Photovoltaic Solar Conversion Systems for Rural Jordan

Mahmoud S. Audi
Professor of Mechanical Engineering
University of Jordan
Amman, Jordan

Marwan M. Mahmoud
Head, Photovoltaic Division
Royal Scientific Society
Amman, Jordan

SUMMARY

The Royal Scientific Society of Jordan has been designing, installing, and testing photovoltaic (PV) solar conversion systems for rural Jordan for about ten years. There are over twenty working PV electric power systems and eighteen PV pumping systems currently in operation throughout rural Jordan. The power systems supply clinics, residences, mosques, radio beacons, and communication relays. They serve agricultural villages, bedouin communities, and travellers far away from the national electric grid. The paper presents descriptions of these systems along with their design criteria, and reviews some of the problems encountered in establishing these systems, and the experience gained from working on them.

INTRODUCTION

Jordan enjoys more than 3200 sunshine hours annually which is among the highest in the world. The annual daily average amount of solar energy collected at nine stations covering all geographical regions of Jordan is about 6 kWh/m^2 on a horizontal surface [1]. The monthly daily averages, however, vary from about 3.5 kWh/m^2 in January to about 8.5 kWh/m^2 in June. Thus, solar energy is available for long hours and at acceptable levels in Jordan for serious utilization.

Private industries have been in the market for more than two decades manufacturing domestic hot water heaters [2]. These systems are in widespread use throughout Jordan. It is estimated that at least 15 % of the residences of Jordan use solar energy for most of their domestic hot water needs.

The use of solar energy for photovoltaic (PV) conversion, however, is only about one decade old. The Royal Scientific Society (RSS) of Jordan has been pioneering a program to supply electric power to rural areas of Jordan from solar PV systems.

This paper presents the design criteria of photovoltaic conversion for electric power and pumping needs, and a description of the program and comments on the problems which arose as a result of its implementation.

Furthermore, the interest of Jordan in solar energy covers a number of research and application areas. The characteristics of solar radiation and its prediction have been studied thoroughly since 1979 [3,4,5,6]; the development of innovative collectors such as nonmetallic collector plates [7], and flat plates with heat transfer medium trickling on its back [8] have also been studied; and system applications such as solar heating using Jordanian rocks for storage [9] and the performance of a solar refrigeration cycle [10] have been considered. Detailed presentation of the solar and wind energy conversion research and applications in Jordan has been prepared by Audi and Alsaad [11].

DESIGN CRITERIA

The design of a PV conversion system is normally based on a number of parameters and considerations, among which are the following:

(1) The required daily demand load on the system. This load is met directly and through a bank of storage batteries in the PV electric power applications. For the PV pumping systems, it is the electric power needed to run the electric prime mover of the pump directly. No storage batteries are used in this type of application.

(2) The daily average solar radiation and other weather parameters, such as the ambient temperature, at the location of the PV conversion station. Solar radiation is the energy input of the system, and the ambient temperature affects the conversion efficiency of the panels.

(3) The power rating of the available PV panels and the temperature at which the rating is stated. Also, the electric characteristics of the designed electric circuit.

(4) The efficiencies of the various components of the system. This includes the PV conversion efficiency, the converter efficiency, the storage efficiency, the invertor efficiency, and the mechanical efficiency of the pump.

The total daily energy load of the electric power system is computed on the basis of the desired number of hours of the daily operation for each load component.

The load of a pumping system is computed on the basis of the desired daily pumped volume, V in cubic meters, and the head, h in meters, through which it is pumped. Thus, the daily energy input E_h to the water is given by the following equation, provided that both the well and the tank are open to the atmosphere:

$$E_h = \rho g V h \tag{1}$$

where ρ is the density of the pumped water, and g is the local acceleration due to gravity. The density and the acceleration are taken as 1000 kg/m^3, 9.81 m/s^2, respectively.

Thus, the daily energy, in kWh, is given by the following :

$$E_h = 0.002725 \times (V \times h) \tag{2}$$

The yearly average of daily solar radiation, e_s in kWh/m^2, is computed from long term measurements of solar radiation taken at the desired site. In some cases, however, long term measurements are not available. In such cases, short term values and available prediction models (for example references [3], [4], [5], and [6] could be used to compute e_s with reasonable engineering accuracy.

