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Renewable Energy 30 (2005) 1649–1669
RENEWABLE ENERGY
www.elsevier.com/locate/renene

A server database system for remote monitoring and operational evaluation of renewable energy sources plants

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Received 20 September 2004; accepted 19 November 2004
Available online 2 February 2005

Abstract

The development of a server database system for monitoring and operational evaluation of remote Renewable Energy Sources (RES) plants is presented. Meteorological and operational parameters of multiple RES systems are measured and transmitted in real-time to a database (DB) server. An integrated data management system, comprised of programs running on the DB server, displays the received data on screen, stores them on local disk and inserts them in the DB in real-time. Remote clients access the DB using the TCP/IP protocol in order to create charts, calculate statistical and operational parameters regarding each RES plant and perform DB administration actions. The proposed system can be used for the exploration of the available RES potential during the design of RES systems, the development of statistical models describing the spatial variability of RES resources and the remote monitoring and control of RES plants.

Keywords: Renewable energy sources; Database; Data-acquisition system; SQL server; Sensors

1. Introduction

Over the last decades, there has been a growing concern about the remaining amount of fossil fuels, which is available to cover the world's continuously increasing energy requirements and the environmental problems caused by conventional energy production

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0960-1481/$ - see front matter
doi:10.1016/j.renene.2004.11.019

units. Renewable Energy Sources (RES) are considered to be the most viable and effective solution to these problems.

The installation cost of RES plants is relatively high, while their design requires detailed knowledge of the meteorological profile of the area where they are installed, since the corresponding energy production is highly influenced by the climatic conditions [1,2]. Thus, it is essential to develop techniques that will aid in assessing the available RES potential at the area of interest resulting in minimum system cost and maximum operational reliability under intermittent energy production conditions. In many cases, meteorological data from many different sites are required in order to evaluate models describing the spatial variability of a RES resource, such as the global irradiation, across an extended geographic region [3] or to fill missing data because of measurements unavailability [4], leading to the development of data-collection networks [5]. Additionally, because of the yearly variation of the climatic conditions, statistical processing of a large volume of data available from past years is required in order to derive accurate models of the RES resources. Thus, the usually applied data organization in text files is inefficient and the development of automated Database Management Systems (DBMS) is indispensable.

Aiming towards the design optimization of RES plants and the development of energy planning strategies, data-acquisition (DAQ) systems have been installed in RES plants under operation in order to measure meteorological and operational parameters and subsequently to evaluate their performance [6]. Such systems typically consist of a microcontroller-based unit for recording the signals of interest, while the collected data are usually transmitted to a PC for storage and further processing.

Performance data from RES plants under operation are also required for the application of diagnostic technologies, thus enhancing the systems reliability. In [7], the data acquired from a Photovoltaic (PV) system, such as the solar irradiation, the PV modules temperature, the ambient temperature, the PV array output voltage and current, etc. are used together with diagnostic criteria in order to provide maintenance advices to the system operator. Furthermore, RES systems are usually installed in geographically isolated areas, while the acquired data must be distributed to several remote users. A PC-based, data-acquisition system is presented in [8], used to measure meteorological and system performance parameters of a RES plant and display the acquired data to remote users in real-time through the Internet.

In this paper, the development of a server database system for monitoring and operational evaluation of remote RES systems, which integrates the aforementioned prerequisites for RES technology promotion, is described. The architecture of the proposed system is depicted in Fig. 1. Meteorological and operational parameters of each RES plant, such as solar irradiance, wind speed, battery voltage, photovoltaic output current, etc. are measured and stored at the corresponding data-acquisition PC (DAQ-PC) and transmitted in real-time to the DB Server. The DB Server receives data from multiple RES plants, displays them on screen and stores them in separate files on local storage. Also, the received data are inserted in the DB in real-time, while remote clients access the DB using the TCP/IP protocol in order to create charts, calculate statistical and operational parameters regarding each RES plant and perform DB administration actions. The advantage of the proposed system is that a large volume of real-time meteorological

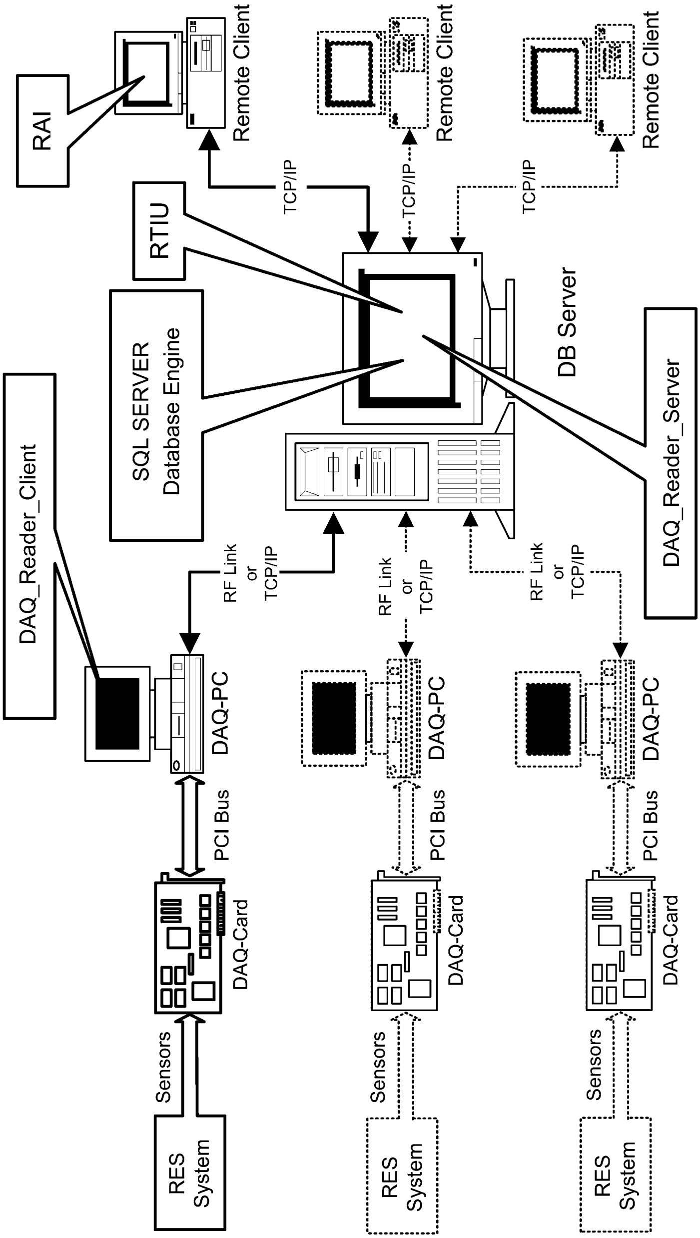

Fig. 1. The proposed system diagram.

and operational measurements from multiple, remote RES plants can be collected on a centralized DBMS. Thus, the proposed system can be used for the exploration of the available RES potential during the design of RES systems, the development of statistical models describing the spatial variability of RES resources and the remote monitoring and control of RES plants.

