A simulation-optimisation programme for designing hybrid energy systems for supplying electricity and fresh water through desalination to remote areas
Case study: the Merssini village, Donoussa island, Aegean Sea, Greece

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Abstract

The aim of the present paper is to develop and apply a software tool for designing hybrid renewable energy systems. The hybrid system consists of a wind generator and photovoltaic modules which are the renewable technologies for energy production. The programme has been applied for simulating a hybrid system with the above mentioned technologies in order cover the electricity and water needs of the Merssini village on Donoussa island in the Aegean Sea of Greece. The Merssini village is occupied by 20 year-round residents while the population is doubled during the summer period. The village is non-electrified and faces a problematic scarcity of fresh water. In the analysis that follows, the considered technical data as well as the results of programme runs for winter and summer seasons are presented. The electricity consumption consists of both the household and desalination plant consumption. The system is supplemented with batteries and a micro hydraulic plant for energy storage. The simulation programme was used to optimise the design of the system as well as to manage the energy supply and energy storage. The results prove that this simulation programme constitutes a valuable tool for the determination not only of the optimum combination of technologies, but also the optimum energy management of complex hybrid systems. © 2001 Elsevier Science Ltd. All rights reserved.
**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A, B$</td>
<td>current change coefficient (Am/°C) and voltage change coefficient (V/°C), respectively</td>
</tr>
<tr>
<td>$A_i$</td>
<td>mean annual temperature (°C)</td>
</tr>
<tr>
<td>$B_i$</td>
<td>amplitude of the annual temperature (°C)</td>
</tr>
<tr>
<td>$F_i$</td>
<td>phase difference (°), or days if it is multiplied by 360/365</td>
</tr>
<tr>
<td>$c_r, c_k, c_a$</td>
<td>average velocity (m/s)</td>
</tr>
<tr>
<td>$c_s$</td>
<td>battery cells in series</td>
</tr>
<tr>
<td>$c_p$</td>
<td>battery cells in parallel</td>
</tr>
<tr>
<td>$d_i$</td>
<td>internal diameters of the pipe (m)</td>
</tr>
<tr>
<td>$D_1, D_2$</td>
<td>diameters of pump rotors (m)</td>
</tr>
<tr>
<td>$e_{oc}, e_{od}$</td>
<td>open circuit voltages at full charge, extrapolated from $V–I$ curves on charge; discharge</td>
</tr>
<tr>
<td>$\text{eff}$</td>
<td>battery charging efficiency (–)</td>
</tr>
<tr>
<td>$f_i, f_s, f_a$</td>
<td>pipe sections (m$^2$)</td>
</tr>
<tr>
<td>$g_{cv}, g_{dv}$</td>
<td>small-valued coefficients of $H$ in voltage–current–state of charge formulas</td>
</tr>
<tr>
<td>$g$</td>
<td>acceleration of gravity (m/s$^2$)</td>
</tr>
<tr>
<td>$H$</td>
<td>daily global radiation incident on a horizontal surface (MJ/m$^2$ day)</td>
</tr>
<tr>
<td>$H_0$</td>
<td>extraterrestrial daily radiation incident on a horizontal surface (MJ/m$^2$ day)</td>
</tr>
<tr>
<td>$H_d$</td>
<td>daily diffuse radiation incident on a horizontal surface (MJ/m$^2$ day)</td>
</tr>
<tr>
<td>$H_1, H_2$</td>
<td>heads at different speeds (m)</td>
</tr>
<tr>
<td>$H_w$</td>
<td>head of the pump-turbine (m)</td>
</tr>
<tr>
<td>$H_t$</td>
<td>level difference between high and low level reservoir (m)</td>
</tr>
<tr>
<td>$I$</td>
<td>hourly global radiation incident on a horizontal surface (kJ/m$^2$ h)</td>
</tr>
<tr>
<td>$I_d$</td>
<td>hourly diffuse radiation incident on a horizontal surface (kJ/m$^2$ h)</td>
</tr>
<tr>
<td>$I_T$</td>
<td>total radiation incident on the module (W/m$^2$)</td>
</tr>
<tr>
<td>$I_o$</td>
<td>extraterrestrial irradiance on a horizontal surface (kJ/m$^2$ h)</td>
</tr>
<tr>
<td>$I_{ref}$</td>
<td>reference insolation (W/m$^2$)</td>
</tr>
<tr>
<td>$I_{sc}$</td>
<td>solar constant (1353 W/m$^2$)</td>
</tr>
<tr>
<td>$I_{max}$</td>
<td>maximum battery current (A)</td>
</tr>
<tr>
<td>$I_{ph}$</td>
<td>current produced by the photovoltaic module (A)</td>
</tr>
<tr>
<td>$I_m$</td>
<td>PV module current at maximum power point (A)</td>
</tr>
<tr>
<td>$I_{scc}$</td>
<td>PV module short circuit current (A)</td>
</tr>
<tr>
<td>$I_{bat}$</td>
<td>battery current (A)</td>
</tr>
<tr>
<td>$I_{zp}$</td>
<td>parameter used in calculating $V_{zp}$ (A)</td>
</tr>
<tr>
<td>$k$</td>
<td>hourly clearness index (–)</td>
</tr>
<tr>
<td>$K_T$</td>
<td>monthly clearness index (–)</td>
</tr>
<tr>
<td>$K_{zp}$</td>
<td>parameter used in calculating $V_{zp}$ (V$^{-1}$)</td>
</tr>
<tr>
<td>$l_i$</td>
<td>lengths of the pipe with different diameter (m)</td>
</tr>
<tr>
<td>$m_c, m_d$</td>
<td>cell-type parameters, which determine the shapes of the $I–V–Q$ characteristics</td>
</tr>
<tr>
<td>$m$</td>
<td>number of hours after the minimum temperature occurs until sunset, (h)</td>
</tr>
<tr>
<td>$n$</td>
<td>number of hours after sunset until the time of the minimum temperature, (h)</td>
</tr>
<tr>
<td>$\eta_w$</td>
<td>pump-turbine efficiency (–)</td>
</tr>
<tr>
<td>$n_1, n_2$</td>
<td>rotation speeds (rpm)</td>
</tr>
</tbody>
</table>
1. Introduction