The total daily input solar energy E_{ipv} is given by the following relationship:

$$E_{ipv} = A_{pv} \times e_s \tag{3}$$

where A_{pv} is the net area of the PV surfaces of the panels. But, the rating of a PV conversion panel is stated as a peak power, P_{pv} in W_p, based on a solar radiation, G_o, of 1000 W/m² and a cell temperature of 25°C.

That is, the rating P_{pv} is defined by

$$P_{pv} = \eta_{pv} \text{ x } A_{pv} \text{ x } G_o \quad (4)$$

where η_{pv} is the efficiency of conversion of the PV component of the system [12].

The daily energy output E_{opv} is related to the daily energy input E_{ipv}, thus:

$$E_{opv} = \eta_{pv} \text{ x } E_{ipv} \quad (5)$$

Therefore, the rating of the PV system required for energy output E_{opv} is obtained from equations (3), (4), and (5) as follows:

$$P_{pv} = \left[\frac{E_{opv}}{e_s}\right] \text{ x } G_o \quad (6)$$

The energy output E_{opv} from the PV system required to drive a pump of mechanical efficiency η_{pp} is given by

$$E_{opv} = E_h/\eta_{pp} \quad (7)$$

where E_h is given by equation (2). If an inverter of efficiency eta_{inv} is included, a greater output must be obtained from the PV panels to deliver the desired hydraulic energy and equation (7) must be replaced by

$$E_{opv} = E_h/\eta_{inv}\eta_{pp} \quad (8)$$

The conversion efficiency of the PV system depends mainly on the type of cells used in the panels, the cell temperature and solar intensity, and the age of the cells. The invertor efficiency is in the range of 70 % to 90 % and the mechanical pump efficiency is in the range of 30 % to 50 %. Proper load matching of the components is also important.

The overall efficiency η_s of a system is given by the following relationship:

$$\eta_s = \left(\frac{E_h}{E_{ipv}}\right) \quad (9)$$

APPLICATIONS

The PV systems installed in Jordan cover areas in rural communities from the north and northeast to the south. The installed systems are of two types: the first type is for electric power supply, and the second type is for water pumping. These systems are considered in some detail in the next two subsections.

Electric Power Systems

A block diagram of a general PV electric power system is shown in Fig. 1. It consists of PV panels interconnected in series and parallel in such a way as to give the desired voltage and current; a regulator which controls the charging process of the storage batteries; a bank of storage batteries; and invertors which supply the various alternating current loads of the system with the specific electricity requirements. If the total load of a system is direct current no invertor will be installed.

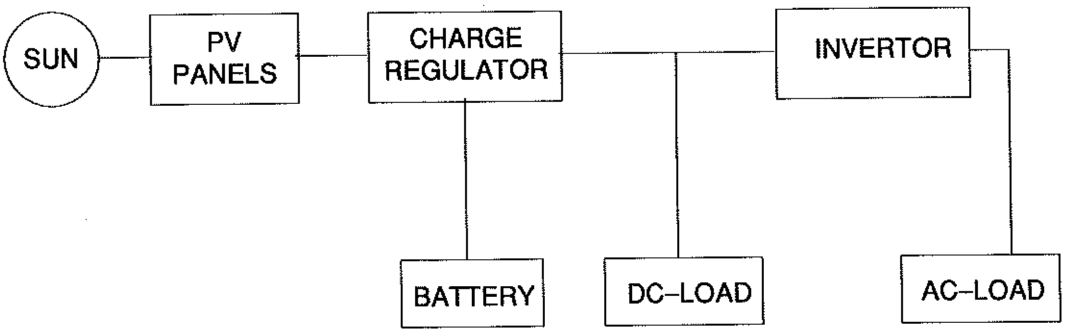

Fig. 1. Block diagram of a PV power system.

All the components are selected on the basis of the design criteria to constitute fully operational integrated systems. A list of the major PV electric power systems installed by RSS is given in Table 1.

Five of the projects serve the residences of male and female teachers of schools in the isolated rural areas of Jordan. The teachers working in these rural areas usually come from the urban centers of Jordan where electricity and water are available. The power needs of these projects are listed in the above table. They are mainly for lights, radios, and televisions.

Three of the systems are for the supply of electric power to mosques. These are mainly for lights, microphones, and loudspeakers.