This paper is organized as follows: a general overview of database systems is presented in Section 2, the proposed system architecture is analyzed in Section 3 and an implementation example is discussed in Section 4.

2. Database systems

Data organization in modern DB systems is based on relational theory [9]. Data are organized into tables corresponding to a subset of the entity represented by the DB (e.g. employees, a department of a company, etc.). Each row of the table describes a subset member, while the columns contain the values of the member attributes.

According to their topology, DB systems are typically divided into two types:

(a) The Server Database Systems, constructed such that a database engine installed on a central computer (server) is shared among multiple users, who connect over a network to an instance of the database engine, using an application (client) running on their local computer. Additionally, the server can be used to run Internet Information Services (IIS), such as a Web page.
(b) The Desktop Database Systems, where the database engine is accessed by applications running on the same computer. The client applications connect to the database engine through local Interprocess Communications (IPCs), such as shared memory.

Server DB systems are characterized by a centralised storage of data having certain advantages:

- The database engine schedules the requests for data modification and retrieval, such that the same data instance is available to all clients.
- DB access rules need only be defined on the server.
- Compared to file server systems, redundant data are not sent to the client application, resulting in network traffic reduction.
- The tasks of processing (i.e. statistical analysis, etc.) and displaying the requested information are shared between the DB server and the clients, respectively, thus the server machine processing load is reduced.
- Maintenance tasks such as backup and data restoration are performed only on the DB server.

A database engine frequently used is the Microsoft SQL Server 2000, since it provides many embedded statistical functions and can handle DBs containing a large volume of data. The SQL Server 2000 can service requests from applications running on both, the same or a remote computer, while it can be efficiently interfaced with Visual Basic applications.

3. The system architecture

The proposed system block diagram is depicted in Fig. 1. It is divided into three parts:

- The DAQ-PCs, used to measure several meteorological and operational parameters of the RES plant. The DAQ_Reader_Client program, running on each DAQ-PC, is used to collect the corresponding sensors readings and transmit them in real-time to the DB Server through either an RS-232 serial port RF Transceiver or a TCP/IP port.
- The DB Server, containing the database engine where the data transmitted by the DAQ-PCs are stored. The DB Management System (DBMS) running on the DB Server is the Microsoft SQL Server 2000. A properly developed program (DAQ_Reader_Server) manages the reception of data from all DAQ-PCs connected to the DB server and stores the received measurements in text files. Subsequently, the Real-Time-Insert-Utility (RTIU) program communicates with the database engine in order to insert the data stored in the text files in the database, also in real-time. Since the data transmitted to the DB Server are first stored in text files instead of being directly inserted in the DB, the DAQ_Reader_Server and DAQ_Reader_Client programs comprise an autonomous data-acquisition system for remote monitoring and control of RES plants, which can be used in case that database facilities are not required.
- The remote clients, connected to the DB Server over the Internet using the TCP/IP protocol. The clients use the RES-Admin-Interface (RAI) program in order to access the DB using either a ‘Guest’ account type, which only enables data retrieval, chart creation and statistical processing of the collected data or an ‘Administrator’ account type, which, additionally, facilitates data insert and export operations and enables remote DB management.

All applications were developed using Microsoft Visual Basic (VB) 6.0, since it offers ready to use and efficient ways to connect to instances of SQL Server 2000, whether the client application is running on the local or a remote PC. The design interface of VB is easy to use, enabling the development of a wide range of Graphical User Interface (GUI) applications, while the components of the resulting applications can be updated through service packs without having to be recompiled.

3.1. The DAQ_Reader_Client

The meteorological and operational parameters of interest at each RES system are recorded using sensors interfaced to a PCI data-acquisition card, which is installed in the DAQ-PC. The DAQ_Reader_Client program, running on the DAQ-PC, is used to control the data-acquisition process. The flowchart of DAQ_Reader_Client is shown in Fig. 2. On user-defined time intervals, all sensors are sequentially sampled and the recordings are calibrated to correspond to physical units. The resulting measurements are displayed on

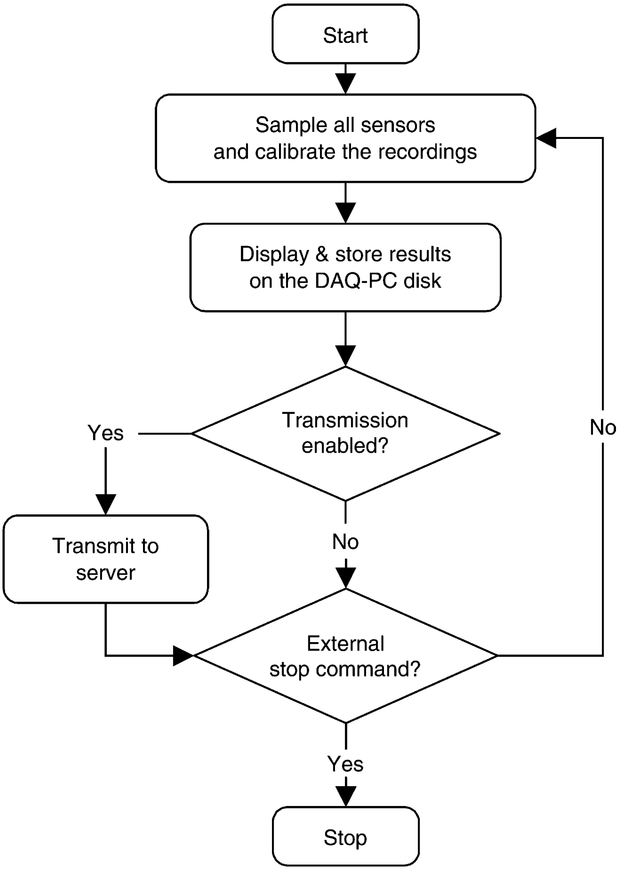

Fig. 2. The DAQ_Reader_Client program flowchart.

the PC screen and stored in text files on local disk for redundancy. The collected data are transmitted in real-time to the DB Server, using either an RF link via the RS-232 serial port of the DAQ-PC or the TCP/IP protocol through an Ethernet connection. The option to transmit the recorded data to the DB Server can be disabled by the system operator. In such a case, the DAQ-PC and DAQ_Reader_Client program comprise an autonomous data-acquisition system.

The communication with the DB Server is performed using a developed communication protocol implementing all the necessary functions, which ensure full and correct interaction with DAQ_Reader_Server. The message format used to exchange information between DAQ_Reader_Client and DAQ_Reader_Server is shown in Fig. 3(a). The field 'NAME' is used to identify the corresponding DAQ-PC, while the field 'CODE' indicates the type of the message, classified according to the message content. The field 'INFO' contains the information to be transmitted, such as the DAQ-PC identification name, an indication for bidirectional communication capability, the active sensors types and calibration coefficients, the sampling period and the sensors measurements. The field

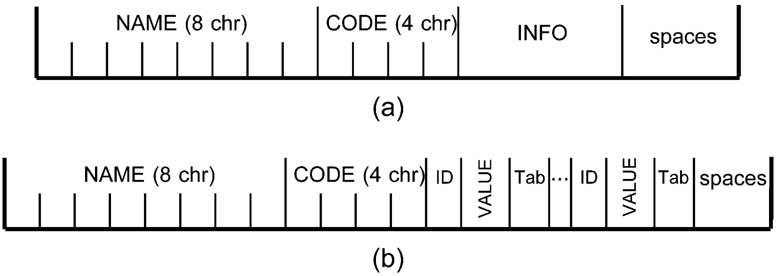

Fig. 3. The communication message format: (a) general message format and (b) message structure for measurements transmission.

