ENERGETSKI EFIKASNO NAPAJANJE AUTONOMNIH POTROŠAČA KORIŠĆENJEM HIBRIDNOG (FOTONAPONSKOG I DIZELAGREGATSKOG) IZVORA

ENERGY EFFICIENT POWER SUPPLY OF AUTONOMOUS CONSUMERS USING HYBRID (PHOTOVOLTAIC AND DIESEL AGGREGATES) SOURCES

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U ovom radu je opisano energetski efikasno rešenje autonomnog napajanja potrošača tokom godine, korišćenjem hibridnog (solarne i dizel agregata) izvora u manastiru Hilandaru. Detaljnije je razmotreno optimalno opterećenje dizel agregata sa minimalnom potrošnjom fosilnih goriva. Prikazani su rezultati jednogodišnjeg ispitivanja, u našim uslovima, dobijanja električne energije iz fotonaponskih panela. Imajući u vidu specifičnu lokaciju i značaj manastira, sadašnje i buduće potrebe manastira i specifičan način života monaha, nov hibridni sistem za dnevnu potrošnju od 400 kWh električne energije i vršno opterećenje od 80 kW je projektovan i objašnjen. Zasniva na kombinovanom korišćenju tri dizel generatora snage 2 x 40 kW i 80 kW, fotonaponskih nominalne snage 75 kW i baterije za skladištenje energije od 400 kW. Primarni cilj novog sistema je da smanji potrošnju dizel goriva i operativnih troškova za potrošnju energije sistema.

Ključne reči: *solarni hibridni dizel snabdevanja; ušteda goriva; dizel agregati; fotonaponske ćelije*

The energy efficient solution of autonomous power supply of consumers during the year, by using of a hybrid (photovoltaic and diesel aggregates) sources in the monastery Chilandar is presented in this paper. In details optimal load of diesel aggregate is discussed with a minimum consumption of fossil fuels. The results of the one year exploitation of the electricity generated from photovoltaic panels in our conditions are presented as well. Taking into consideration the specific location and importance of the monastery, the current and future needs of the monastery and particular way of life of the monks, the new hybrid system for the daily consumption of 400 kWh of energy and peak load of 80 kW has been designed and explained. It is based on the combined use of the three diesel power generators 2 x 40 kW and 80 kW, photovoltaic rated power 75 kW and battery pack for energy storage of 400 kWh. The primary objective of the new system is to reduce the consumption of diesel fuel and operating costs for the system power consumption.

Key words: *hybrid supply; diesel solar supply; fuel saving; diesel aggregates; photovoltaic cells*

1. INTRODUCTION

Holy Mount of Athos (Agion Oros) is one of the most sacral and the most respected places of Christian Orthodox faith. It is located in Northern Greece, at Athos peninsula, 40 km long and up to 10 km wide. Monastery Chilandar is one of twenty existing on the Holy Mount. . Actual isolated power generation systems for supplying monastery consumers with electric current with peak loads under 50 kW , with daily electricity consumption less than 250 kWh was created mostly with diesel aggregates. This system have following problems:

- Quite high investment (capital) costs;
- High operational costs, which are, since recent, less acceptable;
- Transportation of diesel fuel to remote and isolated locations of diesel generations station can be problematic very often, especialy during winter;
- Diesel generators demand permanent maintenance;
- Low loaded, diesel aggregates have increased fuel consumptions, as well as gas emisions.

Autonomous generation of electrical power in the monasteries in Mount Athos has to fulfill some particular conditions, which are mandatory in this, specific area [1]:

- Electrical power source should not produce nither noice nor vibrations;
- Electrical power generation must be ecologically acceptible as much as it is possible;
- Diesel fuel consumption should be minimal;
- The system must operate as autonomous one‘
- The system should be reliable'
- It is essential that the maintenance of the system should be minimal'
- Above all, system should have capital and operational costs as low as possible.

2. PRESENT SYSTEM OF SUPPLAYING MONASTERY CHILANDAR DESCRIPTION

The old diesel aggregate station in Chilandar monastery was built by the end of 20th century, with three diesel electrical generators, accumulating batteries and UPS [2].

