DESIGN AND DEVELOPMENT OF A STAND-ALONE POWER SUPPLY FOR A SMALL INDUSTRIAL CONTROL SYSTEM

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Abstract *— Design and development of a stand-alone power supply (SAPS) system in remote area, where grid electricity is not available, to continuously powering the process control, monitoring and communication equipment (which constitutes the control system) associated with a diesel-powered borehole pump installation is presented. The study site is located at Oaky Creek No. 1 Coal Mine near Tieri in Central Queensland, Australia, which is a remote area where there is no access to grid electricity; therefore a source of alternative energy generation is required. A stand-alone power supply using photovoltaic (PV) generators as the energy source was chosen and implemented because on a small scale, PV installations have the characteristics of competitive cost, low maintenance, high reliability and long system life. Methods of sizing and dimensioning system requirements are presented. The performance of the proposed system is simulated using simulation programs known as HOIMER and PVSYST. Equipment for the real life performance measurement was chosen from the local market, installed, commissioned and tested to verify the success of the design method. The results of the simulation verified the sizing design allowing the correct components to be selected with confidence.*

Keywords — power supply, control equipment, remote area.

INTRODUCTION

Large industrial equipment installed in remote locations, where grid electricity is not readily available, can be powered economically by using a diesel generator energy source. This is particularly beneficial for powering large loads such as electric motors and other equipment for installations including pumps and air compressors. During stand-by periods the large diesel generator is shutdown and the system often has no power source apart from batteries for the purpose of cranking and starting the generator set. Traditionally this equipment has been started manually and monitored by periodical inspection to ensure successful operation. The control strategy for grid connected production equipment differs from the remote installation by the level of automation used. The use of a program logic controller (PLC) and subsequent peer-level and higher-level data acquisition and information management platforms (such as supervisory control and data acquisition (SCADA) and manufacturing execution system (MES)) provide significant benefits including remote and automated control, monitoring and data analysis of the industrial system. The stand-alone power system provides continuous (or very high availability) power for the process control, monitoring, and wireless communication equipment, which forms the industrial control system. This allows an installation to be installed in a remote location yet be integrated transparently into the site-wide control system. Since the loading of the control system electronics are very small, a stand-alone power system using renewable energy generators can be economically achieved. The diesel generator is still required to run the large intermittent loads, such as motors, as it would be considerably uneconomical to run these loads from renewable sources.

This paper focuses on the particular requirements of a practical stand-alone power supply to be installed at Oaky Creek No.1 Coal Mine near Tieri in Central Queensland, Australia. The proposed installation site includes a large diesel generator, 150 kW electric motor and borehole pump. A conventional industrial control system is implemented in the pump control enclosure. Figure 1 shows a block diagram of the major system components including the industrial drives (pump, motor and generator), control system enclosure and the stand-alone power system. The stand-alone power system supplies direct current (dc) power to the control system. The control system is responsible for controlling and operating the installation including monitoring of system variables, start/stop initiation of the diesel generator, and operation and monitoring of the electric borehole pump motor.

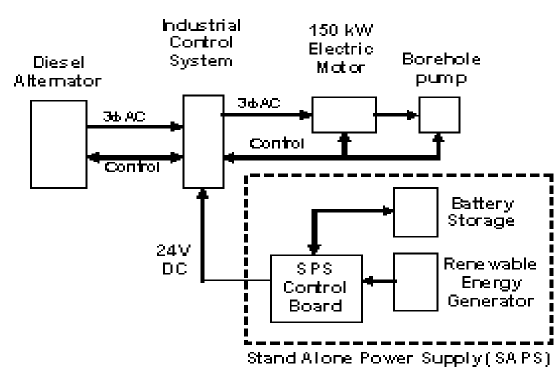

FIGURE 1
BLOCK DIAGRAM OF BOREHOLE PUMP SYSTEM AND STAND ALONE POWER SYSTEM

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SYSTEM SCHEMATIC AND METHODOLOGY

Since the industrial control system is small scale with an average loading of 1.2 kWh/day, the photovoltaic (PV) generators was chosen as a source of renewable energy. A dc only implementation is achieved in the design, which eliminates the need for an ac inverter. This has significantly increased the power conversion efficiency of the SAPS and reduced size and cost of the required system. Figure 2 shows the schematic of a typical PV-Diesel SAPS hybrid system [1]. Table 1 summarises the main component categories.