Six of the systems are for clinics to serve small remote villages and bedouins of the desert of Jordan. The power needed in these clinics are mainly for refrigerators for medicine, lights, and for the operation of small medical tools and instruments. Some of these clinics include residences for physicians, pharmacists, and nurses. One of those clinics (PO-5) has been designed to expand and become a small hospital. It serves villagers, bedouins, and travellers on the nearby highway.

System PO-22 has been designed to operate in conjunction with two 20 kW electric wind generators to supply Jurf El Darawish, a desert village, with most of the electric power it requires.

Two nondirectional radio beacons are served by two of the projects. They serve the air traffic control system at the Aqaba airport. Another two serve as relays for communication between the potash and phosphate companies on one side and their transport fleets on the other side.

Finally, three of the projects supply instrumentation with the required power. One of them is for the data collection at the experimental station at Tal hassan, another is for the control of the

Table 1. PV electric power systems.

System	Type	PV Power (W_p)	Storage (kWh)	Daily Load (kWh)
PO-1	Res	100.0	2.4	0.30
PO-2	Clinic	464.4	7.2	1.30
PO-3	Mosque	120.0	1.2	0.36
PO-4	NDB	2161.6	60.0	6.00
PO-5	Clinic	3072.0	86.4	13.00
PO-6	Res	153.6	3.6	0.60
PO-7	Mosque	120.0	1.2	0.45
PO-8	Mosque	76.8	1.2	0.25
PO-9	NDB	2161.5	60.0	6.00
PO-10	Clinic	537.6	7.2	1.80
PO-11	Relay	2182.0	19.2	6.00
PO-12	Clinic	1344.0	21.6	4.00
PO-13	Clinic	384.4	7.2	1.00
PO-14	Res	100.0	2.4	0.30
PO-15	Res	150.0	2.4	0.40
PO-16	Res	100.0	2.4	0.30
PO-17	Clinic	1072.0	16.8	3.20
PO-18	Insts	364.8	7.2	0.90
PO-19	Relay	1760.0	19.2	4.68
PO-20	Insts	76.8	2.4	0.25
PO-21	Insts	7840.0	176.0	15.00
PO-22	Village	10000	330.0	70.00

Abbreviations in the above table: Res = residence, NDB = Nondirectional radio beacon, Relay = communications relay, and Insts = instrumentations.

instrumentation of the potash skimming machines at the Dead Sea, and the last is for seismographic measurements in the vicinity of King Talal Dam.

All of the people served by the above projects live far away from the national electric grid. It is estimated that at least six thousand villagers, bedouins, and government and company employees benefit from them. In addition, they serve travellers on the southern segment of the national highway and help in the operation of the airport of Aqaba.

Some of these projects replaced diesel engine generators, others provided electric power to communities for the first time in their lives. The PV systems have gained reasonable acceptance and popularity levels among users after initial orientation and adjustment periods.

The PV systems are economically acceptable; they are more reliable during most weather conditions than the diesel engine units which they replaced, they are quieter, and they do not pollute the atmosphere as diesel engines do.

Figure 2 shows the solar power distribution on a typical PV power station (PO-5) and the corresponding power stored during the same hours of the day. It is shown that the power produced by the PV generator is used in charging the battery (E_{iB}) and in supplying the load (E_l). The system

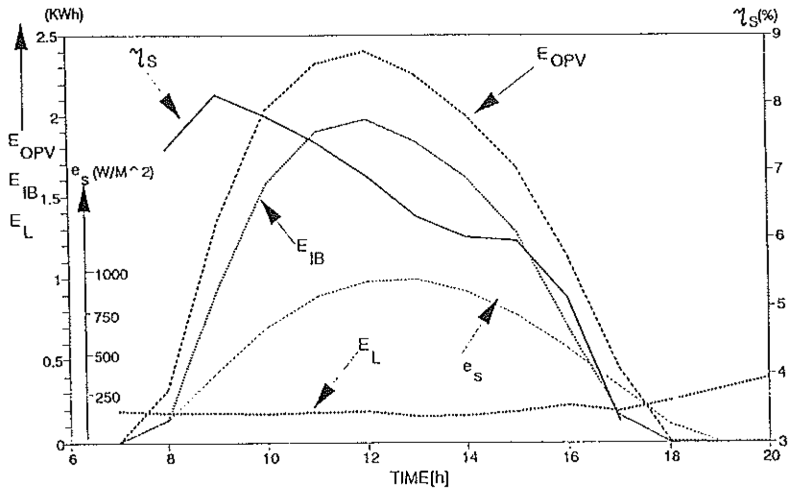

Fig. 2. Characteristics of a PV power system.

efficiency (η_s), as the figure shows, varies with the solar radiation intensity in the range of 3.3 % to 8.1 %.

