtain the global minimum. The enumerative method is simply iterated over every possible solution.

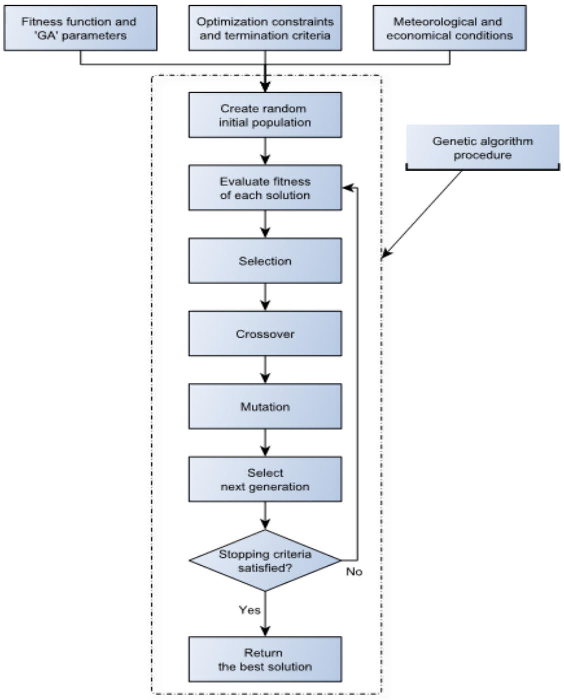

Fig. 3. GA flowchart applied for the optimization of the hybrid system

5.2. *Objective Function Formulation*

The objective function of the hybrid system optimization procedure has the following form:

$$\begin{aligned}&\mathit{Total\_yearly\_cost} = \mathit{fuel\_cost} + (\mathit{start\_penality} * \\ &\mathit{\#of\_starts}) + \mathit{emission\_cost} + \sum_{c=1}^{c} \frac{\mathit{installation\_cost}_c}{\mathit{life\_time}_c} + \\ &\mathit{violation\_penality}\end{aligned} \qquad (7)$$

with *C* being the set of all components in the model and the start/stop penalty applied to the diesel generator only.

A huge violation penalty is added when the constraints are violated. In fact, any real system is subjected to different practical constraints. In the present optimization model, some constraints are implemented, such as the *maximum allowed capacity shortage*, which is a limit on the amount of energy that could not be delivered, and the *minimum allowed renewable fraction*, which is the fraction of generated renewable power out of the total generated power. The total generated power includes the generated renewable energy, i.e. solar and wind, and the generated diesel energy. When these constraints are not met, a penalty factor to the model cost function is added. By doing so, the optimization program is forced to satisfy the applied constraints. Other constraints are the constraints on maximum allowed rated power of each element. These constraints are given as input parameters to the optimization program.

In this section, we present the optimization results for four case studies, which have been chosen in such a way that they have totally different geographic and meteorological conditions. Each case study represents a small village with certain fixed number of population. These villages are not connected to the electrical grid, and the aim is to provide them by electricity via an optimal stand-alone hybrid renewable-conventional power plant.

The mean electrical consumption highly depends on the location's climate and the population's prosperity. However, for the sake of comparison, the annual load curves are kept constant for all case studies with the daily pattern shown in figure 4. The main source of solar radiation and wind speed meteorological data are [14] and [23], respectively. Several meteorological data available online are also useful.

The first case study is to feed a fictive village at Ghent in Belgium. The second case study is at Oslo in Norway, while the third location is at Cairo in Egypt. Finally, the last case study is at Kinshasa, the capital of Democratic Republic of Congo.

At all locations, an optimization problem is solved to find the optimal sizing of the hybrid power plant, while eight parameters are obtained for each case study:

1. The battery capacity [kWh]
2. The rated diesel power [kW]
3. The rated inverter power [kW]
4. The rated rectifier power [kW]
5. The installed PV-power [kW]
6. The number of wind turbines installed
7. The rated power for each wind turbine [kW]
8. The type of controller strategy

The used parameters for the optimization of all case studies are shown in table 2. For the last 3 cases the maximum capacity shortage is reduced to 0.01% which results in a more complex system with the installation of a diesel generator. The last case uses the cycle charge strategy instead of the load following strategy.

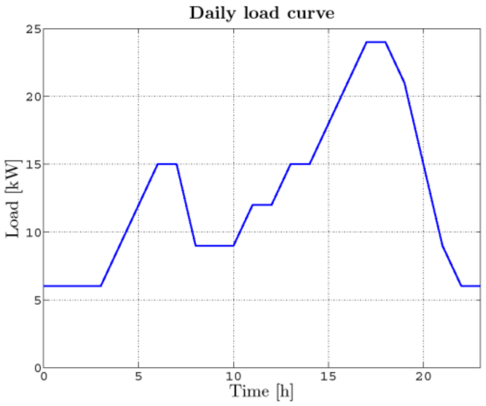

Fig. 4. Daily load curve without added variability.

Table 2. Installation and energy cost.

