Comparison between Different Power Sources for Emergency Power Supply at Nuclear Power Plants

Magnus Lenasson, MSc

Solvina AB, Sweden

Abstract

Currently the Swedish nuclear power plants are using diesel generator sets and to some extent gas turbines as their emergency AC power sources and batteries as their emergency DC power sources.

In the laws governing Swedish nuclear activity, no specific power sources are prescribed. On the other hand, diversification of safety functions should be considered, as well as simplicity and reliability in the safety systems. So far the choices of emergency power sources have been similar between different power plants, and therefore this project investigated a number of alternative power sources and if they are suitable for use as emergency power on nuclear power plants.

The goals of the project were to:

- Define the parameters that are essential for rending a power source suitable for use at a nuclear power plant.
- Present the characteristics of a number of power sources regarding the defined parameters.
- Compile the suitability of the different power sources.
- Make implementation suggestions for the less conventional of the investigated power sources. (unconventional in the investigated application)

10 different power sources in total have been investigated and to various degrees deemed suitable

Out of the 10 power sources, diesel generators, batteries and to some extent gas turbines are seen as conventional technology at the nuclear power plants. In relation to them the other power sources have been assessed regarding diversification gains, foremost with regards to external events. The power sources with the largest diversification gains are:

- Internal steam turbine
- Hydro power
- Thermoelectric generators

The work should first and foremost put focus on the fact that under the right circumstances there are power sources that can complement conventional power sources and yield substantial diversification gains.

1. Background and purpose

This paper is a shortened version of the report "Comparison between different power sources for emergency power supply at nuclear power plants"[1]. The report is financed by Elforsk – Swedish Electrical Utilities' R & D Company.

The background of the report is that the Fukushima accident showed how redundant but not diversified power sources can be destroyed by external events. This might lead to increased focus on diversification, from the industry and/or the regulating authorities.

A number of essential parameters for a power source to work as emergency power supply at a nuclear power plant have been identified; ten different power sources have then been evaluated with respect to these parameters.

The report is supposed to work as a knowledge base and decision support when new nuclear power plants or reinvestments in old ones are considered.

The studied power sources are:

- Diesel generators
- Gas turbines
- Internal steam turbines
- Externals steam turbines
- Hydro power plant
- Batteries
- Fuel cells
- Stirling engines
- Thermoelectric elements
- Flywheels

The power sources are evaluated for five different applications, each application with its own acceptance criteria for each of the essential parameters. The five applications are:

- Onsite emergency AC source
- Onsite emergency DC source
- Alternate AC source, small
- Alternate AC source, large
- Alternate AC source, mobile

Mainly Swedish preconditions are considered in the report, but most of the results are applicable in any other country.

2. Essential parameters

In this chapter the parameters that have been identified as essential for a power source to act as emergency power source at a nuclear power plant are listed and explained. In the original report[1] acceptance criteria for the different applications are defined.

Available power

The parameter demonstrates in which power intervals the power sources are available.

Available energy and energy density

The parameter demonstrates how large quantities of primary energy carrier that is required for the different power sources.

Maximum operation time

The parameter demonstrates if there are limitations on how long the different power sources could be in operation without any planned outages given that fuel is supplied.

Dynamic operation

The parameter demonstrates how the different power sources are controlled (frequency and voltage control) and how they react on motor starts and load rejection for example.

Starting time

The parameter demonstrates how soon after a loss of offsite power the supplied grid can be reenergized.

Realizability of power source within or outside the protected area

The parameter demonstrates how large the power source is and which special preconditions it requires. Based on this an assessment is made if it is feasible to realize the power source within the protected area or outside it.

Availability and reliability

The parameter demonstrates the availability and reliability of the different power sources.

Definitions:

Availability = $1 - \frac{t_{fo}}{t_{tot}}$, where

t_{fo} = Forced outage hours during operation and standby

t_{tot} = Total amount of hours in operation and standby

Reliability = $\frac{n_s}{n_{as}}$, where

n_s = Number of starts

n_{as} = Number of attempted starts

Possibility to classify as safety equipment

This parameter demonstrates if the different power sources have been classified as safety equipment earlier or if it is possible to do so in the future. To evaluate the possibility to classify a power source in the future the main focus is the accumulated operation time of the power source.

Sensitivity to external events

The parameter demonstrates what kinds of external events the different power sources are sensitive to. The different external events are divided into four groups:

- Mechanical impact, for example wind, precipitation (snow), explosions, earthquake
- Impact of water, for example precipitation (rain), sea waves, high sea level, flood.
- Clogging of dampers, air intakes and heat exchangers, for example precipitation (snow), ice storms, missiles due to wind
- Extreme temperatures

This parameter is used to evaluate diversification gains, i.e. if the different power sources are sensitive to the same types of external events or not. Sensitivity to different types of external events makes it less likely that all power sources are taken out simultaneous.

Additional risks of challenging existing equipment

The parameter demonstrates what additional risks the different power sources pose to the existing equipment on site. The additional risks are divided into the following groups:

- Explosives
- Fire load
- Large rotating masses
- Hazardous substances
- Electrical transients

Aspects of maintenance and operational readiness

The parameter demonstrates if any special maintenance measures or measures to assure operational readiness can prevent the possibility to operate the different power sources in the intended way. Special attention is payed to possible tests or measures that have to be performed during the plant's normal operation period.

Mobility

The parameter demonstrates if the different power sources can be made mobile.

Investment and operational costs

The parameter demonstrates the investment costs and the operational costs for the different power sources. The costs are for the equipment alone, so the additional costs for a possible safety classification process and for the projects installing the equipment are not included.

3. Summaries for different power sources

3.1 Diesel generators

The suitability of diesel generators in different applications is seen in table 1. Diesel generators are already implemented as several redundant units in nuclear power plants worldwide.