Pumping Systems

All the PV powered pumping systems installed throughout the eastern and southern deserts of Jordan are identical in their outlooks and in the components which constitute them. A typical system is shown in Fig. 3. Each one consists of PV panels connected in such a way that they supply the desired electric power to an invertor which is connected directly to the motor which runs the pump. The pumps used in these systems are of the submersible type hermetically sealed with their prime movers. A list of these pumping systems is given in Table 2.

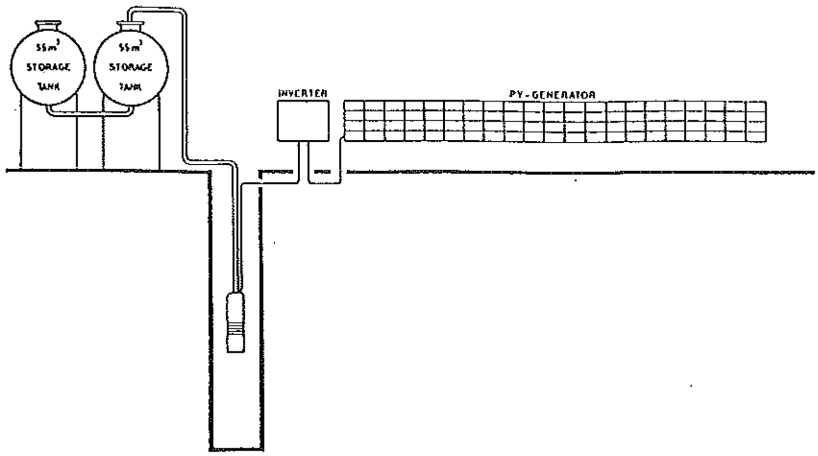

Fig. 3. Schematic diagram of a PV pumping system.

Table 2. PV pumping systems.

Unit	Head (m)	Pump Power (kW)	PV Power (W_p)	Daily Output (m^3)
PS-1	27.0	1.10	1613.0	40.0
PS-2	19.0	1.10	1750.0	55.0
PS-3	19.0	1.10	1656.0	58.0
PS-4	21.0	1.10	1344.0	41.0
PS-5	35.0	1.10	2226.0	40.0
PS-6	12.0	2.20	2150.4	70.0
PS-7	12.0	2.20	2150.4	70.0
PS-8	75.0	3.70	5880.0	40.0
PS-9	51.0	2.20	1800.0	23.0
PS-10	51.0	2.20	3600.0	70.0
PS-11	30.0	2.20	4500.0	99.0
PS-12	30.0	2.20	4500.0	50.0
PS-13	81.0	2.20	6300.0	47.0
PS-14	48.8	2.20	4500.0	54.0
PS-15	53.2	2.20	4200.0	45.0
PS-16	25.0	1.50	2800.0	90.0
PS-17	27.0	12.20	2800.0	66.0
PS-18	45.0	1.50	4200.0	57.0

All the wells were dug by the Water Authority of Jordan (WAJ). Some of them were capped, others had diesel engine direct mechanical coupling pumps installed on them. The pumped water is stored in tanks of 55 m^3 capacity. Some units have one tank, others have two. Water from the tanks fill a drinking trough for sheep and camel herds. Also, there is an overhead mobile filling pipe used for filling small trucked water tanks.

These water stations in the desert of Jordan serve thousands of bedouins and their camels and sheep. Some of the beneficiaries of these systems come from as far as 60 kilometers or more to get their share of the pumped water for their livestock and for their own domestic use.

In a separate study by the second author [13], the economics of PV pumping systems were analyzed. It was shown that for pumping rates, up to about 85 m^3 per day, and heads of seventy meters or more, PV pumping is less expensive than direct diesel engine pumping. Moreover, for pumping at heads of 20 meters or less, PV systems are always less expensive.

