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Solar System Battery Backups for Reactor Coolant Pumps During Electricity Outages Resulting from Natural Disasters

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Abstract

A nuclear power plant's primary safety equipment is its coolant system. Coolant system failures have led to several accidents in nuclear history. A coolant system's failure can be caused by many reasons, including a lack of electric power for the coolant pumps. Nuclear power plants (NPPs) typically have backup power systems. This article focuses on reactor coolant systems and their backup power when main grid lines fail. The article discusses solar backup power for batteries and the increase of safety lines for reactor coolant pumps. Our main goal is to provide a battery backup from a reliable, natural source and ensure electricity for coolant pumps.

Abbreviations

PV	Photo Voltaic
LOCA	Loss of Coolant Accident
RCP	Reactor Coolant Pump
HP	Horsepower
Wh	Watt hour
Ah	Ampere Hour
NPP	Nuclear Power Plant
MW	Megawatt
KW	Kilowatt
BOS	Balance of System
Wp	Watt Peak
KWh	Kilowatt hour
RCP	Reactor Coolant Pump

Keywords: PV solar cell, KWh, Coolant Pump, MW, LOCA, Coolant System, Grid system, Wp, Diesel Generator, Deep cycle battery, Inverter, NPP.

I. Introduction

A nuclear power plant's main reactor coolant pump is like the human body's heart and thus operates in a whole service life. The reactor coolant pump collects heat from the reactor core and exchanges it via heat exchangers by using coolant. If a coolant pump ceases to work at any point, heat generated from nuclear fission reactions is not exchanged via the circulating coolant, and the malfunction causes serious issues in the reactor's operation within merely a few minutes. If the station blacks out during any disaster or from electric disturbance, the main coolant pump must, at any cost, be kept in operation by a backup supply of electricity. So, this article's primary focus is on supplying electricity to coolant pumps from a natural and reliable source.

II. About reactor coolant pumps

A cooling system demands a sufficient, volumetric flow of water (as a coolant for power) to ensure an NPP's safe and reliable operation. Therefore, reactor coolant pumps serve as key components of reactor cooling systems. The cooling water is supplied by four large centrifugal pumps called the main reactor coolant pump (RCP). Each unit of a typical 1150 MW-pressurized water reactor has four 7,230-KW (9,700-HP) RCP motors, which run constantly and are required to be operable 100% of the time in order to maintain the units' power production **[*1*]** for a volumetric water flow of 23,888 kg/sec **[*2*]**. Most reactor coolant pumps are located at the reactor's cold leg and operate with high pressure. The reactor coolant pump has three primary functions:

- Exchanging heat from hot water to cold water by circulating coolant water
- Maintaining stable pressure
- Maintaining regular flow

A. The solar power supply and its function in an NPP

A solar cell is an energy conversion device in which solar energy from sunlight is converted directly to DC electricity. The electricity generated from a solar cell can either be stored in a battery or used directly via an inverter and fed into grid lines. If a station blacks out and the emergency diesel generator fails to kick in, the solar cell would play an important role for the reactor's safety. The solar cell is highly reliable, and in our research, we used a solar PV cell as power for the battery backup because the battery charges from a solar cell by sunlight during the daytime and supplies sufficient electricity for coolant pumps after only 24 hours. The battery continues functioning fully the following day.

B. Using solar as backup power for emergency situations in NPPs

Safety is a nuclear power plant's highest priority. An NPP's key safety feature is continuously running its coolant system in order to transfer the generated core heat. So, the coolant pump must be active during both the plant's operation and closure hours. As we know, while the plant is shut down, the reactor releases decay heat, which can sufficiently melt down the reactor. The reactor core releases decay heat for long periods, such as months or even years. If the system suspects, even slightly, that the reactor's chain reaction may have stopped and thus failed to generate electricity, the reactor coolant pumps begin operating by either grid supply, an emergency diesel generator, or a battery backup's power. If the grid system and emergency diesel generator backup systems fail, then the battery backup is the last source for servicing the coolant pumps. But battery backups can provide power in emergency periods only during certain hours. As such, we are faced with a major question: if the first two power supply systems fail for long periods, how can coolant pumps be kept in operation to avoid a LOCA? Battery backups are active for only a brief duration and fail due to lack of self-charging when station grids fail.