'INFO' is of variable length, thus the data packet is filled with spaces in order to retain a constant total message length. The message format used to transmit the sensor recordings is shown in Fig. 3(b). The field 'ID' is the sensor identification number and 'VALUE' is the corresponding measurement transmitted.

A VB module has been developed, applying a Cyclic Redundancy Check (CRC) algorithm on sent and received messages, in order to verify the integrity of the information exchanged between DAQ_Reader_Client and DAQ_Reader_Server.

The DAQ_Reader_Client program provides an easy to use GUI, facilitating the de/activation of sensors and the modification of their IDs and calibration coefficients. Also, a special form has been developed for displaying and modifying the DAQ-PC identification name, the communication port settings and the data storage files path.

3.2. The DAQ_Reader_Server

The DAQ_Reader_Server program, installed on the DB server, is used to receive data from all available RES plants and store them in text files on the DB server. The flowchart of DAQ_Reader_Server program is depicted in Fig. 4. Upon activation, the communication ports are opened and set to listen mode for incoming connections. When a message is received, sent by any RES plant, then the sender information is checked. If that message originated from a new RES plant, then all of its attributes are logged. These consist of the DAQ-PC identification name, the number of active sensors and the sensors sampling period. In case of an incoming message containing sensor recordings, then the measurements included are displayed on the screen and stored in text files together with the time of receipt. The data storage files are named by concatenating the corresponding data-acquisition station name and the current date in the form 'Year-Month-Day'. The first line in the file contains the type of active sensors on the specific RES system. This process is repeated until the user chooses to stop the program, leading to closing all open communication ports.

The DAQ_Reader_Server program is composed by the necessary functions required to supervise and control the operation of the data-acquisition units interfaced to the DB Server. The communication with the DAQ_Reader_Client applications is based on the protocol described in Section 3.1, including messages for starting and stopping the data-acquisition process, modifying sensor calibration parameters and updating the sampling

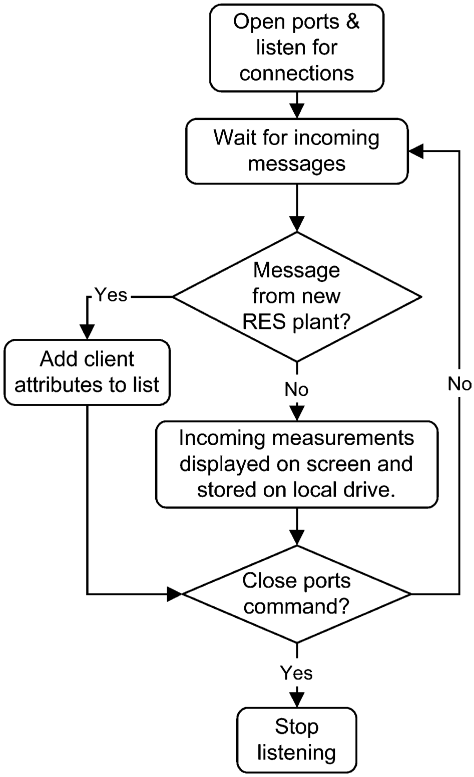

Fig. 4. The DAQ_Reader_Server program flowchart.

period. Thus, the operation of each data-acquisition system can be monitored and controlled from a remote location through the DAQ_Reader_Server user interface. The message structure is the same as that of DAQ_Reader_Client messages, shown in Fig. 3(a). Additionally, a CRC algorithm is applied to all sent and received messages in order to diagnose message integrity degradation because of transmission errors.

3.3. The real-time-insert-utility (RTIU)

The RTIU program, running on the DB Server, communicates with the DBMS in order to insert the RES plants data in the DB, which have already been stored by DAQ_Reader_Server in the corresponding text files. The flowchart of RTIU is shown in Fig. 5. The operational options, loaded at program startup, are defined by the system operator through the RTIU user interface and consist of: (a) the path of the data storage file created by DAQ_Reader_Server for each RES plant registered in the DBMS, including storage devices available through a LAN network and (b) the idle time between consecutive searches of the data files mentioned in (a) for received data, not yet inserted in the DB, thus defining the DB update frequency. At the end of the idle time, all data files corresponding to RES plants are searched for new data. If such data exist in any file, then it

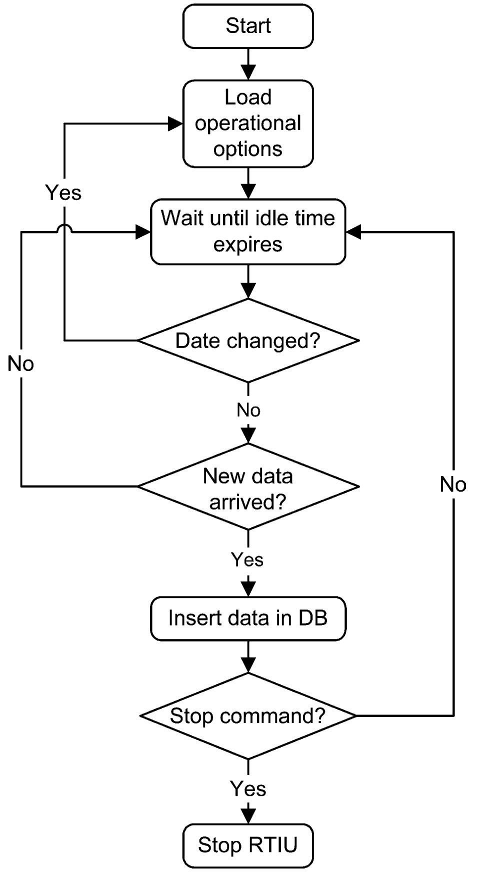

Fig. 5. The RTIU program flowchart.

is traversed line by line and the new measurements are inserted in the DB. For every new set of incoming measurements the system operator is informed about the values of the data inserted in the DB and the RES plant they originate. In case that the date changes, then the RTIU opens the new files created by DAQ_Reader_Server.

The RTIU program communicates with the DBMS using the Structured Query Language (SQL) but this mechanism is transparent to the user.

3.4. The RES-admin-interface (RAI)

Using the RAI program the remote clients connect to the DBMS, installed on the DB Server, in order to process the RES systems measurements. The connection is performed using the TCP/IP protocol over the Internet. An overview of the RAI program features is illustrated in Fig. 6. The remote clients can create charts, calculate statistical and operational parameters regarding each RES plant and perform DB administration actions.