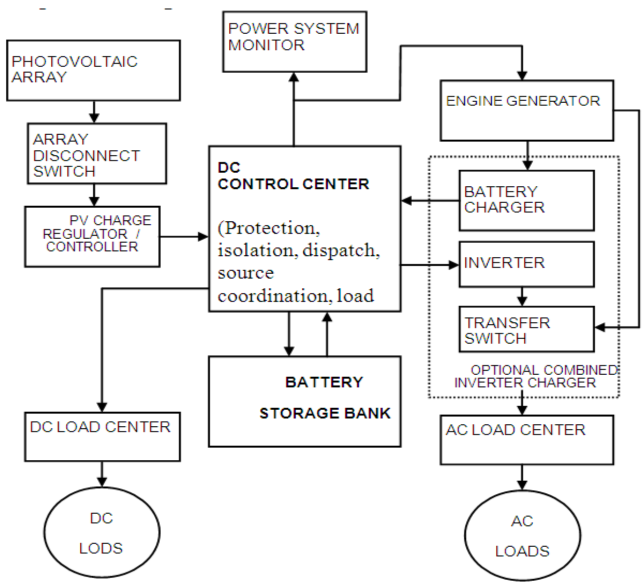

FIGURE 2
A TYPICAL PV-DIESEL SAPS HYBRID SYSTEM

TABLE 1
MAJOR COMPONENT CATEGORIES

Generation equipment	PV array Engine generator
Power conditioning equipment	PV charge regulator Battery charger Inverter
Energy storage	Battery bank
Control, monitoring & metering	Relays, contactors & transfer switch (Dispatch/source coordination, load disconnect, alarms and fault indication/protection) Metering, data recording & display
Isolation & protection	Fuses, circuit breakers, disconnect switches, system earthing, equipotential bonding, lightning protection

The Australian Standards Association methods outlined in AS4509.2 [2] and other applicable Australian Standards were used to determine system sizing and other requirements. Two simulation programs were used to confirm the sizing methods used, and to demonstrate the expected operation throughout the year. These are HOMER [3] and PVSYST [4]. Equipment was chosen based on an assessment of the suitability and cost of available technology versus requirements of the project design. Suitable equipment for the project was chosen and installed at the experimental test site for the purpose of testing and monitoring of system performance and verification of system design. System monitoring was performed using discrete analogue transmitters connected to the control system PLC. The CitectSCADA computer monitored and logged the PLC variables. The variables included system (battery) voltage, PV current, battery current and load current. From this data the operational characteristics and system performance were assessed and verified.

SYSTEM SIZING AND DESIGN

Solar Resource Data

Meteorological data is readily available as average daily irradiation (kWh/sq.m/day) on the global (horizontal) plane, for each month of the typical year. Figure 3 shows the climate data for Emerald from the Australian Bureau of Meteorology [5]. Emerald is bureau of meteorology (BOM) station near to case study site.

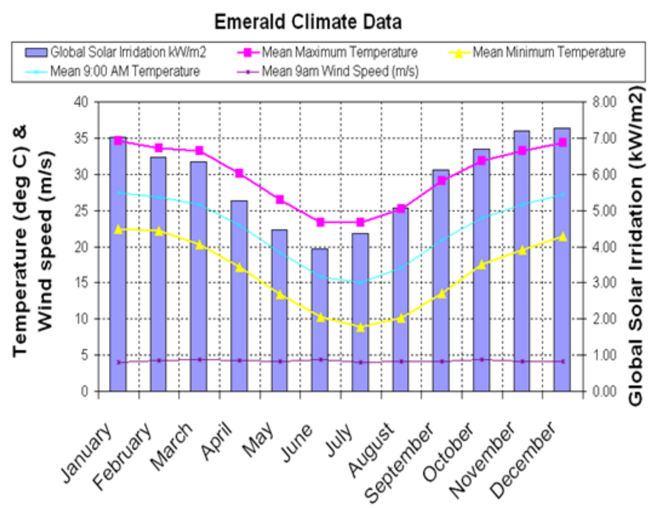

FIGURE 3
AVERAGE CLIMATE DATA FOR EMERALD [5]