Now, there is a solution: if the battery were charged continuously by any reliable external source, it could be used to provide cooling services for longer periods of time. Solar power supplied by a PV cell is a common, reliable source. If a PV solar cell were installed to satisfaction, it would remain in service during floods, cyclones, earthquakes, tsunamis, and other natural disasters. So, PV cells play an important safety role in supplying continuous battery backup in critical situations for reactor coolant systems and save the core from meltdown.

C. Hybrid solar systems *[3]*

A hybrid solar system, also known as "on-grid solar with battery storage," generates power in the same way as a typical grid-connected solar system but has the ability to store the solar energy.

Hybrid solar systems' advantages include:

- Storing and saving solar or cheaper off-peak energy
- Allowing the use of solar energy during peak times (self-use or load-shifting)
- Providing power during a grid outage or blackout
- Enabling energy independence

Hybrid solar systems' disadvantages include:

- Having a higher cost than on-grid solar; the cost increase is primarily due to the batteries
- Requiring more room and having a greater installation cost due to their generally larger, more complex installation

III. A typical hybrid solar system has following main components:

A. PV solar system *[4]*:

A single PV cell is a thin semiconductor wafer consisting of two layers—highly purified silicon PV cells. A PV module consists of many PV cells wired in parallel to increase the current and thereby produce a higher voltage. A PV array is the complete power-generating unit, consisting of any number of PV modules and panels.

1. Charge Controller *[5]*

A charge controller is a voltage or current regulator that keeps batteries from overcharging. It regulates both voltage and the current traveling from the solar panels to the battery.

2. Battery Bank

In a hybrid system, the recommended battery type for the PV solar system is a deep-cycle battery. Deep-cycle batteries are specifically designed to be discharged at low energy levels, and the cycle is charged and discharged, day after day, for years. The battery should be large enough to store sufficient energy to operate the appliances at night and on cloudy days.

3. Inverter *[6]*

A solar inverter's primary function is to convert DC power generated by the PV array into usable AC power. Hybrid inverters go a step further and work with batteries to store excess power as well. Once the batteries are fully charged, the excess solar power is not required for running the pumps and is thus exported to the grid.