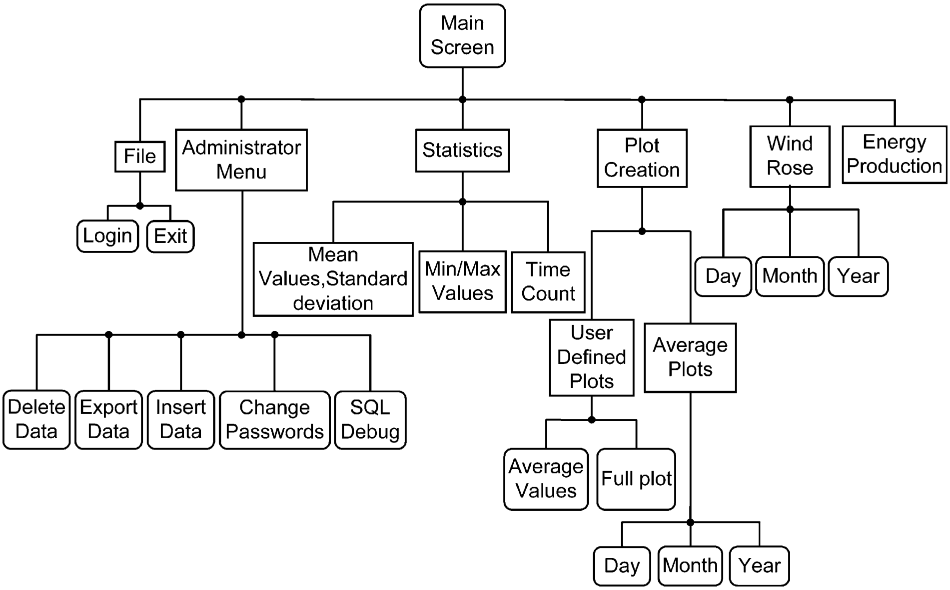

Fig. 6. An overview of the RAI program features.

The user is able to select the plant of interest among the RES systems available and then to process the measurements of any sensor associated with the selected RES plant.

The average value, $\bar{X}$, of sensor measurements falling into a user-defined time interval is calculated using the following equation

$$\bar{X} = \frac{\sum_{i=1}^{N} X_i}{N} \tag{1}$$

where X_i is the ith sensor measurement and N is the total number of measurements during the time interval under consideration.

The standard deviation, s, of sensor measurements over a user-defined time period is calculated using the following equation:

$$s = \sqrt{\frac{\sum_{i=1}^{N} (X_i - \bar{X})^2}{N-1}} \tag{2}$$

Options are available for calculating the maximum and minimum values of sensor measurements during a time period of interest. The user can also request the total time a sensor has recorded values that satisfy certain criteria, such as being above or below a threshold or within a range of user-defined values. In this case, the average value of measurements satisfying the restrictions is also displayed along with the requested time interval.

The total energy, E (kW h), produced from any RES source is calculated using the corresponding output voltage, V_i (V) and current, I_i (A), measurements stored in the DB, as follows

$$E = \frac{\sum_{i=1}^{N} V_i \cdot I_i}{3600 \cdot f_s \cdot 10^3} \quad (3)$$

where f_s is the sampling frequency (Hz).

The RAI facilitates the creation of charts depicting the variation of any sensor's measurements over a user-defined period of time. Two types of plots are available: (a) user-defined plots, where the user can view either the variation of sensor measurements over a selected day, described as full plots in Fig. 6, or the average values of sensor measurements over a user-defined time period with the desired averaging interval and (b) average plots, depicting the hourly average values over a day, the hourly or daily average values over a month and the daily or monthly average values over a year. The option to display the corresponding values from two different RES systems is also available. The full plots are created only over a single day in order to avoid sending a large amount of data to the client, since the RAI is a network-based application and response times have to be taken under consideration. However, full plots for time intervals more than one day can be created offline using the data export option of the RAI and any commercially available software with chart creation features. The RAI program can also be used for the creation of Wind Rose (WR) charts based on daily, monthly or yearly intervals for each RES plant connected to the DB server. All charts can be exported to image and text files for further processing by other programs, such as Microsoft Excel.

To distinguish between users categories of the DB, two account types have been developed. An 'Administrator' account type, providing privileges for complete control over the DB and full access to the RAI operations outlined in Fig. 6 and a 'Guest' account type, prohibiting access to the administrator menu options.

During the insertion process, featured only in the administrator menu options, the new data are checked for values that already exist in the DB and for bad syntax. The data with values within a user-defined range can be deleted by the DB administrator, in case that filtering for erroneous data, such as extreme temperature recordings due to a malfunctioning sensor, is desired. Also, for system debugging purposes, the RAI program facilitates the database engine manipulation by the DB administrator using SQL commands.

The RAI program can be installed either on the DB Server, resulting in a Desktop Database System application, or on a remote client's computer. Thus, two versions with identical operational capabilities but different communication methods between the RAI and the database engine, as analyzed in Section 2, have been developed. Assuming a broadband Internet connection and equally fast DB server and client machines, the version running on the client PCs has shorter response time, since the processing load is distributed between the client PC and the DB Server, instead of being directed to one machine only.

The RAI program includes an error handling function that generates appropriate error messages in case of connection failure.

4. An implementation example

A server database system has been implemented according to the methodology described above, in order to monitor the operation of a hybrid RES system, depicted in Fig. 7, which is installed at the Technical University of Crete (TUC) campus. It consists of a 2 kW nominal power Wind-Generator (WG), two PV arrays having 900 W total nominal power, battery chargers for the WG and PV array, a lead-acid battery bank and DC/AC inverters supplying power to the electrical grid and to a local load. A number of meteorological and electrical parameters are monitored using laboratory-built sensor interface electronic circuits, a PCI data-acquisition card and a DAQ-PC. The parameters measured are: (a) ambient temperature, humidity, atmospheric pressure and global solar irradiation, (b) wind speed and direction, (c) temperature, heat flux and water content of