The lack of water is a common phenomenon in Mediterranean islands and its coastal areas. However, in these areas the wind and solar potential is usually high and allows for the efficient use of renewable energy technologies such as wind energy and photovoltaics. The possibility of
Greek symbols

\(\alpha\)  the lag coefficient for the maximum temperature (h)
\(\beta\)  the nighttime temperature coefficient (–)
\(\delta\)  declination (rad)
\(\varepsilon\)  absolute roughness of the pipe wall (m)
\(\zeta_{\text{tot}}\)  coefficient of total pipe losses (–)
\(\zeta_{\text{kr}}\)  coefficient of total pipe losses (–)
\(\vartheta\)  latitude (rad)
\(\lambda_{i}\)  friction factor (–)
\(\mu\)  dynamic viscosity of the fluid (Pa s)
\(\rho\)  fluid density at mean temperature (kg/m\(^3\))
\(\rho_{g}\)  ground albedo (–)
\(\omega\)  hour angle solar noon zero and mornings positive (rad)
\(\omega_{s}\)  the sunset-hour angle for an horizontal surface (rad)

efficiently using a combination of renewable technologies (hybrid energy systems) for supplying electricity is studied in this paper. The case of the Merssini village at Donoussa island (Aegean Sea, Greece), which is not electrified and faces a fresh water supply problem, is used here, Merssini village is occupied by 20 year-round residents while the population is doubled during the summer season. The suitable size of the hybrid technologies greatly influences the system cost and efficiency [1–3]. For this reason, a simulation programme has been developed and applied for optimising the system size. The programme consists of routines which simulate the operation of all the available technologies such as wind generator, photovoltaics, batteries and a micro hydraulic plant which form the energy storage as well as a reverse osmosis desalination plant.

Fig. 1 schematically shows the technologies. The electricity produced by the wind and the photovoltaic generators is driven to the different energy sinks through an intelligent energy management centre. The sea water is pumped from sea level to the desalination cartridges at a pressure of about 70 bar. The brine is used to drive a turbine in order to recover part of the energy used by the high-pressure pump. Electricity is supplied to a pump to lift the fresh water from the desalination plant to the upper reservoir. The fresh water reservoir has the capacity to fully satisfy year-round, the needs of the village for drinking, washing, etc. and also to irrigate small pieces of land for the local production of high value vegetables. Any power surplus is consigned to the innovative storage system (consisting of both micro-hydraulic and battery systems mentioned earlier) of the PV-Hydro. This storage is used in order to partially replace the batteries which have several disadvantages, particularly limited life duration (up to several years depending on the maintenance) and the toxic wastes that their use implies.

Total elimination of the batteries is not feasible since they are able to undertake peak instantaneous loads and, thus, play a key role regarding the electrical stability of the system. On the other hand, the major benefits of the use of a micro hydraulic subsystem as energy storage are: no standby losses, reliable power production, simple construction and low maintenance cost and no special-
Fig. 1. Schematic diagram showing the integration of wind and solar technologies for supplying electricity and water. The electricity flow is shown by thin dashed lines, the water flow by thick continuous lines.

ised staff required for the maintenance of the system which is a very important factor for a system installed in an isolated area. In addition, hydraulic plants are, in general, environmentally friendly. In the previous version of the programme, a system consisting of photovoltaics and both batteries and a micro-hydraulic plant as energy storage was studied [4]. This latest version additionally embodies the wind generator and reverse osmosis desalination technologies.

2. Simulation-optimisation programme

2.1. Simulation components

A computer simulation of the solar, wind and desalination technologies has been developed which includes the following components:

2.1.1. Total solar radiation

The solar routine may estimate hourly the total tilted surface irradiation [5,6] [see Appendix A, Eqs (A1)–(A15)].

2.1.2. Mean ambient temperature

The air temperature routine may hourly estimate the air temperature if the minimum and maximum day air temperature, the time lag in maximum temperature after noon and the time lag in minimum temperature after sunrise are known [7] [see Appendix A, Eqs (A16)–(A18)].
2.1.3. The PV array module simulator

The PV simulator is based on the well-known TRW model, which assumes an analytical expression for the array current and voltage (I-V) characteristics [8]. It takes into account the short and open circuit currents as well as the current and voltage at the maximum power point and calculates the array output current as a function of the array voltage, the current and voltage change temperature coefficients and the array series resistance [see Appendix A, Eqs (A19)–(A26)].