Solar Irradiation on the PV Module Surface

Methods of converting irradiation from horizontal to incident on the plane of array (POA) were used. The pre-feasibility program RETScreen [6] was used to convert horizontal to POA irradiation. Generally, the total solar radiation on a tilted surface is calculated by adding the beam and diffused components. The beam irradiation incident upon the array can be determined using geometrical techniques described in Wenham *et al* [1] and Yang *et al* [7]. The diffuse component can be assumed to emanate from the entire sky dome and thus can be approximated as being independent of POA (for small tilt angles). More complex diffuse models account for circumsolar, horizontal brightening and isotropic diffuse radiation [8]. The clearness index can be determined by comparing the monthly average site irradiation with the theoretical clear sky site irradiation. A tilt angle of 30^o, with an azimuth of 0^o was implemented for this installation. By using a tilt angle slightly larger than the latitude angle of 23^o, the incident winter irradiation is increased. Using the tilted array significantly flattens the available monthly irradiance reducing the size of the required system. Figure 4 shows the daily solar irradiation for a tilt angle of 0^o and 30^o, the clearness index is also shown.

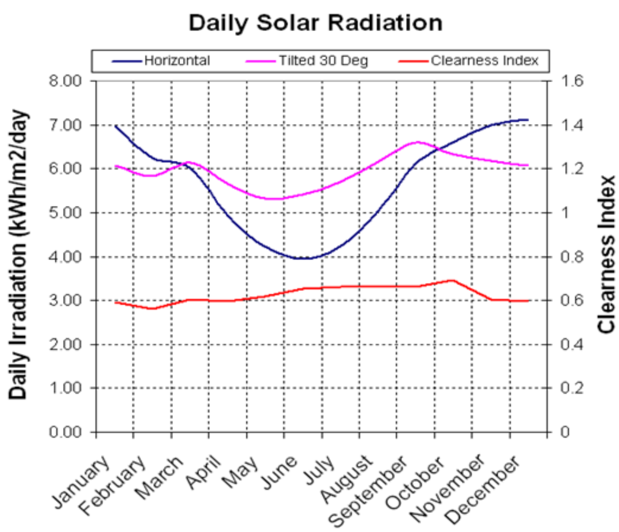

FIGURE 4
DAILY SOLAR RADIATION FOR TIERI – HORIZONTAL, 30DEG. TILT AND CLEARNESS INDEX

PV Array

Mono-crystalline silicon cell technology, used in this study is mature, radially available and offers high conversion efficiency. Two flat plate PV modules of fixed orientation and tilt were used to satisfy the design requirement. The modules had the following characteristics: Peak output power 170W; Short circuit current 5.23A, and Open circuit voltage 43.9V. Array current output was determined at the fixed voltage operating point on the module IV response curve. The operating point, set by battery voltage, was in the approximate range of 24 to 28.8V. The response curves for the PV module used were modelled in PVSYST [6]. The calculations for nominal operating cell temperature (NOCT) can be used to determine PV cell temperatures [9]. The single diode model and subsidiary temperature models determine the IV curve. Increasing the cell temperature has the effect of moving the knee of the response curve closer to the operating point. This reduces the current yield slightly during summer with increasing temperature. An approximate temperature of 25^o C above ambient is common for the site location. The two panels can produce approximately:

- 54Ah/day during winter (5% oversize)
- 64Ah/day in September (24% oversize)
- 60 Ah/day annual average (16% oversize)

This satisfies the required array output of 51.6Ah/day, made up of 50Ah/day load consumption and 1.6 Ah/day battery coulombic charging efficiency loss.

Battery Storage

Valve regulated lead-acid (VRLA) battery technology with gelled electrolyte immobilisation offers significant improvements in available capacity, reduction in dangerous hydrogen gas production and reduced maintenance requirements. A battery bank of 330Ah capacity at 24V was implemented, based on a load consumption of 50Ah/day, five days of autonomous operation, a maximum depth of discharge of 80% and a temperature compensation factor of 96% to account for the small loss of capacity experienced during winter. Batteries are segregated from the remaining system by their own enclosure. The risk of fire or explosion from hydrogen gas produced during battery charging is thereby minimised. Ventilation exceeding the required rate was provided to ensure that hydrogen build-up is minimised.