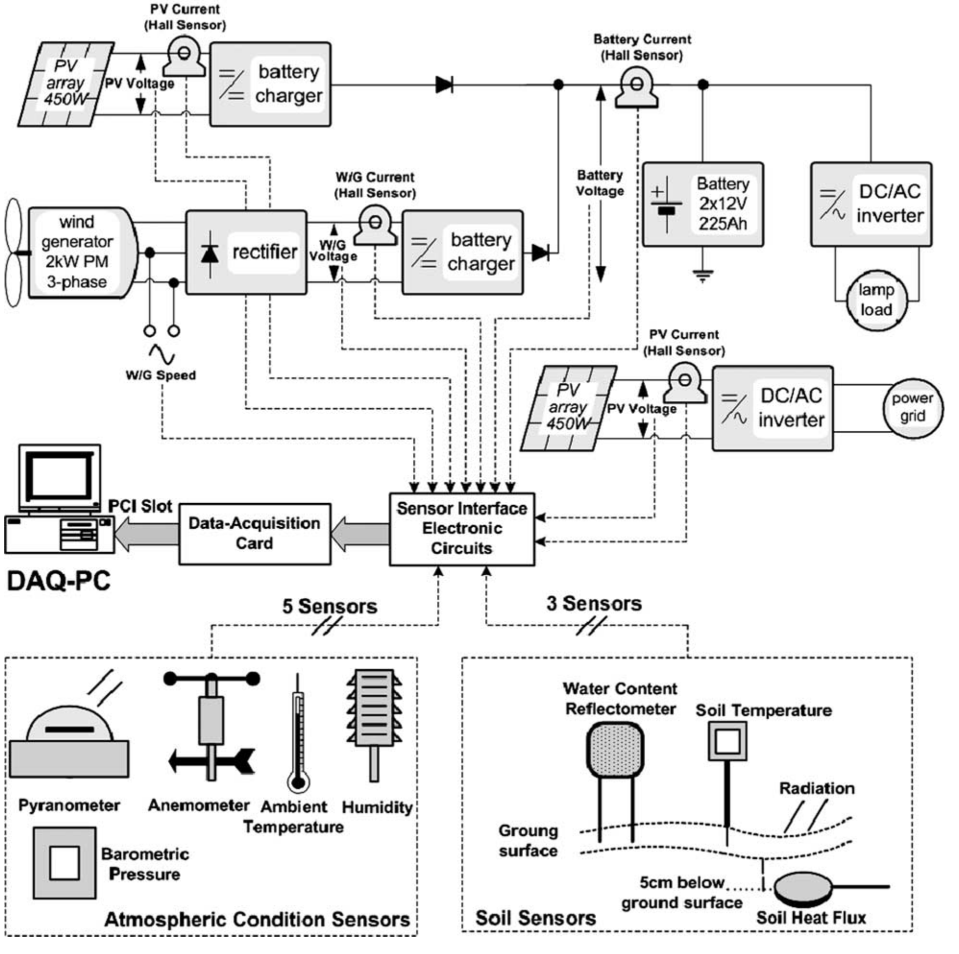

Fig. 7. The hybrid RES plant and data-acquisition interfaces used for testing of the proposed system.

the soil, (d) the wind generator voltage, current and rotational speed, (e) voltage and current of both photovoltaic arrays, and (f) the batteries voltage and current. The DAQ-PC transmits a complete set of the above measured data to the DB Server every 1 min, by means of an RF link. Since the change rate of the measured signals is low, this transmission rate is adequate. The distance between the RES plant and the DB Server unit is approximately 200 m, covered by the RF link. The DB update time interval has been set to 1 min through the RTIU interface.

The DAQ_Reader_Client runs on a desktop PC that uses a Pentium I processor at 133 MHz and 32 Mbytes of RAM under Windows 98. The DAQ_Reader_Server and the RTIU programs run on a PC using a Pentium IV processor at 3 GHz and 512 Mbytes of RAM under Windows 2003 Advanced Server operating system. Finally, RAI runs on a Pentium II processor at 400 MHz and 256 MBytes of RAM under Windows 2000. The system is in use for an extended period of time and it has been tested using both a LAN and a 56 Kbit dialup internet connection and proved acceptable performance.

The DAQ_Reader_Server program interface is illustrated in Fig. 8, while a similar interface has been developed for the DAQ_Reader_Client program. The RTIU user interface is depicted in Fig. 9. The names of the registered RES plants along with the last data packet inserted in the DB are displayed on the screen.

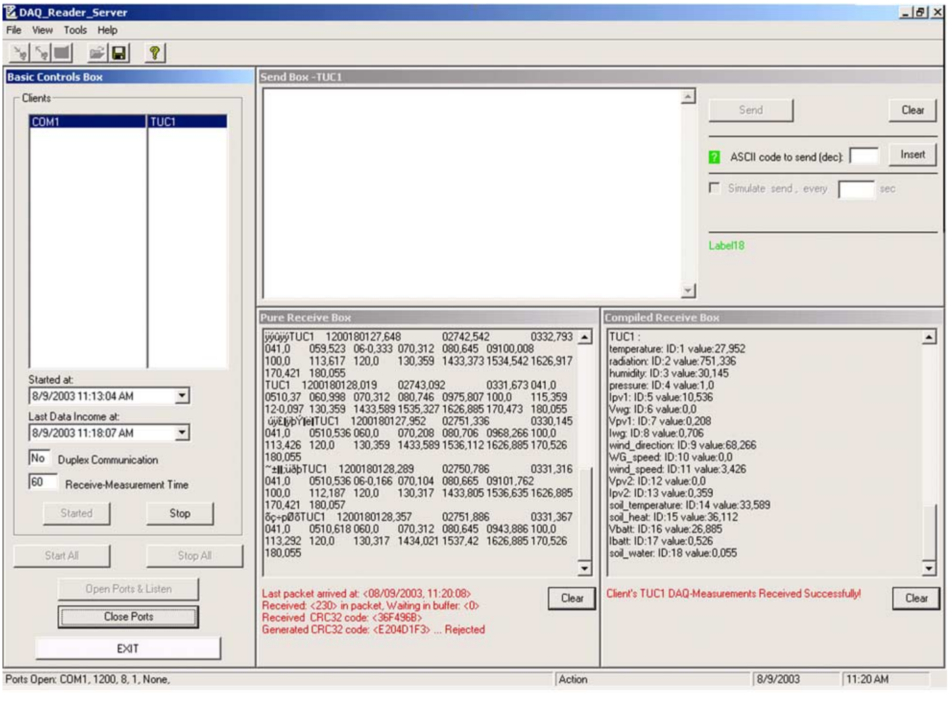

Fig. 8. The DAQ_Reader_Server program user interface.

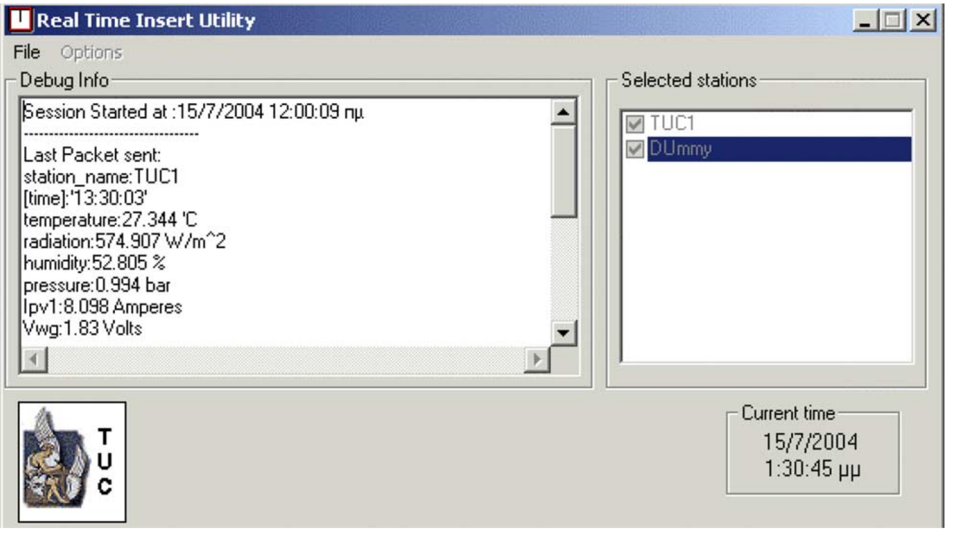

Fig. 9. The RTIU program user interface.