Installation costs				
	Installation cost		Lifetime	
Battery bank	160	$/kWh	10	year
Diesel	1500	$/kW	20	year
Inverter	550	$/kW	10	year
Rectifier	50	$/kW	10	year
PV-	4400	$/kW	20	year
Wind Turbine	--	$/kW	20	year
	Installation cost		Rated power	
Wind turbine	2000	$/kW	1	kW
	1560	$/kW	18	kW
	980	$/kW	850	kW
	900	$/kW	1500	kW
Fuel/Penalty cost				
Hourly fuel consumption			3.979	L/h/kW
Load fuel consumption			0.023	L/kWh
Fuel price			0.68	$/L
CO$_2$ emission penalty			6	$/ton
Start/stop penalty			1	$
Control strategy	Load following			
Maximum capacity	1 %			

An example of the convergence of the objective function to a global minimum is shown in figure 5. In most cases the convergence takes longer than just 15 generations as stated in [22]. In this study, a total number of 30 generations is assumed to be sufficient.

The resulting systems are shown in tables 3 for Belgium, 4 for Norway, 5 for Egypt and 6 for Congo case study. No diesel generator is installed in the first case because of the shortage allowance of 1 %. The other systems are well designed with a diesel generator and renewable energy sources according to the applicable weather conditions.

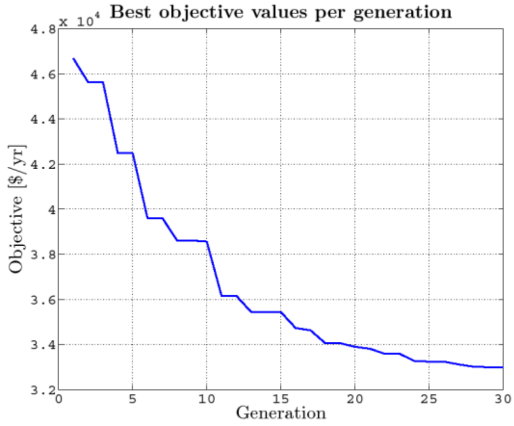

Fig. 5. The convergence of the objective function (Congo case study).

Table 3. Optimized parameters for Belgium case study.

Optimized parameter	Value	
The battery capacity	269	kWh
The rated diesel power	0	kW
The rated inverter power	50	kW
The rated rectifier power	0	kW

The installed PV-power	0	kW
The number of wind turbines installed	1	
The rated power for each wind turbine	64	kW
Total yearly cost	11943	$/year

Table 4. Optimized parameters for Norway case study.

Optimized parameter	Value	
The battery capacity	411	kWh
The rated diesel power	16	kW
The rated inverter power	47	kW
The rated rectifier power	0	kW
The installed PV-power	25	kW
The number of wind turbines installed	1	
The rated power for each wind turbine	106	kW
Total yearly cost	33779	$/year

Four case studies were investigated in the previous section. In general, all optimized cases are feasible and are satisfying all predetermined constraints. The results mentioned in tables 4-6 show systems with a significant higher cost than the Belgium case, *i.e.* table 3. The main cause is the limitation on maximum allowed capacity shortage which has been reduced to 0.01%. This is a very important factor when designing a system. The installation of a diesel generator as conventional energy source will ensure the reliability. The results given in table 5 shows a system with a significant higher cost than the Belgium case but lower than the Norway case study. This can be justified by the higher amount of solar radiation available in Egypt which allows reducing the amount of installed power on other sources.

Table 5. Optimized parameters for Egypt case study.

Optimized parameter	Value	
The battery capacity	347	kWh
The rated diesel power	12	kW
The rated inverter power	57	kW
The rated rectifier power	0	kW
The installed PV-power	22	kW
The number of wind turbines	1	
The rated power for each wind	78	kW
Total yearly cost	29337	$/year

Table 6. Optimized parameters for Congo case study.

Optimized parameter	Value	
The battery capacity	427	kWh
The rated diesel power	11	kW
The rated inverter power	54	kW
The rated rectifier power	55	kW
The installed PV-power	97	kW
The number of wind turbines	2	
The rated power for each wind	1	kW
The state of charge set point	29	%
The minimum diesel running time	8	h
Total yearly cost	34231	$/year

The results illustrated in table 6 show similar results to Egypt case study *i.e.* table 5. In this case study, the system has a cycle charge strategy with a state of charge set point lower than the minimum state of charge set point which results in a system configuration that uses the load following strategy with a minimum diesel running time of 8 h. Some evident improvements with a small impact can be seen. For instance, the use of 2 wind turbines will be more costly than the use of a single wind turbine with rated power of 2 kW. Other improvements can be made at the rectifier and inverter rated power.

In this research work, the hybrid renewable-conventional electrical energy system was simulated, controlled and optimized. Based on four case studies, the developed optimization model was validated. Better system reliability, robustness and efficiency were achieved with the minimum total cost.

The proposed optimization study is definitely important for power system planning to maximize the system performance, as well as, minimizing the total cost. The performance and cost are highly dependent on the correct choice of all components sizing. We are convinced that the optimization procedure will guide the systems' designers into the right directions for every specific condition.

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