4. Block diagram of a 7.5 MW hybrid solar plant for auxiliary power:

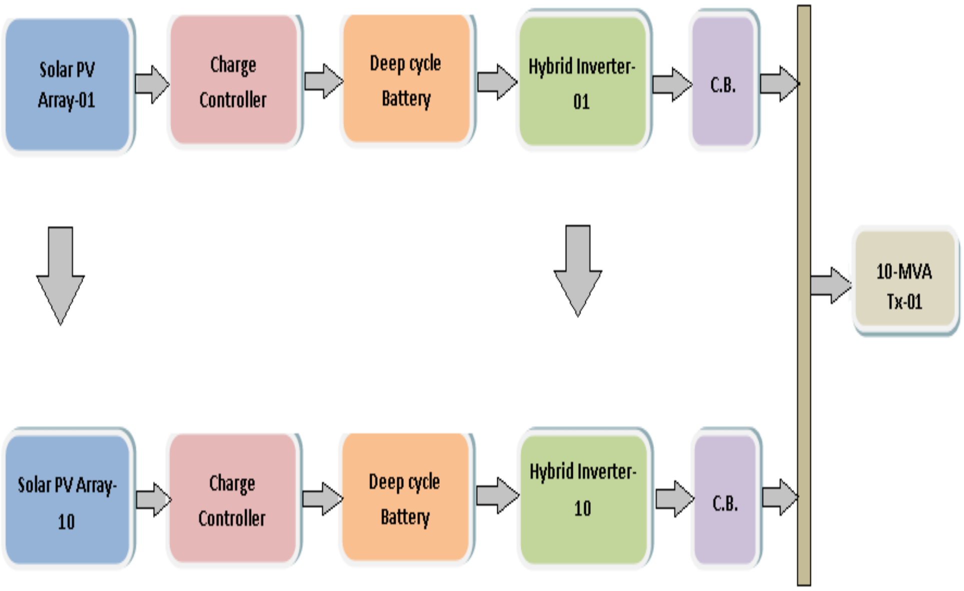

Figure 1. 7.5 MW Solar Array Connections

5. Arrangements of a grid tie solar plant's connection:

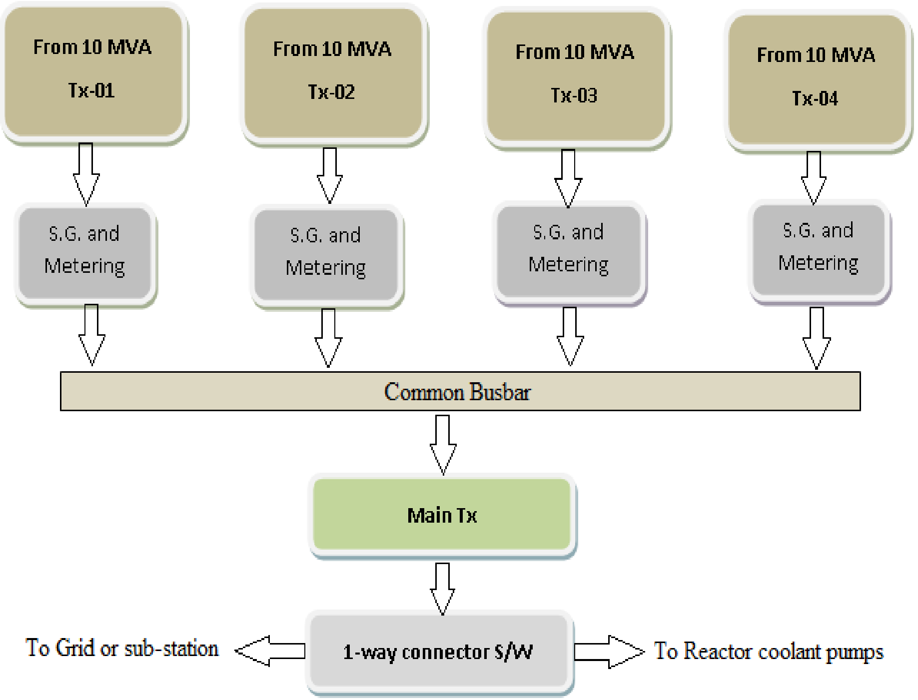

Figure 2. Grid Tie Connection Diagram of 7.5 MW x 4 Solar Plant

6. Specifications of main components:

Solar PV Specification **[7]**:

Nominal power:	300 Wp
Rated voltage:	54.7 V
Rated current:	5.49 A
Maximum system voltage:	1000 VDC (IEC)
Panel dimensions:	1559mm × 1045mm × 46mm
Efficiency:	18.4%

Inverter specification **[*8*]**:

Maximum permissible DC voltage:	1000 V
Nominal AC power (at 40° C):	1000 KVA

Battery specification **[*9*]**:

Weight (dry):	536 kg
Dimensions:	1092mm × 686mm × 580mm
Battery voltage:	32 V
Capacity:	936 AH

7. Technical Calculation ***[10]***:

Step 1: Input energy for coolant pumps:
1200 MW reactor coolant pump-driven motor rating: 7,230 KW (9700 HP) [1]
Number of coolant pumps: 04
Total pumps rating: 7,230×04 = 28,920 KW ~ 30 MW
Needed input energy for pumps/day: 30 MW×24 hrs = 720 MWH

Step 2: PV modules supplied energy:
Multiply pump's daily input energy times 1.3 (the energy lost in the system) to determine DC energy, which must be provided by the solar panels.
Solar panel-supplied energy/day for pumps: 720 MWH × 1.3 = 936 MWH

Step 3: PV modules quantity calculation:
We choose, module watt-peak = 300 Wp

$$\text{GF} = \frac{\text{Supplied energy for pumps}}{\text{PV generated energy}} = \frac{\text{Service time in hours}}{\text{Generated sun light hours}} = \frac{\text{24 hours}}{\text{consider 7 hours}} = 3.43$$

$$\text{PV modules quantity} = \frac{\text{936 MWH}}{3.43 \times 300\ \text{Wp}} = 933333.33\ \text{quantity} \sim 934{,}000\ \text{quantity}$$

Meaning, if we connect 934,000 300 Wp solar modules, the amount of AC power generated is 30 MW over 24 continuous hours.

Step 4: Deep-cycle battery calculation

$$\text{Battery capacity (Wh)} = \frac{\text{watt}-\text{hours used} \times \text{days of anatomy}}{\text{depth of discharge} \times \text{battery loss} \times \text{nominal battery voltage}}$$

$$= \frac{720{,}000{,}000\ \text{Wh}}{0.75 \times .085 \times 800} \times 1.3$$

$$= 1{,}835{,}294.11 \text{ Wh} \approx 1{,}836{,}000 \text{ Wh}$$

Choose a 75% deep-cycle battery and a battery loss of 0.85. Consider an 800-volt battery (25 quantity 32-volt 936 Ah batteries connect in series). For safety of operation in cloudy or less sunny weather, choose days of autonomy as 1.3 (the number of days that we need the system to operate when there is no power produced by PV panels).