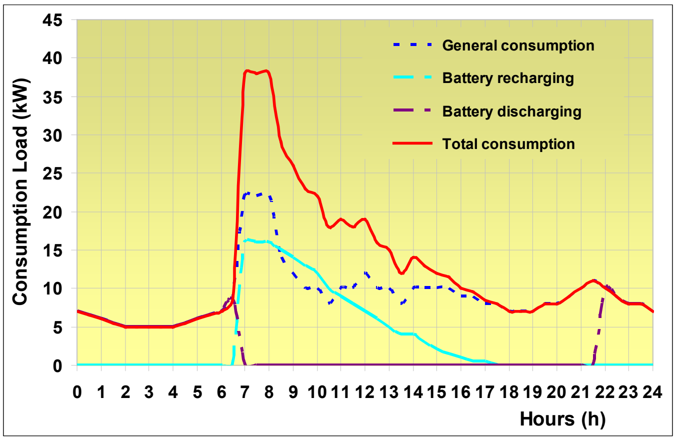

Figure 2 Load chart of diesel aggregates station, during daylight and night,with total electrical energy of cca 223 kWh/day

The biggest diesel aggregate, has the rated power of 135 kVA. The second aggregate is 60 kVA rated power, and the third, have rated output power of 55 kVA. The batteries for energy storage have the rated voltage of 360 V and five-hours-lasting capacity of 250 Ah. These batteries, via an inverter of rated power 60 kVA supply the power grid in the monastery at standard voltage 3 x 380 V, 50 Hz.

One diesel aggregate starts its operation at 7:00 AM, taking the whole consumption load of the monastery [3]. In the same moment, UPS device change its operation mode automatically, from DC/AC into AC/DC, starting the recharging the batteries. At 9:30 PM the diesel aggregate switches off and the whole supply comes from accumulation batteries.

Daily load chart of present diesel aggregates station was recorded in June 2008 [4]. It has been estimated that daily electricity consumption in Chilandar monastery is cca 223 kWh, during summer period. During daylight, the amount of 141 kWh can be spent on different devices and other consumers. Around 82 kWh are used for battery recharging, while during night cca 63 kWh of that energy are delivered back to consumers.

3. THE USE OF PHOTOVOLTAIC SUPPLY

Examinations of PV supply possibilities, conducted in Serbia, during 2012 [5], as the result gave the values of generated electrical power, monthly, at the outputs of PV panels. These values are shown in Fig. 3. During examination, PV panels, rated power $5.006\ W$, have been used, fixed in the position under the angle 35^0 towards the horizontal axis, oriented directly to the south.

Minimal electricity generation was recorded in February, and it was only 90,7 kWh. Maximal generation of electricity was measured in August, 891,5 kWh. Photovoltaics delivered total of 6211,7 kW of electric energy into electric network. The total losses in the energy conversion are 14% between photovoltaic and electric network, so photovoltaic generate 7.222,9 kWh of electric energy at the end of panels

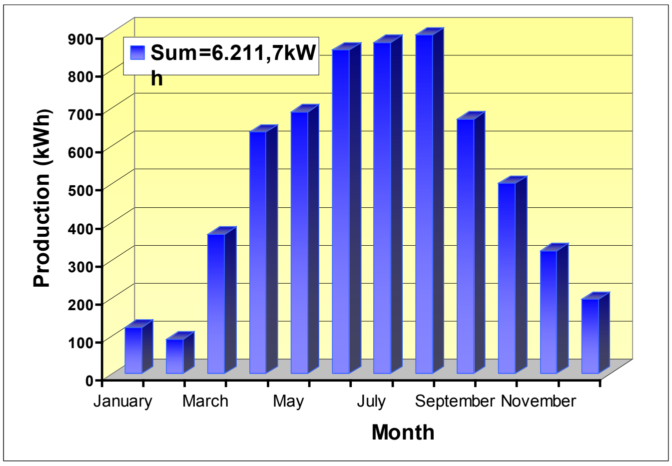

Figure 3 Annual electrical power generation from PV panels of rated power 5.006 W, fixed under the angle 35⁰ towards the horizontal axis

Average available time for electricity generation, T_{PV}, during three summer months (June, July and August) in Serbia is cca 6,6 h. During three winter months (December, January i February) it is only cca 1,06 h, so.

$$1.06\,h \le T_{PV} \le 6.6\,h \quad . \tag{1}$$

The total annual number of hours with insolation in Serbia in 2012 was:

$$T_A = \frac{\sum_{i=1}^{12} E_i}{P_{PV}} = 1.442{,}8h \tag{2}$$

Taking into account the fact that Belgrade lies much northern from Mount Athos, has continental climate and more restrictive conditions concerning insolation, the results achieved by this examination, would give the final results on the secure side. This value is very similar to data obtained from EU Interactive maps for photovoltaic GIS[6].