The RAI program statistics calculator tab, depicted in Fig. 10, has been used to calculate the average and standard deviation values of ambient temperature, solar irradiation and humidity, corresponding to the measurements recorded at the RES plant from August 30, 2000 until September 4, 2003. Also, the corresponding results of multiple stations can be displayed simultaneously. The total time that ambient temperature was between 20 and 40 °C, during the same time period, has been calculated as shown in Fig. 11.

The plots of hourly average ambient temperature during April of 2001 and 2002, respectively, are depicted in Fig. 12. The horizontal lines in the plot represent the corresponding monthly average values, indicating an increase by approximately 2.5 °C of the average ambient temperature for the months in discussion.

The wind rose produced using the RAI, indicating the wind profile of the area, is shown in Fig. 13. It can be observed that the winds in the area of interest are mostly of western direction and have speeds that tend to be limited in the range of 3–9 m/s. Such information is valuable in the design of wind energy conversion systems.

The total energy produced by the PV and WG energy sources from August 30, 2000 until September 4, 2003 was calculated using the RAI and it was found to be approximately 1477 kWh, as shown in Fig. 14.

In order to test the database administration capabilities of RAI, data stored in text files were massively inserted in the DB. All erroneous values were successfully detected and logged. The corresponding data insertion form along with the error logging window, are illustrated in Fig. 15. Additionally, data sets can be exported in text files, using the export data form of RAI. The user can define delimiters between the exported data and export

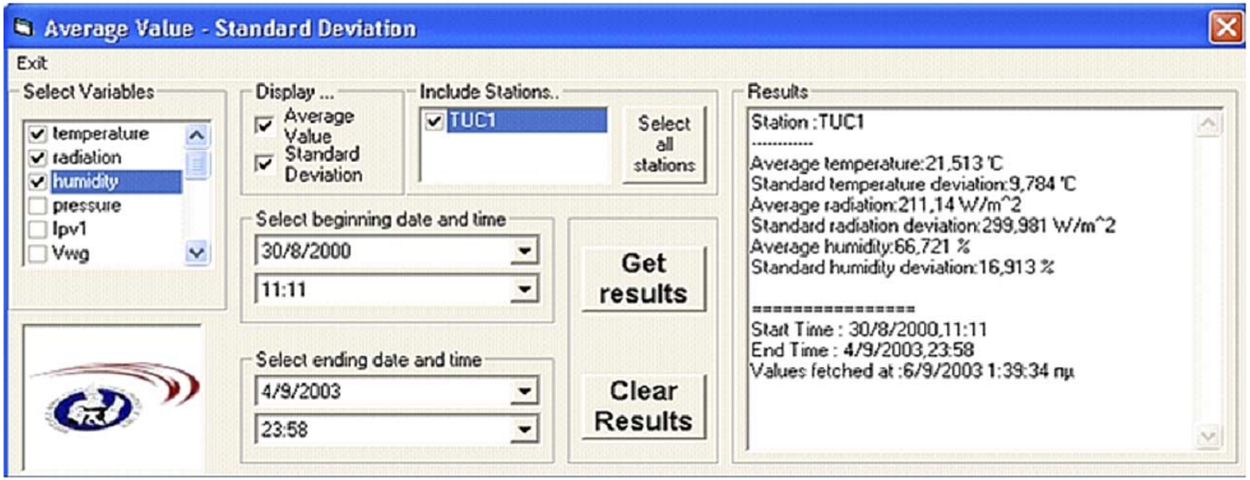

Fig. 10. The average and standard deviation values of ambient temperature, solar irradiation and humidity, corresponding to the measurements recorded at the RES plant from August 30, 2000 until September 4, 2003.

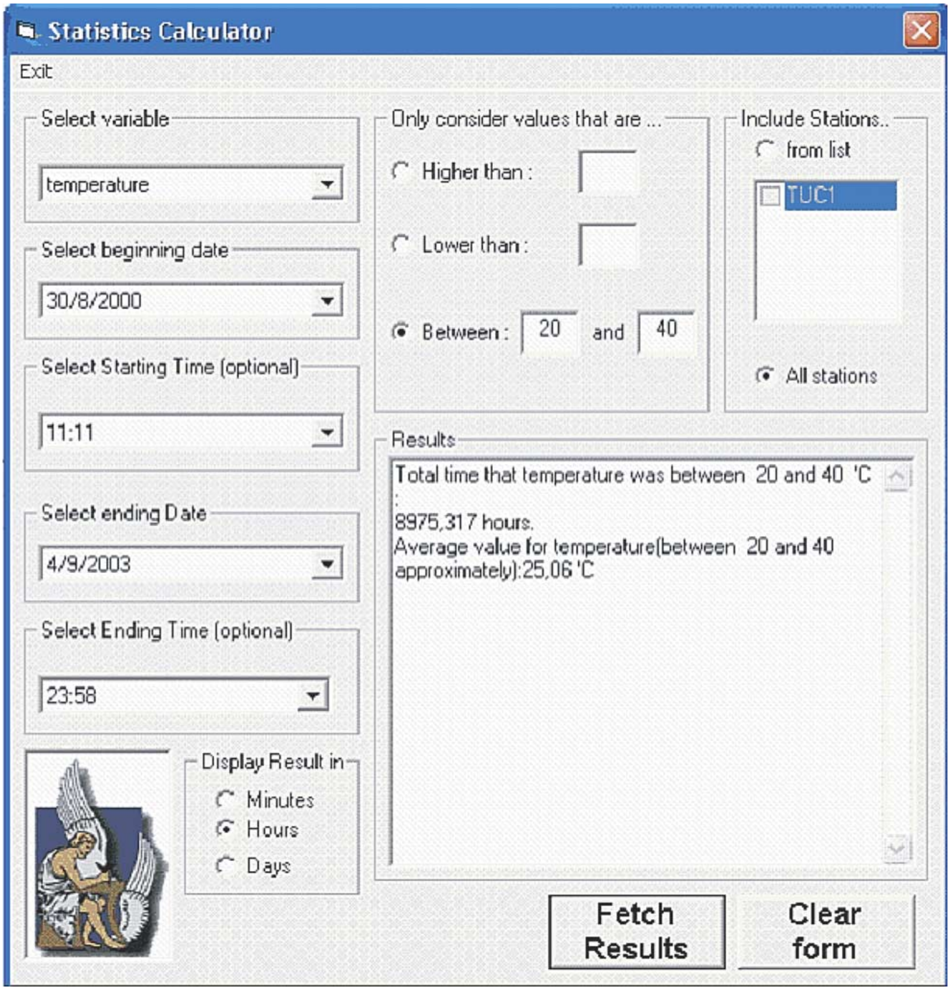

Fig. 11. Calculation of the total time that ambient temperature was between 20 and 40 °C, from August 30, 2000 until September 4, 2003.

measurements with values within a specified range. The resulting text files can be imported in Microsoft Excel for further processing.