Battery parallel lines = $\frac{1{,}836{,}000 \text{ Ah}}{936\text{Ah}}$ = 1961.53 ≈1962

So, the total number of batteries = 49,050, in which series × parallel becomes 25 × 1962.

8. Cost Evaluation:

Due to safety concerns, typical installation costs for a nuclear power plant are higher than for other power plants. However, the capital cost of a PV (150MW) solar power plant is only $3,873 per KW, while a nuclear power plant's (dual unit 2230 MW) capital cost is $5,530 per KW **[*11*]**.

As mentioned, a 1200 MW NPP costs approximately $6.7 billion, whereas the draft cost of 30 MW solar plant is $120 million. But a PV solar plant's service life is 25-30 years, whereas a new-generation NPP's service life is 60 years. Thus, for solar panels, we must invest twice during an NPP's life. So, the maximum investment for PV solar power becomes $300 million, including heavy civil construction, batteries, inverters, and the BOS. About 25% to 30% of an NPP's total investment budget goes toward its safety features, whereas our PV system uses only 4.5%. But the great advantage of this backup power is that it recoups its investment within 20 years by supplying electricity to grid lines; the remaining 30 to 40 years equate entirely to profit. Other types of safety equipment have not recouped their investments, but adding solar outfits to NPPs as emergency battery backups not only recoups investments but generates profit as well. However, profit is merely an added benefit, as the primary and central goal is to continue the uninterrupted power supply for reactor coolant pumps when the grid and emergency diesel generators fail.

9. Land Evaluation:

The land required for establishing 1200 MW nuclear power plants is 1000 acres (1.56 km^2) **[*12*]**. But our highly efficient, high peak wattage solar panels require a maximum of 450 acres for a 30 MW solar plant designed for 100% plant capacity by using storage batteries. The main challenges in installing a PV solar system relate to land management. We have many options, though. The surrounding area of a nuclear power plant has too many evacuation zones, and such land is effectively useless.

The estimate for the required land thus becomes: 25 solar panels' required area (8×5.3) ≈ 42.4 m^2. So, the total area = 934,000 × $\frac{42.4 \text{ sq.m}}{25}$ ≈ 1584064 m^2 ≈ 392 acres. Figure 3 shows a PV array design:

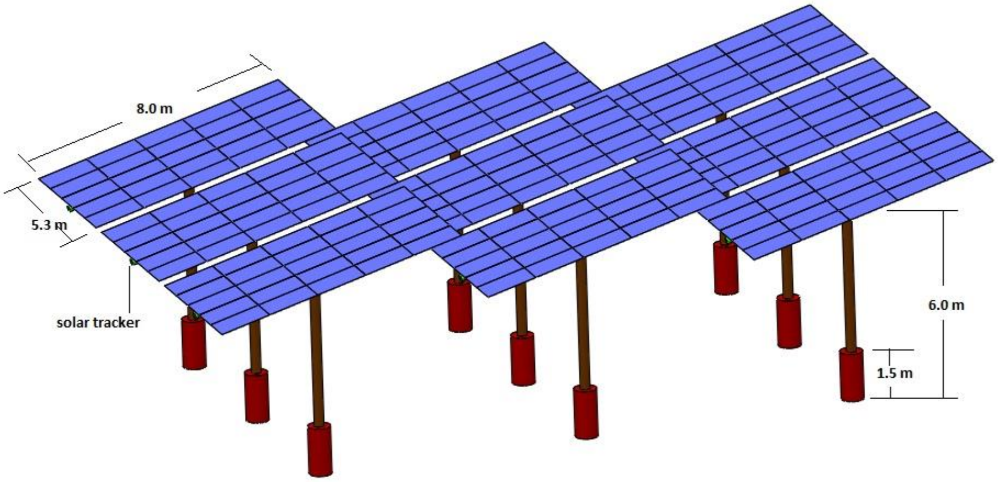

Figure 3. Solar PV Array Arrangement

Figure 4 shows an area of an evacuation zone where we easily placed our required solar panels. The area is constructed with RCC columns for strength in withstanding natural disasters, and it is built at least six meters above ground level for ensuring safety against floodwaters or tsunamis. Also, PV modules installed at a significant height have advantages which reduce space by using a setup inverter, batteries, and charge controller at the bottom of the solar module, with protective barriers. Below, figure 4 shows a typical NPP with a solar PV module in an evacuation boundary.