4. EFFICIENT USE OF THE FUEL IN DIESEL AGGREGATES

Typical chart of specific fuel consumption in a diesel engine, of rated power 80 kW, shown in Fig. 4, points to the fact that the optimal operation of the engine is in the power generating regime, i.e., by constant speed of rotation of 1,500 $\min^{-1}$, in the range from 70 to 90 % of engine's rated power [7].

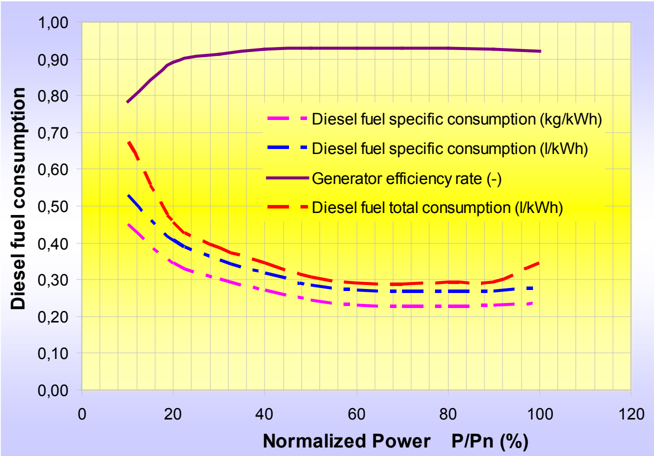

Figure 4 Specific diesel fuel consumption versus aggregate's load

The basic task was to optimize the operation of the whole power plant, and to minimize the fuel consumption.

Optimal operating range of diesel aggregate can be defined according to the following relation:

$$0.6 \cdot P_{DA,n} \leq \Delta P_{DA,opt} \leq 0.8 \cdot P_{DA,n} \quad , \qquad (3)$$

where $P_{DA,n}$ and $P_{DA,\max}$ are rated power and optimal range of a diesel engine operation.

The basic idea was the following: diesel engines should always be loaded with constant power, and to operate in the point of optimal consumption, as sources of permanent load. For diesel engines with low rated powers and medium speeds of rotation, it is common to use convex curve with minimum value of cca 80% of rated power, i.e., 0,8 $P_{n,g}$.

5. EFFICIENT USE OF THE BATTERIES FOR ENERGY STORAGE

Even though the battery storage is the oldest and most familiar energy storage device, significant advances have been made in this technology in recent years to deserve more attention. Lead–acid batteries are the most common batteries used in solar applications today. Lead–acid batteries should not be discharged by more than 80% of their rated capacity or depth of discharge (DOD). Exceeding the 80% DOD shortens the lifetime of the battery [8].

Operational range of the battery can be defined according to the relation:

Battery systems are quiet and non-polluting, and are installed near the center of the load. These batteries have efficiencies in the range of cca 85% [9].

A lead–acid nonaqueous (gelled lead acid) battery uses an electrolyte paste instead of a liquid. These batteries do not have to be mounted in an upright position. There is no electrolyte to spill in the case of an accident. Nonaqueous lead–acid batteries typically do not have as high a life cycle, and are more expensive than flooded deep-cycle lead–acid batteries.

Lead–acid batteries are inexpensive, readily available, and are highly recyclable, using the elaborate recycling system already in place.

6. A PROPOSAL OF HYBRID SOLUTION FOR MONASTERY SUPPLY

Our proposal of hybrid solution for supplying the monastery with electric power[10] consists of photovoltaic panels, diesel aggregates, accumulating batteries and power converters. There are several articles and papers dedicated to modeling of such systems [11], optimal choice of their components [12, 13] as well as practical realizations [14].