2.1.4. The model of a lead-acid battery storage

This routine operates in conjunction with the PV array and power conditioning components. It specifies how the battery state of charge varies over time given the rate of charge or discharge. The routine also uses formulas that relate battery voltage, current and state of charge [9] [see Appendix A Eqs (A27)–(A32)].

2.1.5. The regulator/inverter component

This routine is used to simulate the DC power distribution from the PV array panel to and from a battery and another component, the inverter. A cut-off voltage on charging \(V_{max}\) (e.g. 2.35–2.45 V per cell) and discharging \(V_{min}\) (e.g. 1.75–1.85 V per cell for shallow discharged battery) and also a maximum charging current \(I_{max}\) (e.g. \(Q_m/5\) or at most \(Q_m\)) and a minimum discharging current \(I_{min}\) (e.g. \(-Q_m/5\) or at most \(-Q_m\)) have been taken into account. The abovementioned limits for charging and discharging differ from battery to battery but they are provided by the battery manufacturer and are used to prolong battery life. The inverter converts the DC power to AC and sends it to the load [see Appendix A Eqs (A33)–(A36)].

2.1.6. The pump and turbine simulator

The pump and turbine characteristics (head-flow rate and efficiency-flow rate) are treated in dimensionless form. For a given value of the best efficiency point of the pump and turbine, the variation of the power absorbed by the pump as well as the power generated by the turbine is then calculated as a function of the corresponding head and flow rate (see Figs. 2 and 3). The presented curves were assumed as representative for a wide range of centrifugal pumps and Pelton turbines with different nominal characteristics [see Appendix A Eqs (A37)–(A43)].

The pump is operated at variable speeds in order to better adjust the operating point. The flow rate, head and power as a function of rotation speed follow the below equations respectively from the speed \(n_1\) to the speed \(n_2\) [10].

2.1.7. The pipeline simulator

The pipeline losses can be calculated applying the Colebrook equation [11] [see Appendix A Eqs (A44)–(A52)].

2.1.8. The wind generator simulator

This routine is based on the wind generator characteristic curve. The power produced by the wind generator depends on the wind data and the size of wind generator [12] (Fig. 4).
Fig. 2. The flow rate versus head and flow rate versus efficiency pump curves in dimensionless form for a typical centrifugal pump.

Fig. 3. The flow rate versus head and flow rate versus efficiency turbine curves in dimensionless form for a typical Pelton turbine.

2.1.9. The reverse osmosis (RO) desalination plant component

The RO desalination plant component takes into account the net power required for seawater desalination which is the power that the desalination plant consumes minus the power recovered by the recovery turbine plus the power required for lifting water from sea level to the of drinkable water reservoir. Some power consumption of auxiliary equipment, such as dosing pumps, have been taken into account.

\[ P_{\text{dn}} = P_{\text{des}} + P_{\text{lift}} + P_{\text{aux}} - P_{\text{rec}}. \] (1)
2.2. Simulation-optimisation programme of a wind-solar-hydro micro power system

The programme for that simulation-optimisation of the solar wind and hydro power plant has the following structure:

Step 1. Input of several parameters and constants (PV panel characteristics, initial number of PV panels, piping data, initial characteristic curves of pump and turbine, battery constants, wind generator curve, etc.).

Step 2. For a pre-defined cycle of days (e.g. 15 days), the hourly variation of the following variables is calculated: total solar radiation intensity on inclined surface and air temperature. In cases where hourly solar radiation and ambient temperature data are available, the programme can use them directly. The duration cycle can vary from days up to several years according to the data available.

Step 3. Two typical profiles of electrical and drinkable water consumption are introduced (one for winter and another for summer), i.e. power to be consumed on hourly basis, plus the power consumption of the desalination plant, reduced by the recovery power through the recovery turbine of the desalination plant. The total power required for the desalination plant is increased by the power required for lifting fresh water from the desalination plant to the fresh water reservoir.

Step 4. For a given number of PV panels, a certain wind generator, pump, turbine and desalination plant, the following calculations are performed:

— The power $P_{pr}$ produced by the wind generator $P_{win}$ and the PV panels $P_{ph}$, taking into account the solar radiation and cell temperature, calculated as a function of the ambient air temperature:

$$P_{pr} = P_{ph} + P_{win}.$$  \hspace{1cm} (2)

— The total electric power consumption $P_{ct}$ is the sum of household and municipal electricity consumption $P_{c}$ according to the corresponding load profile and the electrical power for reverse osmosis $P_{dn}$ according to water demand defined by the water consumption profile.
\[ P_{ct} = P_c + P_{dn}. \] (3)

\( P_{dn} \) is negligible when the drinkable water reservoir is full.