Power Conditioning

Power conditioning was achieved using a series pulse-widh modulation (PWM) constant potential regulator including display meter, serial Modbus communication of internal data, and control of auxiliary relays. The current rating of the regulator was chosen to exceed 125% of the short circuit current rating of the array. A supplementary mains-powered battery charger was chosen to supplement the system during periods when the large diesel generator was running. The control system was designed to minimise power consumption during standby, and therefore its implementation has achieved a reduction in the required SAPS system size. The battery charger also acts as a back up in case of excess battery discharge. A low system warning can initiate the start request of the pump system, thus allowing the diesel energy source to charge the SAPS batteries.

RESULTS AND DISCUSSION

Simulation programs operate on an hourly time step instead of the daily average values used for the sizing techniques. Synthetic data was generated from the daily averages using statistical variance techniques to convert the monthly average meteorological climate data to representative beam and diffuse irradiance components for each hour of the typical year. Figure 5 shows the simulated daily values of horizontal global and horizontal diffuse irradiation from PVSYST. Incident irradiance on the plane of array (POA) was calculated for each hourly time step based on the suns position in the sky relative to the POA, and the irradiance intensity from the simulated data. The PV array response

was determined by the single diode model and subsidiary cell temperature models. Array and other system losses were calculated and applied to determine the system energy production. Once the array yield was known, the energy flow to and from the battery was modelled to determine the storage characteristics including voltage and state of charge (SOC). The ability of the battery to maintain favourable SOC determines the system ability to meet the load demand.
Table 2 summarizes the system gains and losses associated with the PV installation. The losses show the reduction in yield from the rated peak wattage output of the array at standard test conditions (STC). The system losses become quite significant, and if not considered fully, would lead to an overestimation of array yield and poor determination of system size. Figure 6 shows the production and loss factors as monthly percentages of the theoretical maximum output. This diagram graphically summarizes the losses listed in Table 2. The monthly average electric production of the PV array is shown in Figure 7. It can be seen that the tilt angle has produced consistent year round energy production. Table 3 summaries the system performance values.

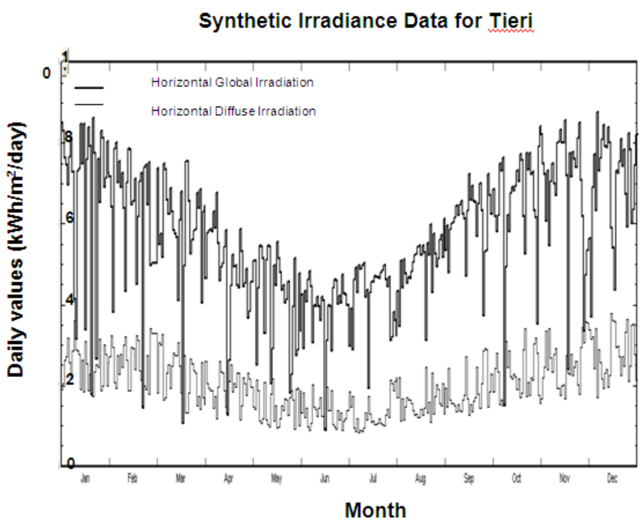

FIGURE 5
SYNTHETIC IRRADIATION DATA FOR TIERI FROM PVSYST

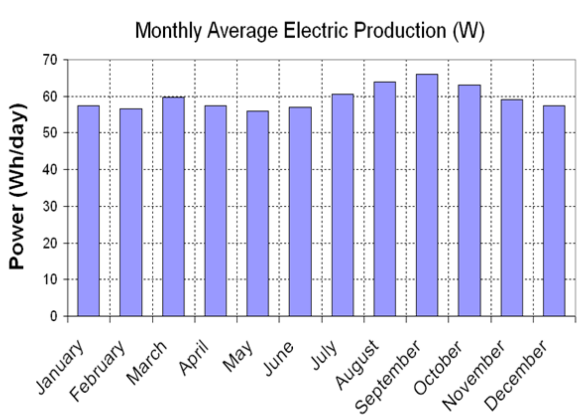

FIGURE 6
NORMALIZED PRODUCTION AND LOSS FACTORS [4]