Proposed small electric power plant should generate **400** kWh electrical energy per day, which is the forecasted quantity of electricity consumption in the monastery. Estimated daily peak load, $P_{c,\max}$, will be **80** kW **.**

The new solution of hybrid system for electrical power generation (Fig. 5) would consist of: photovoltaic (PV) panels, of total installed power 75 kW, as basic energy source; two diesel aggregates (D1 and D2) of rated power 55 kVA (44 kW) each; one diesel aggregate (D3) of 100 kVA (80 kW); three single-phase inverters (DC/AC), rated power 25 kW each; inverter with rectifier (UPS) of rated power 125 kVA (100 kW) and accumulating battery (AB) for energy storage in amount of 400 kWh. Diesel aggregates (D1 and D2) would operate as the sources of permanent power (of cca 35,2 kW), in the optimal operational point, with minimal fuel consumption per one kWh of generated electrical energy, and with minimal emision of dangerous, exshausted gasses and maximal possible operational lifetime.

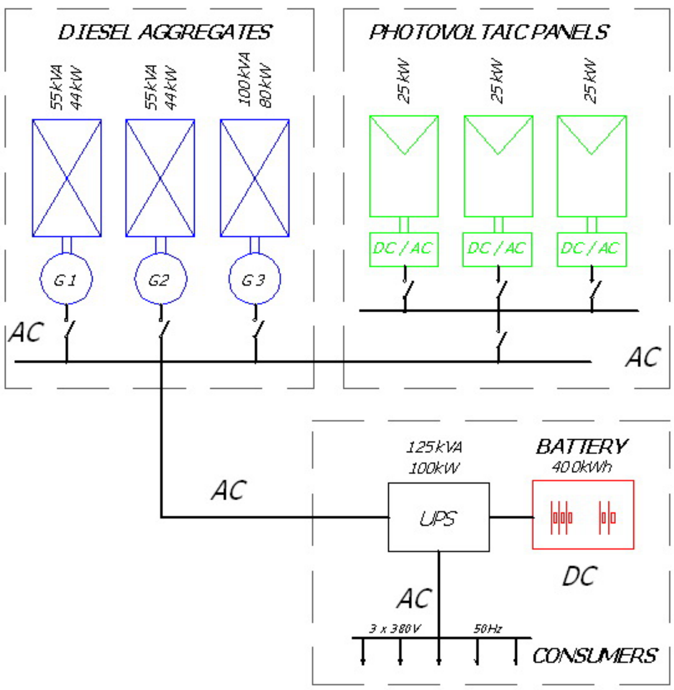

Figure 5 Single-phase scheme of proposed, new, hybrid system for electricity supply

Photovoltaic (PV) panels are the basic source of electrical power, planned for priority use, while two smaller diesel aggregates (D1 and D2) represent additional sources of electricity. They would be used in periods without sufficient insolation. Third diesel aggregate, with the highest rated power, is also an additional source of electricity, planned for operation in cases with extremely high energy demand or emergency, when basic system or its parts (PVs, D1, D2) are out of order.

Described new solution was created under the assumption that average daily consumption in the monastery and related auxiliary buildings is cca 400 kWh. As we already saw, the peak load in daily load chart occurs in early morning hours (see Fig. 2), when regular daily activities start: meals preparation in the kitchen, construction works on monastery's reconstruction and renewal, regular duties of each monk and activities of pilgrims. Concerning the fact that in the batteries would always be at least 50% of required energy amount (400 kWh), the only constraint for the peak load is inverter with rectifier (UPS), whose provided rated power is 125 kVA (100 kW).

With sunrise starts the battery recharge from PV panels, via three single-phase inverters, rated power of 25 kW each, i.e., 75 kW in total. In the case of the lack of consumption in the monastery, this power corresponds to 5-hours power of battery recharging. During winter period, of course, battery recharging from PVs is waeker and shorter.

Diesel aggregate (D1 or D2) would start automatically, if it is necessary, when the level of stored electricity in the batteries drops under 50% of their reated capacity (and forecasted energy demand), which means under 200 kWh. Diesel aggregate would be switched off when energy stored in the batteries reached 80% of their capacity, i.e., 320 kWh. Parallel operation of diesel aggregates is not foreseen.

In the case that level of energy stored, for some reason, drops to 35% of energy demand, i.e., 140 kWh, D1 or D2 would be also turned off, but reserve diesel aggregate D3, the biggest one, would be switched on. It would recharge the batteries then, in forced manner, and supply consumers in the monastery, at the same time. This diesel generator could be also switched on if normal supply fails, to supply consumers in the monastery directly.