— If \( P_{pr} > P_c + P_{dn} \) and if the desalination plant operates (fresh water reservoir not full), the power surplus \( (P_{pr} - P_c - P_{dn}) \) is used to charge the batteries. If the desalination plant does not operate (fresh water reservoir full) then the power surplus \( (P_{pr} - P_c) \) is used for batteries’ charging. When the battery bank is fully charged, the excess power (if any exists) is used to pump water from the lower to the upper reservoir (hydraulic energy storage). If the micro hydraulic upper reservoir is full, the excess power (if any exists) is dumped. According to the pump characteristics (i.e. the flow rate, the head and the power available), the volume of the pumped water (during 1 h) is calculated as well as the mean efficiency of the pump at the actual operating point.

— If \( P_{pr} > P_c \) and \( P_{pr} < P_c + P_{dn} \) and if there is need for fresh water production (fresh water reservoir empty) the required power for desalination plant operation is covered by the energy storage (batteries and hydraulic power). The water turbine of the micro hydraulic plant operates in priority and when the water in the storage reservoir is worn out, the batteries undertake to satisfy the consumption. If there is no need for more fresh water (the level in the fresh water reservoir is between the upper and lower limits), the difference \( P_{pr} - P_c \) is used to charge batteries (if there are not already fully charged). Any additional available power is used to pump water from the lower to the upper reservoir (energy storage). If this reservoir is full, excess power is dumped.

— If \( P_{pr} < P_c + P_{dn} \) then the energy deficit is defined as \( (P_c + P_{dn} - P_{pr}) \) if the desalination plant operates, or it is defined as \( (P_c - P_{pr}) \) if the desalination plant does not operate. In both cases, this energy deficit is covered by the operation of the hydro-turbine. According to the turbine characteristics (i.e. the flow rate, the head and the power demand), the volume of the turbined water during one hour is calculated. If the energy demand exceeds the power produced by the turbine, the batteries cover the energy required.

In the case that the batteries’ discharging level is lower than the Depth of Discharge (DOD) defined by the batteries manufacturer, the system is led to deficit, meaning that larger amount of power generation is needed. Thus, a rearrangement of the inputs related to the power generation is necessary. The rearrangement concerns the number of PV-modules and the nominal power of the wind generator. It deserves to be mentioned that the battery bank sizing has to take into account several days of energy autonomy of the system, in order the uninterrupted power supply being assured even in cloudy and calm time intervals.

The following results concern the case of Merssini village on Donoussa Island.

2.3. Water and electricity consumption profiles

Fig. 5 shows the considered electricity demand profiles of the Merssini village. These two profiles refer to the summer and winter electricity consumption due to the variation of population between these seasons. It is assumed that only the basic electricity needs will be covered by the hybrid system, i.e. lights, TV apparatus, refrigerator for every house. The number of inhabited houses throughout the year is 7, but in summer they are 13.

Two fresh water consumption profiles, one for winter and another for summer, have also been considered (see Fig. 6). The fresh water profiles are considered in order to cover all fresh water needs of the village residents (not only drinking demand).
Fig. 5. Typical Mersini village electricity consumption profiles for winter time (continuous line) and summer time (dashed line).

Fig. 6. Typical water consumption profile of Mersini village for wintertime (continuous line) and for summer time (dashed line).

2.3.1. Technical data

In this section the technical data of the equipment considered in the programme are presented.

2.3.1.1. Pv module

Table 1 summarises the technical characteristics of the PV modules, which have been used as programme inputs.

2.3.1.2. Wind generator

Fig. 7 illustrates wind generator curves of different output power. Several programme runs are realised in order to select the optimum one.
Table 1
Technical characteristics of the PV array

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (Wp)</td>
<td>60</td>
</tr>
<tr>
<td>Voltage at maximum power (V)</td>
<td>27</td>
</tr>
<tr>
<td>Current at maximum power (A)</td>
<td>2.3</td>
</tr>
<tr>
<td>Short circuit current (A)</td>
<td>2.5</td>
</tr>
<tr>
<td>Open circuit voltage (V)</td>
<td>36</td>
</tr>
</tbody>
</table>

Fig. 7. Wind generator curves used as programme inputs to select the optimum one (cut-in velocity 4.5 m/s, cut-off velocity 30 m/s).

2.3.1.3. Pump and turbine characteristic curves The height difference (head) between the high and the low-level reservoirs can be considered as constant. Since various micro-hydro equipment (pump and turbine) can be selected as a function of flow rate, the optimum is the one that assures the better exploitation of the excess power of the PV generator. Figs. 8 and 9 display the characteristic curves of the selected equipment. The volume of the storage reservoir is defined to 100 m$^3$. Table 2 summarises the technical characteristics of the pump and the turbine.

2.3.1.4. Pipeline Table 3 summarises the technical data of the pipeline.

2.3.1.5. Battery cells Table 4 summarises the technical characteristics of the battery cell, which has been considered as programme inputs.

2.3.1.6. Desalination plant Table 5 presents the technical data of the assumed desalination plant. The consumption of the high-pressure pump, of the feed pumps and of the dosing pumps is included in the total installed power.

2.3.1.7. Inverter/regulator/rectifier The efficiency of this equipment has been assumed to be 0.95.
Fig. 8. Characteristic curves of the selected pump. The continuous line indicates the head as a function of flow rate and the dashed line indicates the efficiency as a function of the flow rate.