TABLE 2
ARRAY AND SYSTEM GAINS/LOSSES

Description of loss	Percentage
Incident irradiation on tilted plane (30°)	+ 5.5%
Incidence angle modifier (IAM) reflection losses due to incidence angle	- 3%
Efficiency loss (reduced efficiency from STC due to reduced irradiance levels)	- 2.6%
PV operating temperature	- 9.5%
Array soiling loss	- 10.6%
Module quality loss (manufacturers tolerances)	- 2.3%
Module array mismatch	- 3.1%
Ohmic wiring loss	- 0.5%
Loss by operation away from the Maximum power point	- 9.5%
Unused energy (full battery loss)	- 6.6%
Battery efficiency loss (gassing and self discharge)	- 6%
Total	-48.2%

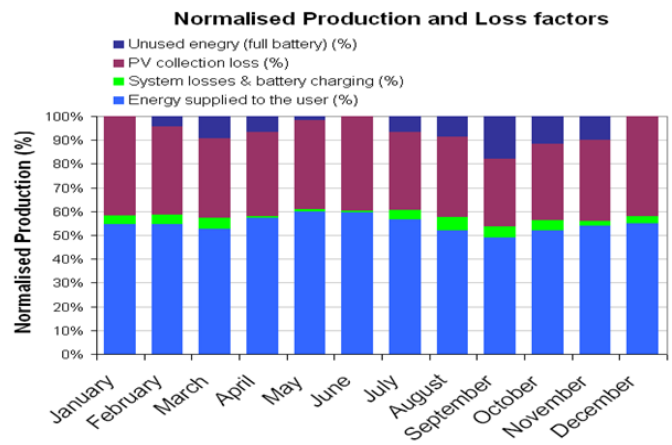

FIGURE 7
MONTHLY AVERAGE ELECTRIC PRODUCTION PER DAY

TABLE 3
SYSTEM PERFORMANCE SUMMARY

Quantity	Value (Units)	Percentage
Total PV array production.	521 kWh/year	100
Mean PV output	144 kWh/day	
Total dc load consumption	438 kWh/year	84
Mean dc load	1.2 KWh/day	
Excess electricity from PV array	83 kWh/year	16
Battery losses	59 kWh/year	10
Unused electricity	24 kWh/year	4.6
Battery nominal capacity	7.92 kWh	
Battery usable capacity	6.34 kWh	80
Autonomy	127 hr	
Battery energy in	307 kWh/year	100
Battery energy out	247 kWh/year	80
Direct use	162 kWh/year	37
Stored	276 kWh/year	63

The statistical analysis of the state of charge (SOC) revealed that, it is above 40% throughout the year and has a characteristic semblance to electricity production curve.

The system was monitored to determine the system performance and to verify the success of the design process. Figure 8(a) shows the results of the system monitoring and Figure 8(b) shows the simulated results on system monitoring from PVSYST. A close correlation between the actual and simulated data is observed which acts to validate the design. The baterry voltage shows a favourable state of charge response characteristics which also indicates successful system design.

Figure 9 indicates the clear sky performance for one day (27/09/08). The bulk and absorption charging stages are shown by the response of the voltage and current. During the early part of the day; the bulk charging occurs, the PV array is directly connected to the battery and load, the fixed voltage operating point is equal to the battery voltage and the current flow from the array is close to the maximum available (short-circuit current). As the incident solar irridiation increases during the day, the current rises (resembling a sinusoid under clear sky conditions) and the system voltage rises indicating that the battery is accepting charge. Once the regulation voltage is reached, absorption (fixed potential) charging occurs, the charge regulators regulate the array output voltage at the fixed potential regulation set-point and the charging current reduces so that the voltage is maintained at the fixed potential set-point. During the evening, the battery voltage falls due to discharge.

A clear sky irridiance of approximately 10.5 amps at peak irridiance (solar noon) was obtained in October, which compares favourably with the array short circuit current at STC of 10.46 amps.