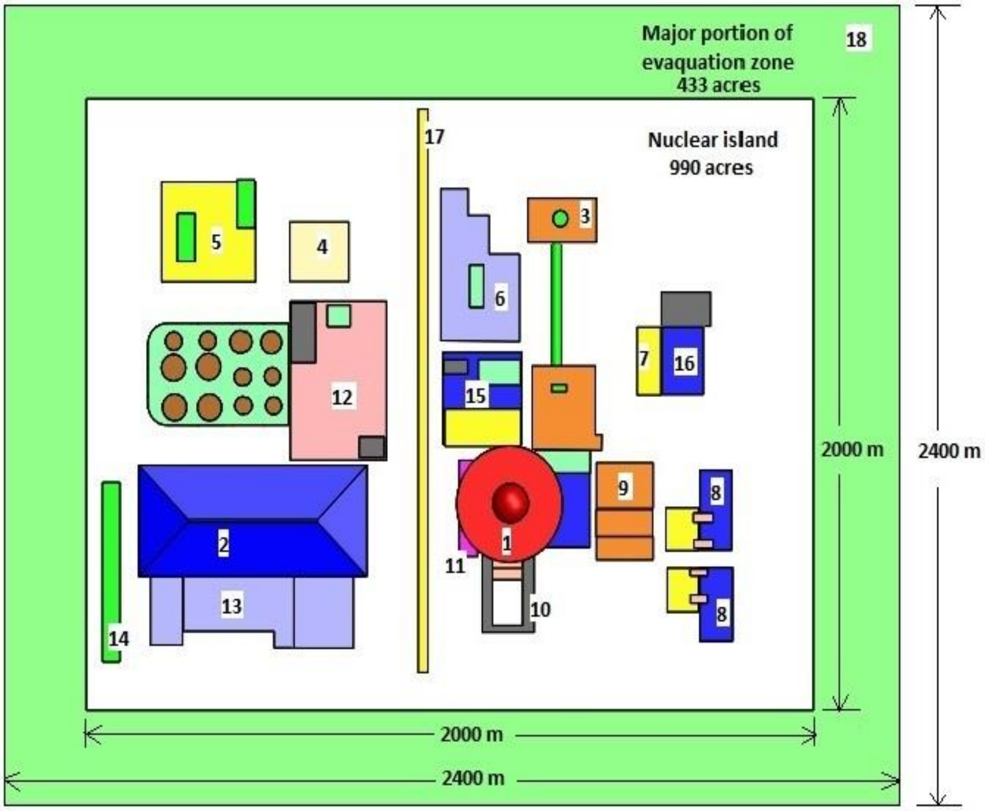

Figure 4: A Typical 1200 MW NPP with Solar Panels

The main components of a typical NPP with solar panels are listed below **[*13*]**:

1. Reactor building
2. Turbine building
3. Vent Stack
4. Treatment Plant
5. Diesel Generator Building
6. Nuclear Service Building
7. Auxiliar Building
8. Emergency Diesel Generator Building
9. Safety Building
10. Transportation Lock Trestle Sling
11. Steam Cell
12. Water Treatment Building
13. Power Supply Building
14. Unit Transformer
15. Control Building
16. Fuel Storage Building
17. Separator From Primary to Secondary Circuit
18. Solar Panel Area

IV. Conclusion:

Nuclear power is essential and necessary if we are to meet future demands, but we must be concerned about nuclear power's safety. The loss of auxiliary power causes a coolant pump's failure, and the result is core meltdown. The Fukushima Daiichi nuclear disaster of 2011 is one such type of accident. In the Fukushima accident, after the station grid's failure, which caused the emergency diesel generator to become immerged in salty seawater—meaning that the battery couldn't function as long as it needed—the result was that the core melted down. So, continuously supplying power to the coolant pumps presents a safety challenge. To mitigate this challenge, sufficient battery backup should be provided from reliable sources, and solar power is one such source. A typical solar plant requires more space, but coolant pumps are only 2.5% of total generated power. So, these demands for coolant pumps are easily met by solar plants, and much unused land surrounds NPPs as evacuation zones, which can be used for solar plants.

Both nuclear and solar power are roughly CO_2 and NO_X emission-free and reduce the effects of greenhouse gases. NPPs produce large-scale power by using less space when solar power is chosen for coolant pumps' safety. Because solar sources are reliable, adding solar to NPPs as safe backup sources of power would enhance nuclear power stations' function in one step.

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