5. Conclusions

The development of a server database system for remote monitoring of RES systems is presented in this paper. Meteorological and operational measurements recorded at multiple, remote RES plants are collected by a centralized DBMS in real-time. Remote

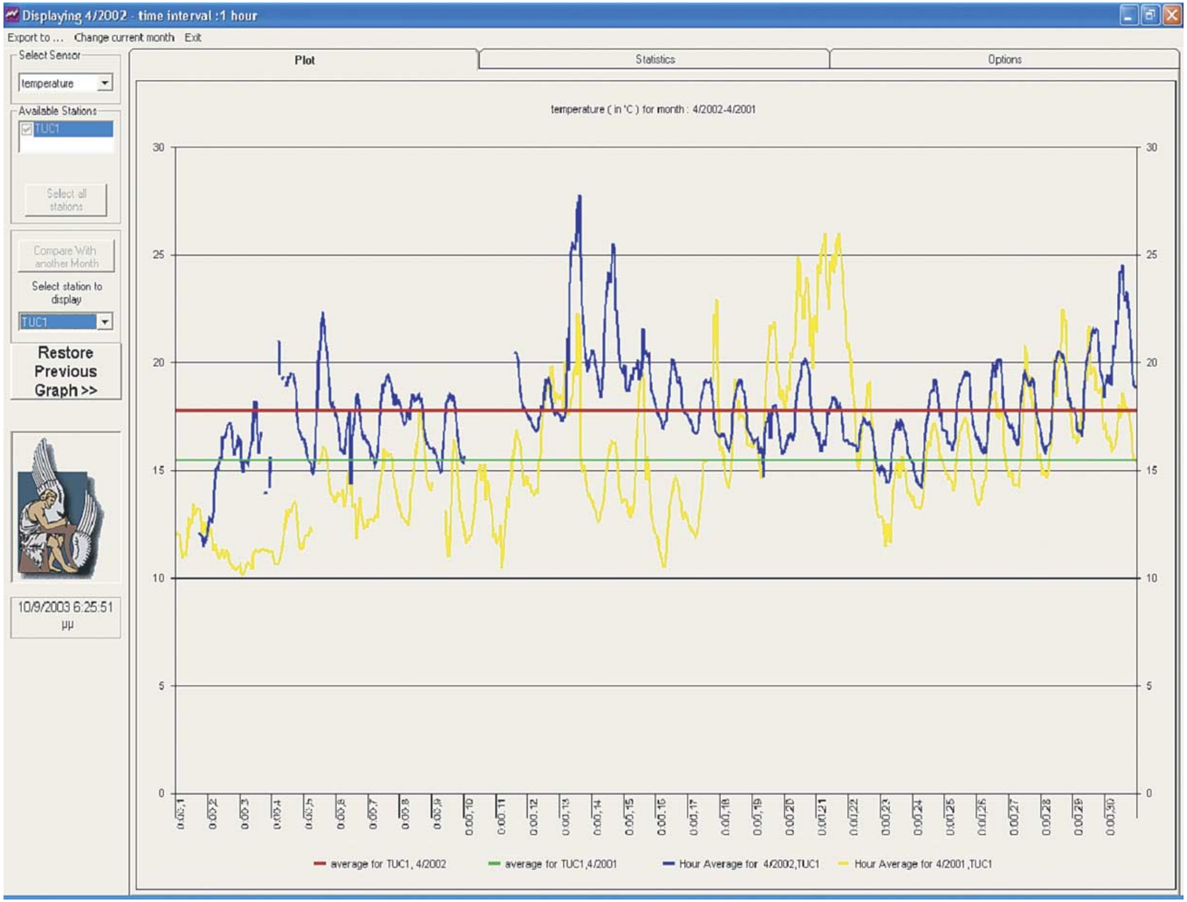

Fig. 12. The plots of hourly average ambient temperature during April of 2001 and 2002.

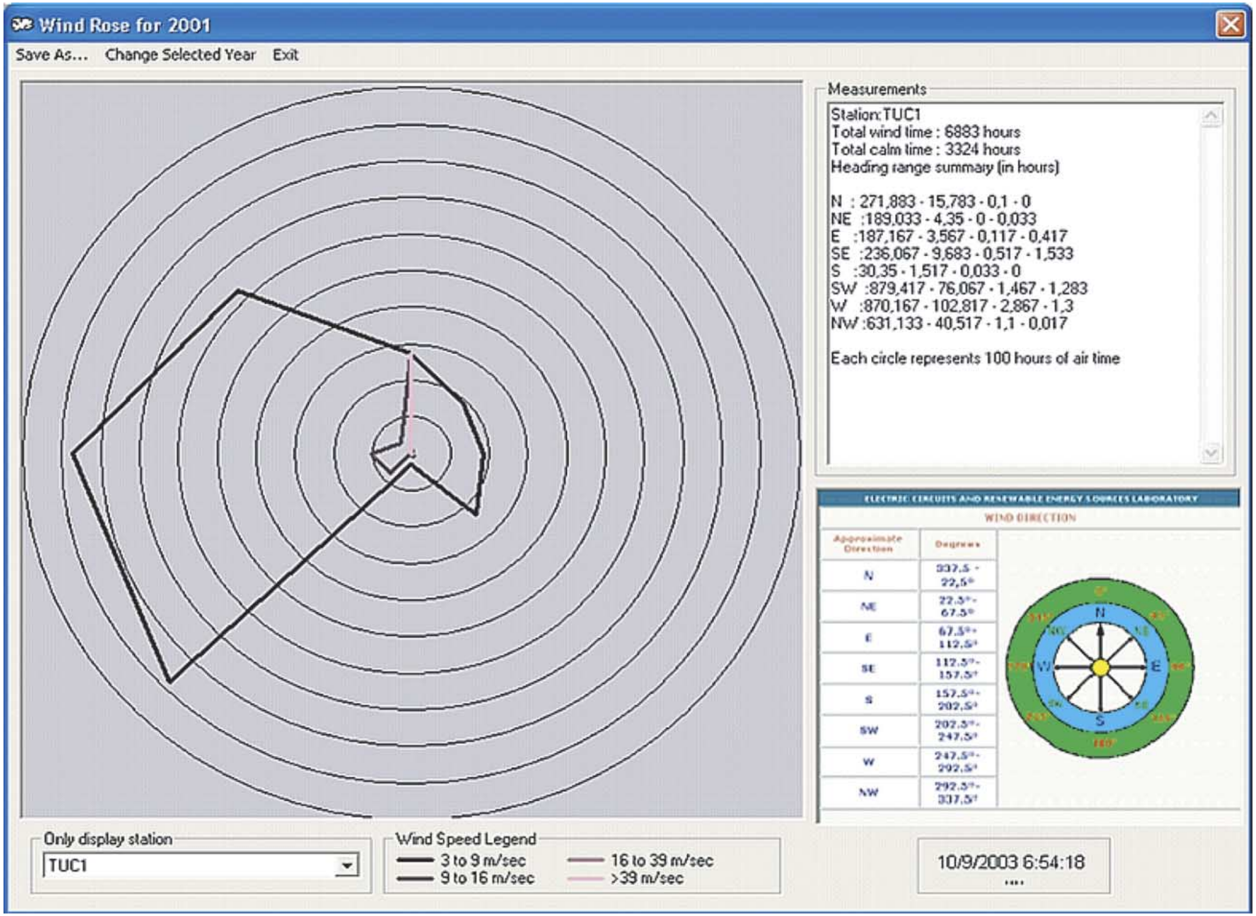

Fig. 13. Wind rose of year 2001 for the area of Technical University of Crete campus.