Figure 4 shows the solar power distribution, the corresponding hydraulic power and the overall system efficiency throughout a representative day of operation. The overall system efficiency of this particular system (PS-16) is obtained by dividing the hydraulic power by the input power of the PV panels. It is obvious that this efficiency varies very little with the available solar radiation. The component efficiencies, however, include that of the PV panels, the invertor, and the motor pump coupling. These values are in the range of 10 %, 95 %, and 45 %, respectively.

As the figure shows, the system starts pumping at 7:00 am when the solar radiation intensity is under 300 W/m^2 and stops at 5:15 pm when the solar radiation intensity drops to 200 W/m^2.

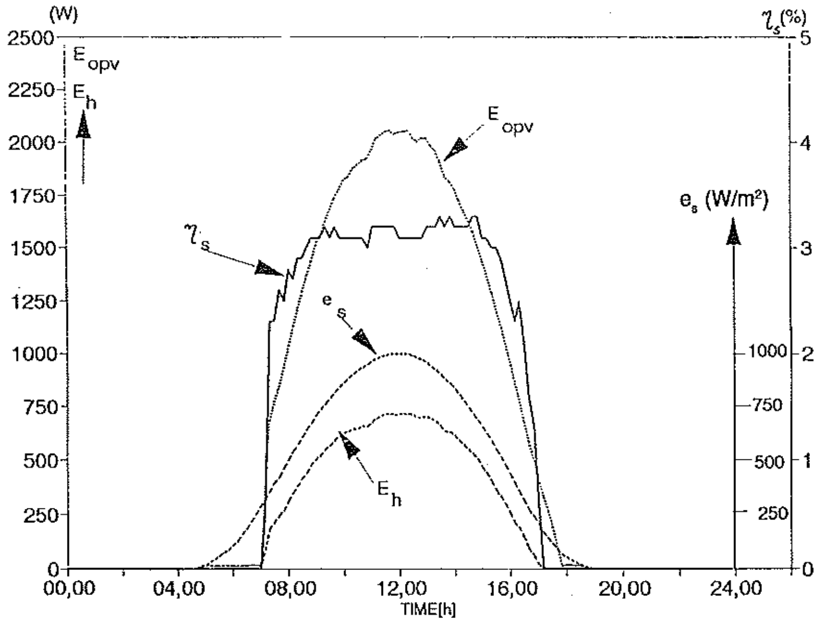

Fig. 4. Characteristics of a PV pumping system.

DISCUSSION

It has been the policy of the government of Jordan to supply its inhabitants with electricity and water wherever they are. Electricity supplied through the national electric grid and water supplied by the many projects of WAJ have reached more than ninety percent of the population. The remainder of the population is found in very small agricultural and industrial villages and bedouin communities spread throughout the desert of Jordan. These are difficult to reach by the traditional means available to urban areas. It is also uneconomical to supply them with electricity from the national grid. The current cost of electric power line installations is about 30,000 US dollars per kilometer. Therefore, these communities could be ideally served by PV system installations. This has been the interest of RSS and the government.

The growth in the number of installations of PV systems in Jordan during the past decade is shown in Fig. 5. The current total installed power is about 96 kilowatts for electric power and pumping. Most of these systems were installed after a short learning period. The beneficiaries from these systems are thousands of bedouin settlers and their herds of sheep and camels, company workers, and school children.

Both the RSS engineers and the end users of the installed systems had to go through an initial learning period. The sizing of a PV system must take into serious consideration the variable nature of solar radiation. Also the sizing of the storage capacity of the electric power systems had to take into consideration this variability and the nature of the application.

Some of the systems included a safety factor of 7.0 in sizing their storage capacities. These systems are those which power the nondirectional radio beacons of the airport of Aqaba. Other systems, such as those for clinics included safety factors of 2.0, and residences included safety