![Characteristic curves of the selected pump.](image)

Fig. 9. Characteristic curves of the selected turbine. The continuous line indicates the head as a function of flow rate and the dashed line indicates the efficiency as a function of the flow rate (Pelton turbine).

![Characteristic curves of the selected turbine.](image)

Table 2

<table>
<thead>
<tr>
<th></th>
<th>Pump (centrifugal)</th>
<th>Turbine (Pelton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (kW)</td>
<td>6.6</td>
<td>5.0</td>
</tr>
<tr>
<td>Flow rate (m³/h)</td>
<td>18</td>
<td>30</td>
</tr>
<tr>
<td>Head (m)</td>
<td>97</td>
<td>97</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.72</td>
<td>0.64</td>
</tr>
<tr>
<td>rpm</td>
<td>2900</td>
<td>1500</td>
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</table>
Table 3
Pipeline technical data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe length (m)</td>
<td>380</td>
</tr>
<tr>
<td>Pipe diameter (mm)</td>
<td>100</td>
</tr>
<tr>
<td>Pipe roughness (mm)</td>
<td>0.080</td>
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</tbody>
</table>

Table 4
Technical characteristics of the battery cells

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal voltage (V)</td>
<td>2</td>
</tr>
<tr>
<td>Efficiency in charge</td>
<td>0.9</td>
</tr>
<tr>
<td>Maximum charge current (A)</td>
<td>85</td>
</tr>
<tr>
<td>Maximum discharge current (A)</td>
<td>-85</td>
</tr>
<tr>
<td>Cut-off charge voltage (V)</td>
<td>2.35</td>
</tr>
<tr>
<td>Cut-off voltage in discharge (V)</td>
<td>1.75</td>
</tr>
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</table>

Table 5
Technical data of the desalination unit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh water capacity (m³/h)</td>
<td>0.4</td>
</tr>
<tr>
<td>Net absorbed power (kW)</td>
<td>5</td>
</tr>
<tr>
<td>Volume of fresh water reservoir (m³)</td>
<td>50</td>
</tr>
</tbody>
</table>

3. Results and discussion

Several programme runs were elaborated in order to select the equipment best suited to the case of Donoussa Island. This equipment is described below. In order to obtain an overview of the system operation, two groups of results, one for winter and one for summer, are presented in the next section.

The optimum selected equipment are presented below.

— Wind generator
A wind generator of about 10 kW rated power best suits the system. Fig. 10 shows the characteristic curve of the selected wind generator while Table 6 summarises some of its basic technical characteristics.

— PV array and battery cells capacity
The optimum number of PV modules is defined as 300. The PV modules are considered to be connected in groups of 15 in a series that gives an operation system voltage of about 400 V. The number of battery cells is defined as 186 in series, with a capacity of 100 Ah.

— Desalination plant
It has been already mentioned that a desalination plant with a fresh water capacity of 0.35 m³/h has been selected. In the following, results of test runs for winter and summer period are presented using the technical characteristics of the selected equipment.
3.1. Results of the programme runs for winter and summer time

The results of the programme run for winter and summer period; are shown in Figs. 11–17. Fig. 11 shows the air temperature and the distribution of solar radiation intensity on a south-
Fig. 12. Typical July day air temperature (dashed line) and solar radiation (continuous line) intensity data used in the simulation.

Facing surface tilted 45° during a typical day of January (the coldest month with the lower solar radiation). Fig. 12 illustrates the air temperature and the distribution of solar radiation intensity on a south-facing surface with a tilted 45° during a typical day of July (the hottest month with the higher solar radiation). These data were calculated taking into account the corresponding mean measured values for the island of Naxos (the closest meteorological station).

Fig. 13 displays the PV and the wind generator power production for a duration of 15 days (360 h) for January and July respectively.

Fig. 14 displays the total consumption (household and municipal, as well as the desalination unit consumption). In the desalination unit consumption, the recovered energy has been taken into account, as well as the required energy for lifting water from the sea level to village level.

Fig. 15 shows water flow rates during the operation of the pump and the turbine. The pump...
Fig. 14. Electricity consumption (continuous line) and RO desalination plant consumption (dashed line) for January (upper diagram) and July (lower diagram). The dashed line peaks show the desalination plant operation according to the available power.

Fig. 15. Flow rate of pump of variable speed (continuous line) and turbine operation (dashed line) for January (upper diagram) and July (lower diagram).

is of variable speed as is clearly seen from the fluctuation of the pump flow rate (continuous line). The application of a variable speed pump allows the exploitation of even a small amount of excess energy produced by the PV arrays and the wind generator, significantly improving the efficiency of the whole system.

Fig. 16 presents the variation of the water volume in the storage and fresh water reservoirs. The reduction of the fresh water reservoir volume follows the water consumption profile (see Fig. 6). Peaks appear as soon as the desalination plant operates. Respectively, the water volume in the storage reservoir increases when the pump operates and decreases when the turbine operates.
The volume of the fresh water reservoir was determined after several programme runs and the criterion for its capacity selection is to assure the water consumption even in periods of continuous lack of wind. The volume of the storage reservoir is chosen so that the total volume of pumped water is equal to the volume of “turbined” water during the of 15 day cycle.