7. DISCUSSION

Described hybrid solution is created as optimal one, under the assumption that average daily consumption in the monastery and related auxiliary buildings is cca 400 kWh. However, until the completion of all buildings related to the monastery's complex and renewal of monastery itself, after disasterous fire in 2004, average daily consumption of electricity in it will be less.

1. Advantages of proposed, new system for electricity supply

New supplying system is designed to meet the need for electricity during summer months almost completely from PV panels. During winter months, electricity generation would rely more on diesel aggregates D1 and D2, and fuel consumption would grow significantly.

According to very uneven loads which occur during a year, the system should be flexible, and to allow higher consumption of electricity in those days when it is necessary.

The hybrid solution may obtain, during summer months, in normal operational conditions, cca 845 kWh of electrical energy from diesel aggregates and 510 kWh from PV panels, i.e., maximum cca 1.355 kWh per day. During those, summer months, however, PV supply is sufficient to cover complete electricity consumption in the monastery. That way, by proposed hybrid solution, significant savings of diesel fuel would be achieved, in comparison with the present solution, based exclusively on diesel generators.

During winter months, the hybrid solution may obtain, in normal operational conditions, cca 845 kWh of electrical energy from diesel aggregates and only 60 kWh from PV panels, i.e., maximum cca 905 kWh per day. During that period, PV supply only partially could recharge the batteries and achieve reduced savings in fuel consumption.

In emergency situations, diesel aggregate D3, of rated power 100 kVA (80 kW) could obtain electricity amount of 1,920 kWh per day.

The only constraint for the peak load represents the inverter with rectifier (UPS) of rated power 125 kVA (100 kW).

Proposed hybrid solution has an important characteristic related to reliability of such systems: if UPS operation failed for some reason, or normal regime of monastery supply drops, it is possible to start reserve diesel aggregate D3 and to supply the monastery directly, with rated power of 100 kVA (80 kW).

2. Annual savings of diesel fuel

Supposing that average daily electricity consumption is 400 kWh during whole year, total annual consumption in the monastery would be cca 146,000 kWh.

With assumption that it would be only 1,444.5 h/year with sun (like in Belgrade, which is on the secure side for relevant calculations), PV panels of total power of 75 kW could generate useful electrical energy of cca 81,795 kWh/year. We supposed that total losses in the system are 24.5%, according to EU Interactive maps for PV GIS [6].

Remaining 64,205 kWh is necessary to obtain from diesel aggregates. Taking into account specific diesel fuel consumption of 0.3 l/kWh, it is possible to determine annual diesel fuel consumption of cca 19,261 l, necessary to generate remaining amount of electrical energy for the monastery.

On the contrary, if only diesel aggregates operate, in the present regime, with average specific fuel consumption of 0.5 l/kWh, to produce complete amount of electrical energy needed in the future, i.e., 146,000 $kWh/year$, it is necessary to combust 73,000 l of diesel fuel per year.

Hence, by realizing and apply of proposed, hybrid system, annual savings would be cca 53,739 l of diesel fuel. Fuel consumption during each year, of course, would vary, and in winter period it would be significantly higher than during summer monhts.

3. Operational lifetime of hybrid power plant

Previous diesel electrical power stations in Chilandar monastery had operational lifetime of cca 15 years. Diesel aggregates mainly operated 15,000 to 20,000 working hours, in total. After that period they were substituted with another, new ones.

If diesel aggregates D1 and D2 should generate 64,205 kWh of electrical energy per year, as our calculations shown, together they have to be in operation during:

$$T_{DA} = \frac{E_{DA}}{P_D} = \frac{64{,}205\,kWh}{35.2\,kW} = 1{,}824\,h \quad . \tag{4}$$

From (4) stems that in hybrid power plant diesel aggregates should operate in total 1,824 h per year, or cca 912 h each. It is expected that in optimal conditions and with regular maintenance, these aggregates can work up to 25,000 h or 25 years.

Photovoltaic panels normally have the lifetime of 25 years, when occurs the reduction of the level of conversion of sun irradiation into electricity, for cca 15%.

Under previosly elaborated operational conditions, the lifetime of accumulating batteries would be cca 9 years.