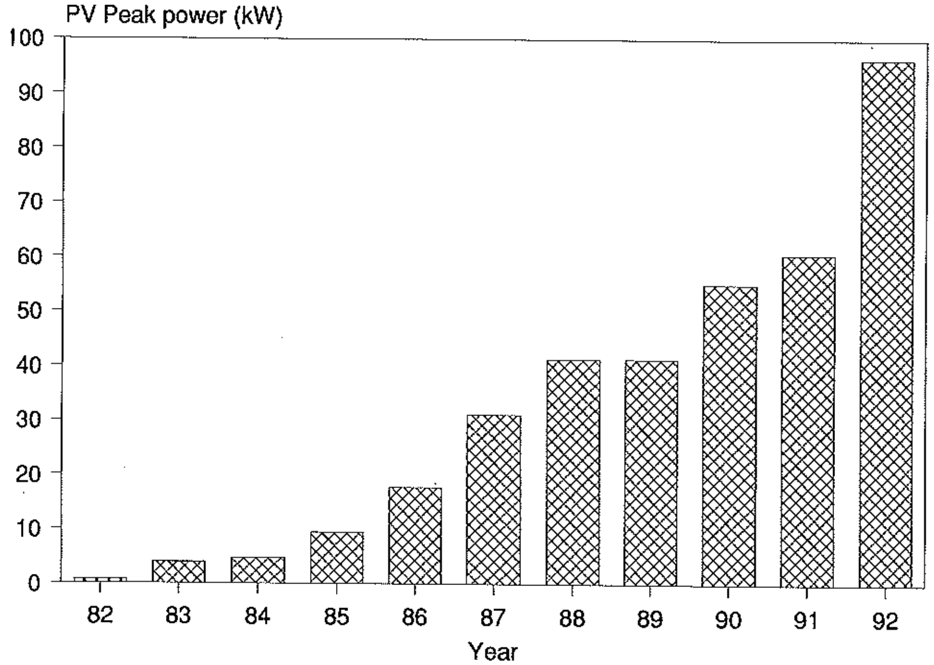

Fig. 5. Growth of a PV installed power in Jordan.

factors of 1.5. The proper estimation and inclusion of these factors in the design is very important as over-sizing of a system may make it economically undesirable and under-sizing may make it unreliable.

The sizing of a pumping system was based on the dynamic water level of the well and the rate at which water is replenished from its basin, and the available solar energy in the installation region. The water storage capacity depends on the daily water consumption level. However, it is either one or two 55 m^3 tanks. The early morning start up of the system took place at a solar radiation intensity of 200 to 300 W/m^2, and stopped in the afternoon when this intensity dropped to a value between 150 and 200 W/m^2. In the early systems, when the storage tanks were filled, water was channelled back to the wells. In the most recent units, the system switches off automatically when the tanks are full.

The problems associated with the users were numerous. Many of them were probably caused by lack of adequate education or inadequate orientation of the users. Continued education of the users by RSS engineers helped in minimizing repeated stoppage of the systems.

An example of a serious problem is the burnout of a large part of a system which was installed to supply electricity for lights, radio, and television to the teachers' residence in one of the rural communities served by the program. This system replaced an old diesel power unit. One night, when the batteries discharged completely, and the lights went out, one of the teachers started the diesel generator and connected it to the PV system supply lines. Consequently, all the lights burnt out.

Other problems include the deformation and subsequent damage of sealed batteries due to excessive heat in the desert, the damage of charge regulators in the early systems due to replacing fuses by normal wires, and the dry-out of batteries due to negligence.

RSS personnel visit each of the systems eight to twelve times a year for periodic maintenance and checking of vital data. For RSS these systems are considered to be pilot projects and will remain under surveillance and study. The technical and economic feasibility of such systems are under continuous review. The daily care, however, is done by the users of the electric power systems and the guards of the pumping systems. This was limited to washing off the dust collected on the surface of the panels.

CONCLUSION

RSS designed and installed all of the systems presented in this paper. However, the components, which include the solar panels and pumps, were obtained from Germany as part of a technical assistance program to Jordan. Additional financing was obtained from the beneficiaries of the systems. In fact, Germany has been involved in the renewable energy program of RSS since the early seventies when the first author was the director of an RSS solar desalination project. RSS has also joint renewable energy projects with some Arab countries.

The systems installed in rural Jordan, and others which may be installed as the current installations gain popularity and the word spreads among villagers and bedouin communities of the benefit of these systems, do in effect help the Jordanian government in its resolve to supply all Jordanians with electricity and water. It is obvious that people in these communities do not have the resources to invest in such systems, and the current market is inadequate for free enterprise to get involved.

As a result of the experience gained from the current projects, it is believed that education about renewable energy utilization must be stepped up at the national level through the mass media and educational institutions. Also, proper orientation and training programs must be conducted to help the end-users take care of the systems installed for their well-being.

Some of the components are already designed by RSS engineers. Joint venture programs with German and other European firms may become necessary to help Jordan develop an industry in this field. Such an industry would have markets beyond the borders of Jordan.

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