Fig. 17 shows the battery state of charge $F$. During programme runs, when values of $F$ lower than 0.8 were obtained, the battery bank characteristics were changed, i.e. capacity, number of cells and the results were evaluated again. When $F$ remained low, more significant adjustments to the system had to be realised (i.e. increase the number of PV panels). $F$ values slightly above 1.0 (due to time step selection) indicate complete charging.
In Tables 7 and 8, the results of the simulation for the typical winter and summer period (cycle of 15 days) are summarised.

It can be seen in upper diagram of Fig. 13 that the total power produced by the PV generator is about 6 kW. This period of time corresponds to the lowest solar radiation during the year. During that time, the system is considered to be in a state of energy deficit. Carefully examining the presented figures, it is apparent that the system operates without any power interruption. A further analysis of the upper diagrams of Figs. 14–17 shows the following:

(a) When there is sufficient wind energy production (see Fig. 13, at the right hand side of the upper diagram) the water volume in the energy storage reservoir remains unchanged and the storage reservoir is full (see Fig. 16, at the right hand side of the upper diagram). Consequently, there is no need for water to be pumped (see Fig. 15, at the right hand side of the upper diagram), because the load and the desalination plant consumption are both fulfilled by the PV and wind generator energy production. For the same reason, batteries remain fully charged at that time (see Fig. 17, at the right hand side of the upper diagram). The available power is then exploited by the desalination plant and thus the fresh water reservoir also remains full (see Fig. 16, at the right hand side of the upper diagram). In conclusion, under such circumstances, the system storage, consisting of batteries and micro-hydro, does not operate at all and the consumption is satisfied by the energy produced (PV, wind generator).

(b) When there is no sufficient wind energy production (see Fig. 13, at the left hand side of the upper diagram) the water volume in the storage reservoir drops during the night due to the turbine operation and increases during the day because of the pump operation which exploits the excess power from the PV array (see Fig. 16, at the left hand side of the upper diagram).
As soon as the water in the storage reservoir is depleted, the batteries start to supply electricity and, consequently, the factor \( F \) is reduced (see Fig. 17, at the left hand side of the upper diagram). It is worthwhile to mention that, for the operation of the desalination unit, at least 3 kW are necessary. If this power is not available, the desalination plant does not operate.

The results of programme runs for the summer period are presented in lower diagrams of Figs. 13–17. The lower diagram of Fig. 13 shows the solar radiation and mean ambient air temperature variation in the typical day of the hottest month (July). Fig. 13 shows (lower diagram) the power provided by the PV array and the wind generator. In this case, the total PV energy production is more than double of that in the winter case. On the other hand, the household and municipal electricity consumption and also the electricity consumption of the desalination unit is also increased for the following two reasons:

— the number of residents is increased during the summer season; and
— the water consumption is increased during the summer season.

In the lower diagram of Fig. 14 the household and desalination plant electricity consumption are shown. The need for more fresh water during the summer season requires longer operation of the desalination plant in relation to the winter season and this is done when the wind speed is sufficiently high.

The lower diagram of Fig. 15 illustrates the pump and turbine operation in the same period of time. Because of the existence of more energy produced than the winter season, available from wind and PV generator, it can be easily seen that the total amount of energy for water pumping (storage system) is greater than this of the winter case. As a consequence, there is a better hydraulic backup as is shown in the lower diagram of Fig. 16. The battery storage also has a better state of charge during this period (see Fig. 17, lower diagram).

The conclusions derived from the diagrams presented in Figs. 13–17 in relation to the system operation coincide to those made for the winter case. Thus, when there is not sufficient wind power, water is pumped during the daytime exploiting the excess power from the PV array if any exists. On the other hand, water is turbined and batteries are discharged during the periods when there is insufficient PV power. Depending on the pump or turbine operation, the volume of the water reservoir increases or decreases. The fluctuations of the volume of the fresh water reservoir follow the desalination plant operation. Thus, the volume increases when the desalination plant operates and decreases, due to the fresh water consumption, when the desalination plant does not operate.

4. Conclusions

Computer simulation programmes are valuable tools to determine the optimum combination of technologies to be integrated as well as to determine an optimum energy management of complex integrated systems, i.e. setting the priorities for energy production and energy storage for each system technology.
Appendix A. Total solar radiation

The procedure for the calculation of the radiation is as follows; the hourly radiation incident $I_T$ on an inclined surface is provided by the Eq. (A1):

$$I_T = rI$$  \hspace{1cm} (A1)

where,

$$I = kI_0$$  \hspace{1cm} (A2)

and

$$I_0 = I_{sc} \left[ 1 + 0.033 \cos \left( \frac{360N}{365} \right) \right] \left[ \sin(\vartheta) \sin(\delta) + \cos(\vartheta) \cos(\delta) \cos(\omega) \right]$$  \hspace{1cm} (A3)

where:

$$\delta = \frac{\pi}{180} 23.45 \sin \left[ \frac{360(284+N)}{365} \right]$$  \hspace{1cm} (A4)

and for the hour $i$:

$$\omega = \frac{\pi}{180} 15(i-12)$$  \hspace{1cm} (A5)