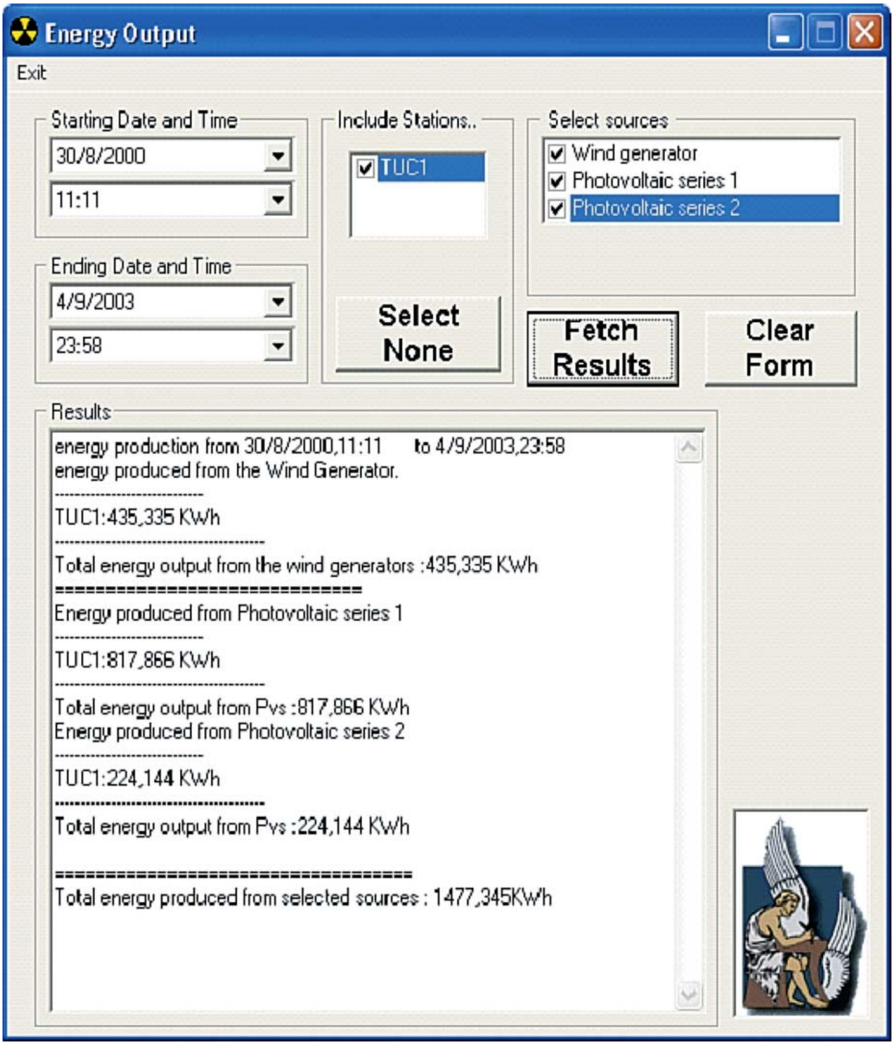

Fig. 14. Total energy production of the RES plant from August 30, 2000 until September 4, 2003.

clients access the DB Server using a properly developed interface in order to create charts, calculate statistical and operational parameters regarding each RES plant and perform DB administration actions.

No special knowledge of any programming language is required for the system operator since all programs functions are based on mouse driven GUIs. The system architecture presented in this paper has been tested using a pilot low-power RES plant but it can be easily adapted to alternative RES plant topologies of any size.

The proposed system can be used for remote monitoring and control of RES plants, development of statistical models describing the spatial variability of RES resources or it

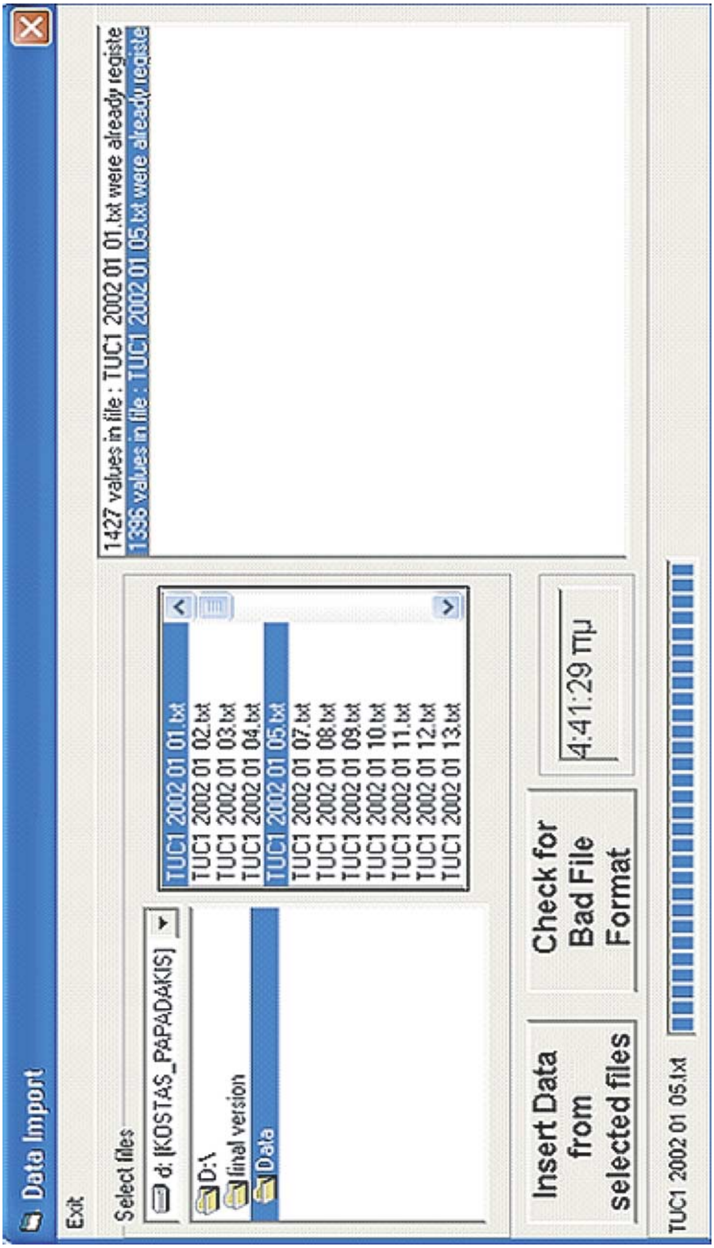

Fig. 15. The data insertion window of the RAI program.

can be incorporated in a Geographic Information System (GIS) [10] supporting the design of RES systems and the development of energy planning strategies.

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