Whence the lifetime of the main system's components, PV panels, is cca 25 years, proposed hybrid power plant would have its lifetime of 25 years, too. It is significantly longer than the lifetime of previous diesel electrical power stations. However, in the new plant, the batteries should be replaced each 9 years.

8. CONCLUSION

Proposed and elaborated technical solution of hybrid system with combined, different sources for electric power generation, intended for Chilandar monastery supply, is the optimal one. Applying it, the following parameters and conveniences would be achieved:

1. For average daily electricity consumption of 400 kWh, annual consumption of diesel fuel would be cca 19,261 l, in normal operating conditions.
2. Electical power plant would be able, even under the worst operating conditions, to generate 925 kWh/day.
3. Estimated maximal daily peak load, in the planning horizon, is 80 kW.
4. Projected lifetime of the hybrid power plant is 25 years.

Beside previous, and very important are the following facts:

5. Silence and peace would be provided in the monastery, without noice and vibrations, usually produced by diesel engines.
6. Proposed solution would achieve annual savings in diesel fuel of 53,739 l, compared with the present solution, based on exclusive use of diesel aggregates.
7. Environment pollution with products of diesel fuel combustion would be significantly reduced and become minimal.
8. Maintenance of the system would be minimal, because diesel aggregates would operate in the best, generation regime, as sources of constant power, in optimal operating point.
9. Minimal specific fuel consumption per generated kWh of electricity would be achieved, as well as minimal emission of exhausted gasses, and the lifetime of diesel aggregates would be extended.
10. By this solution, the best energy efficiency of electrical power sources in Chilandar monastery would be achieved.

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REFERENCES

[1]. Bogdanović D, Đurić V.J, Medaković D, Chilandar: On the Holy Mountain, Belgrade, Jugoslovenska Revija, 1978.

[2]. Nikolić Z, Vasiljević J, Škrnjug S, Šiljkut V, Electrification of the Chilandar monastery and the contribution of the Electricity Distribution Company “Elektrodistribucija Beograd”, Elektrodistribucija, 2000; 28, 2: 147-160. (in serbian)

[3]. Nikolić Z., Electrification of the Chilandar Monastery and its properties, In: The Holy Mountain – thought and studies, volume 4, Zivojinovic M, editor, Prosveta, Belgrade, 2005, 430 – 464. (in serbian)

[4] Nikolić Z, Nikolić D, Šiljkut V.M, The island power supply of Chilandar monastery using diesel generators and photovoltaic panels, Energy, Environment, Economy, 2011; 13, 2: 042 – 048. (in serbian)

[5]. http://www.piko-solar-portal.de/PlantViewCharts.aspx

[6]. Photovoltaic Geographical Information System, European Commission Joint Research Centre, Ispra, Italy, http://re.jrc.ec.europa.eu/pvgis/

[7] Logenthiran T, Srinivasan D, Optimal selection and sizing of distributed energy resources for distributed power systems, J. Renewable Sustainable Energy 2012; 4, 053119

[8] Cape Barren Island Power Station, Operation & Maintenance Manual, 2010, Hydro Tasmania Consulting

[9] Rehman S, Al-Hadhrami L.M, Study of a solar PV–diesel–battery hybrid power system for a remotely located population near Rafha, Saudi Arabia, Energy, 2010; 35, 12: 4986–4995.

[10] Zoran Nikolić, Vladimir M. Shiljkut, Dušan Nikolić, Diesel-solar electricity supply for remote monasteries, J. Renewable Sustainable Energy **5**, 041815 (2013); http://dx.doi.org/10.1063/1.4813068

[11] Nfah E.M, Ngundam J.M, Tchinda R, Modeling of solar/diesel/battery hybrid power systems for far-north Cameroon, Renewable Energy, 2007; 32, 5: 832–844.

[12] Hakimi S.M, Moghaddas-Tafreshi S.M, and Hassanzadeh Fard H, Optimal sizing of reliable hybrid renewable energy system considered various load types, J. Renewable Sustainable Energy 2011; 3

[13] Logenthiran T, Srinivasan D, Optimal selection and sizing of distributed energy resources for distributed power systems, J. Renewable Sustainable Energy 2012; 4, 053119

[14] Hydro Tasmania Consulting, “Cape Barren Island Power Station”, Rev. 1, 2010, 15.