$k$ is calculated by Eq. (A6):

$$k = K_T [a + b \cos(\omega)]$$  \hspace{1cm} (A6)

where:

$$a = 0.409 + 0.5016 \sin(\omega_s - 60)$$  \hspace{1cm} (A7)

and

$$b = 0.6609 - 0.4767 \sin(\omega_s - 60)$$  \hspace{1cm} (A8)

with

$$\omega_s = \cos^{-1} \left[ -\tan(\vartheta) \tan(\delta) \right]$$  \hspace{1cm} (A9)

$r$ is provided by the following equation:

$$r = \left( 1 - \frac{I_d}{I} \right) \frac{I_0}{I} + \frac{I_0 (1 + \cos(S))}{2} + \frac{\rho_s (1 + \cos(S))}{2}$$  \hspace{1cm} (A10)

with,

$$r_b = \frac{\cos(\vartheta - S) \cos(\delta) \cos(\omega) + \sin(\vartheta - S) \sin(\delta)}{\cos(\vartheta) \cos(\delta) \cos(\omega) + \sin(\vartheta) \sin(\delta)}$$  \hspace{1cm} (A11)

and
\[ I_d = \frac{H_d/H}{a + b \cos(\omega)}. \]  

(A12)

For Greece, the ratio \( H_d/H \) is provided by Eq. (A13):

\[ \frac{H_d}{H} = 1.446 - 2.965K_T + 1.727K_T^2. \]  

(A13)

For a typical day of a certain month the clearness index \( K_T \) is calculated:

\[ K_T = \frac{H}{H_0} \]  

(A14)

\( H_0 \) is defined by the following equation:

\[ H_0 = \left( \frac{24}{\pi} \right) I_{sc} 3600 \left[ 1 + 0.033 \cos\left( \frac{360N}{365} \right) \right] \]  

(A15)

\[ [\cos(\vartheta) \cos(\delta) \sin(\omega_s) + \omega_s \sin(\vartheta) \sin(\delta)] \]

A.1. Mean ambient temperature

Eqs (A16) and (A17) are used for the calculation during daytime and nighttime respectively:

\[ T_{\text{air}} = (T_{\text{max}} - T_{\text{min}}) \sin\left( \frac{\pi m}{Y + 2\alpha} \right) + T_{\text{min}} \]  

(A16)

\[ T_{\text{air}} = T_{\text{min}} + (T_s - T_{\text{min}}) e^{-\beta n / z}. \]  

(A17)

The mean maximum and mean minimum air temperature is provided by the following Eq. (A18), putting the appropriate parameters \( A_{\text{max}}, B_{\text{max}}, F_{\text{max}} \) and \( A_{\text{min}}, B_{\text{min}}, F_{\text{min}} \) instead of \( A_i, B_i, F_i \):

\[ T_i(N) = A_i + B_i \sin\left( \frac{360}{365} N - F_i \right) \]  

(A18)

A.2. The PV array module simulator

The \( I-V \) function is described by the following equation when the insolation \( I \neq I_{\text{ref}} \) and \( T_{\text{cell}} \neq T_{\text{ref}} \):

\[ I_{\text{ph}} = I_{\text{sc}} [1 - C_1 (e^{V_{\text{oc}}/V_{\text{oc},\text{ref}}} - 1)] + I_d \]  

(A19)

where:

\[ I_{\text{ph}} \] is the photocurrent generated by the PV array module simulator.

\[ I_{\text{sc}} \] is the short-circuit current of the PV array module simulator.

\[ C_1 \] is a constant parameter.

\[ V_{\text{oc}} \] is the open-circuit voltage of the PV array module simulator.

\[ V_{\text{oc},\text{ref}} \] is the reference open-circuit voltage.

\[ e^{V_{\text{oc}}/V_{\text{oc},\text{ref}}} \] is the exponential function of the ratio of the open-circuit voltage to the reference open-circuit voltage.

\[ I_d \] is the dark current of the PV array module simulator.
\[ C_1 = \left(1 - \frac{I_m}{I_{sc}}\right) e^{-\frac{V_m}{e V_{ocv}}} \]  
(A20)

and

\[ C_2 = \frac{\frac{V_m}{V_{ocv}} - 1}{\ln\left(\frac{I_m}{I_{sc}}\right)} \]  
(A21)

\[ I_D \text{ and } V_D \text{ are provided by the equations:} \]

\[ I_d = A \frac{I}{I_{ref}} DT + \left(1 - \frac{I}{I_{ref}}\right) I_{sc} \]  
(A22)

\[ V_D = -BDT - R_s I_d \]  
(A23)

while DT is:

\[ DT = T_{cell} - T_{ref}. \]  
(A24)

The cell temperature is calculated through Eq. (A25):

\[ T_{cell} = T_{air} + t_c I_T. \]  
(A25)

The power produced by the photovoltaics is:

\[ P_{ph} = I_{ph} V_{ph} N_{par} N_{ser} \]  
(A26)