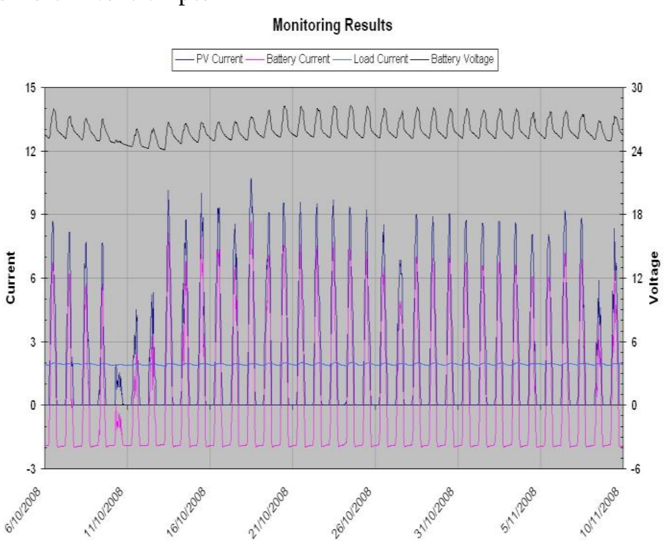

FIGURE 8(a)
MONITORING RESULTS FOR 1 MONTH

CONCLUSIONS

This study successfully designed and developed a stand-alone power supply (SAPS) to power a small industrial control system associated with a diesel-powered borehole pump installation. The results of the simulation verified the sizing design allowing the correct components to be selected with confidence. The Australian Standards were useful in determining a wide range of installation requirements including protection, isolation and arrangement of system components. This helped to ensure that high levels of safety, serviceability and reliability were achieved in the design.

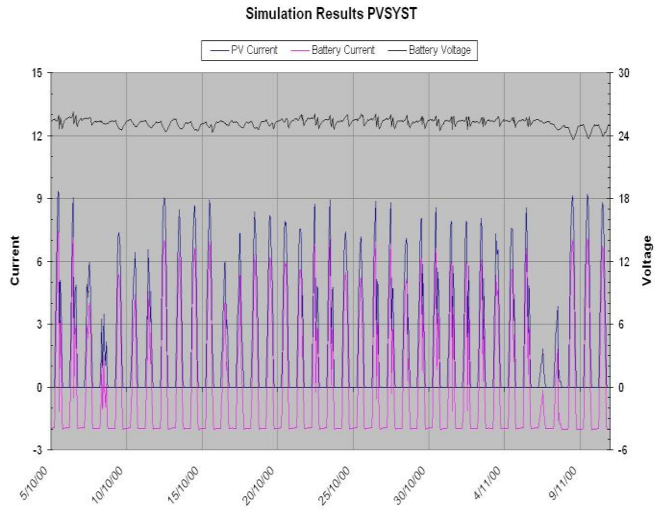

FIGURE 8(b)
SIMULATED RESULTS FOR 1 MONTH

Significant losses were apparent in the determination of array and system requirements. An accurate assessment of the implications of these losses ensured that a suitably sized system was implemented. The system monitoring results proved that the implemented design was successful. The system was able to continuously supply the expected loading whilst maintaining suitable operational characteristics including battery state of charge. The correct charging modes of operation were observed by the system monitoring.

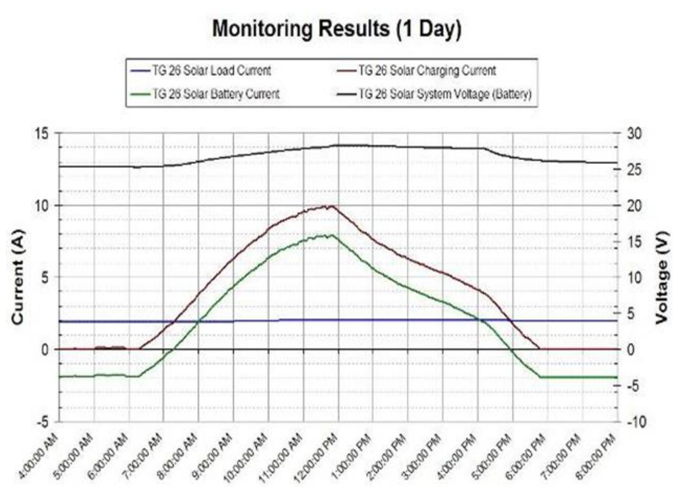

FIGURE 9
MONITORING RESULTS FOR ONE DAY (27/09/2008)

The successful implementation of this project has proved that a conventional industrial control system can be implemented for diesel-powered equipment in isolated locations. Future installations can be designed to utilise the same principle thereby eliminating the need, and prohibitive cost, of grid infrastructure in the isolated location. The increased flexibility and potential mobility of the implemented system is also apparent in this system design.

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