A.3. The model of lead-acid battery storage

During battery cell discharge, the relationship between voltage and current is described by the following equation:

\[ V_{bat} = V_{boc} - V_{zp} - g_d W + I_{bat} r_{qd} \left(1 + \frac{m_d W}{Q_d/Q_m - W}\right) \]  
(A27)

and on cell charge:

\[ V_{bat} = V_{boc} - V_{zp} - g_c W + I_{bat} r_{qc} \left(1 + \frac{m_c W}{Q_c/Q_m - W}\right) \]  
(A28)

where,

\[ V_{zp} = \frac{1}{K_{zp}} \ln\left(\frac{I_{bat}}{I_{zp}} + 1\right) \]  
(A29)
and
\[ V_{boc} = \frac{1}{2}(e_{qd} + e_{qc}). \]  \hspace{1cm} (A30)

For the specification of the state of charge during charge–discharge the following equation is applied
\[ \frac{dQ}{dt} = \begin{cases} I_{bat} & \text{if } I_{bat} \leq 0 \\ I_{bateff} & \text{if } I_{bat} > 0 \end{cases}. \]  \hspace{1cm} (A31)

The battery power is calculated as follows:
\[ P_{bat} = I_{bat} V_{bat} c_{p}. \]  \hspace{1cm} (A32)

**A.4. The regulator/inverter component**

The equations describing the regulator operation are the following:

—Voltage regulation,
\[ \text{if } V_{bat} > V_{max} \Rightarrow V_{bat} = V_{max} \] \hspace{1cm} (A33)

else if \( V_{bat} < V_{max} \Rightarrow V_{bat} = V_{bat} \) \hspace{1cm} (A34)

—Current regulation,
\[ \text{if } I_{bat} > I_{max} \Rightarrow I_{bat} = I_{max} \] \hspace{1cm} (A35)

else if \( I_{bat} < I_{max} \Rightarrow I_{bat} = I_{bat} \). \hspace{1cm} (A36)

**A.5. The pump and turbine simulator**

The flow rate, head and power as a function of rotation speed follow the below equations respectively from the speed \( n_1 \) to the speed \( n_2 \):
\[ \frac{Q_1}{Q_2} = \left( \frac{D_1}{D_2} \right)^3 \left( \frac{n_1}{n_2} \right) \] \hspace{1cm} (A37)
In the case of the identical pump, \( D_1 = D_2 \).

The power absorbed by the pump is given by Eq. (A40):

\[
P_{pu} = \frac{\gamma H_w Q_w}{\eta_w} \quad (A40)
\]

in every rotation speed. The pump is of variable speed in order to exploit all the available excess power provided by the system.

The operating point is defined as the intersection of the pump characteristic and pipeline characteristic provided by Eq. (A41):

\[
H_w = H_t + \xi_{1on} Q_w^2. \quad (A41)
\]

The turbine operates in constant rotation speed and the power provided is given by the formula:

\[
P_{tu} = \gamma H_w Q_w \eta_s \quad (A42)
\]

while the operation point is the intersection of flow rate–head turbine characteristic with the pipeline, which is provided by Eq. (A43):

\[
H_w = H_t - \xi_{1on} Q_w^2. \quad (A43)
\]

### A.6. The pipeline simulator

The pipeline losses can be described by the following equation:

\[
\Delta H_i = \Delta H_{lin} + \Delta H_{loc} + \Delta H_{kin} \quad (A44)
\]

where \( \Delta H_{lin} \) represents the linear losses, \( \Delta H_{loc} \) are the local losses and \( \Delta H_{kin} \) is the kinetic energy of the fluid that enters to the high level reservoir and which is finally transformed to heat.

The coefficient \( \lambda \) of linear losses is calculated by the application of the relation of Colebrook:

\[
\Delta H_{lin} = \sum_i \lambda_i \frac{l_i c_i^2}{d_2 g}. \quad (A45)
\]

Eq. (A45) represents the head loss in pipeline sections with different diameter or material. The friction factor is a function of the pipe roughness, inside diameter and the Reynolds number:

\[
Re = \frac{d c \rho}{\mu}. \quad (A46)
\]
The Colebrook equation is as follows:

\[
\frac{1}{\sqrt{\chi_i}} = 1.74 - 2\log_{10}\left(\frac{2\varepsilon}{d_i} + \frac{18.7}{\sqrt{\chi_i}}\right)
\]  

(A47)

\(\chi_i\) is constant in the case of turbulent flow.

The local head loss is described by the following equation:

\[
\Delta H_{\text{loc}} = \sum_k \zeta_k \frac{C_k^2}{2g}
\]  

(A48)

where \(\zeta_k\) are coefficients of the local head losses which can be considered as constant in the case of turbulent flow, while:

\[
\Delta H_{\text{kin}} = \frac{C_a^2}{2g}
\]  

(A49)

Since \(Q_w\) is constant,

\[
Q_w = f_i c_i = f_k c_k = f_a c_a
\]  

(A50)

and thus,

\[
\Delta H_t = \zeta_{\text{tot}} Q_w^2
\]  

(A51)

with:

\[
\zeta_{\text{tot}} = \sum_i \lambda_i \frac{l_i}{d_i 2g f_i^2} + \sum_k \zeta_k \frac{1}{2gf_k^2} + \frac{1}{2gf_a^2}.
\]  

(A52)

References