Table 1. The suitability of diesel generators

Diesel generators			
Application	**Suitable**	**Suitable under certain preconditions**	**Unsuitable**
Onsite emergency AC source	X		
Onsite emergency DC source			X[1]
Alternate AC source, small	X		
Alternate AC source, large		X[2]	
Alternate AC source, mobile	X		

[1]) Unsuitable due to starting time>0

[2]) Suitable if several units are connected in parallell.

3.2 Gas turbines

The suitability of gas turbines in different applications is seen in table 2. Gas turbines are suitable to implement as several redundant units.

Table 2. The suitability of gas turbines

Gas turbines			
Application	**Suitable**	**Suitable under certain preconditions**	**Unsuitable**
Onsite emergency AC source			X[1]
Onsite emergency DC source			X[1]
Alternate AC source, small	X		
Alternate AC source, large	X		
Alternate AC source, mobile		X[2]	

[1]) Unsuitable due to starting time>20 s

[2]) Suitable if less than 72 hours' worth of fuel is accepted or a separate solution for the fuel is provided.

3.3 Internal steam turbine

The concept "internal steam turbine" is a steam turbine driven by steam from the main process in the nuclear power plant. The suitability of internal steam turbines in different applications is seen in table 3. Internal steam turbine is only suitable to implement as a single unit due to lack of power.

Table 3. The suitability of internal steam turbine

Internal steam turbine			
Application	**Suitable**	**Suitable under certain preconditions**	**Unsuitable**
Onsite emergency AC source			X[1]
Onsite emergency DC source			X[2]
Alternate AC source, small		X[3]	
Alternate AC source, large			X
Alternate AC source, mobile			X

[1]) Unsuitable due to lack of power at reactor outages and damages at the RCPB

[2]) Unsuitable due to starting time>0

[3]) Suitable if the available power is sufficient

[4]) Unsuitable due to lack of available power

[5]) Unsuitable power source to make mobile

3.4 External steam turbine

The concept "external steam turbine" consists of an offsite heat and power plant (CHP) that has a dedicated line to the nuclear power plant. At a blackout the offsite plant disconnects from the grid and starts feeding the nuclear power plant. The suitability of external steam turbines in different applications is seen in table 4. External steam turbines can be implemented as several redundant units in case suitable units can be found in the vicinity of the nuclear power plant and the separation between them is sufficient.

The concept with external steam turbines is characterized by:

- Relatively large diversification gains due to a site separated from the nuclear power plant.
- No challenges to existing equipment
- Many external parameters that should coincide: Possibility to depose enough heat, existence of suitable external power plant (or willingness to invest in one), willingness to act as emergency power supply to nuclear power plant.
- Existing power plants hard to classify as safety (1E / CatA etc.) equipment
- The line between the external power plant and the nuclear power plant must be protected.

Table 4. The suitability of extern steam turbine

External steam turbine			
Application	**Suitable**	**Suitable under certain preconditions**	**Unsuitable**
Onsite emergency AC source		X[1]	
Onsite emergency DC source			X[2]
Alternate AC source, small		X[3]	
Alternate AC source, large			X[4]
Alternate AC source, mobile			X[5]

[1]) Suitable provided that a suitable power plant exists/is built and that safety classification can be achieved

[2]) Unsuitable due to starting time > 0

[3]) Suitable provided that a suitable power plant exists/is built

[4]) Unsuitable due to lack of available power

[5]) Unsuitable power source to make mobile

3.5 Hydro power plant

The concept "hydro power plant" consists of an offsite hydro power plant that has a dedicated line to the nuclear power plant. At a blackout the offsite plant disconnects from the grid and starts feeding the nuclear power plant. The suitability of hydro power plants in different applications is seen in table 5. Hydro power plants can be implemented as several redundant units in case suitable units can be found in the vicinity of the nuclear power plant and the separation between them is sufficient.

The concept with hydro power plants is characterized by:

- Large diversification gains due to a site separated from the nuclear power plant and that the power generation is not based on combustion.
- No challenges to existing equipment
- Hard to evaluate the suitability of a hydro power plant without testing it's island operation capabilities.
- Some external parameters should coincide: Existence of suitable hydro power plant (or willingness to invest in one), willingness to act as emergency power supply to nuclear power plant.
- Existing power plants hard to classify as safety class (1E / Cat A etc.) equipment
- The line between the external power plant and the nuclear power plant must be protected.

Table 5. The suitability of hydro power plant

Hydro power plant			
Application	**Suitable**	**Suitable under certain preconditions**	**Unsuitable**
Onsite emergency AC source		X[1]	
Onsite emergency DC source			X[2]
Alternate AC source, small		X[3]	
Alternate AC source, large			X[4]
Alternate AC source, mobile			X[5]

[1]) Suitable provided that a suitable power plant exists/is built and that safety classification can be achieved

[2]) Unsuitable due to starting time>0

[3]) Suitable provided that a suitable power plant exists/is built

[4]) Unsuitable due to lack of available power

[5]) Unsuitable to make mobile

3.6 Batteries

The suitability of batteries in different applications is seen in table 6. Batteries are already implemented as several redundant units in nuclear power plants worldwide.

The concept with batteries is characterized by:

- Operation time normally <24 hours
- Possible to dimension power and energy modularly
- Continuously loading and able to deliver power instantly.
- Well established technology, new types are developed continuously

Table 6. The suitability of batteries

Batteries			
Application	**Suitable**	**Suitable under certain preconditions**	**Unsuitable**
Onsite emergency AC source			X[1]
Onsite emergency DC source	X		
Alternate AC source, small			X[1]
Alternate AC source, large			X[1]
Alternate AC source, mobile			X[1]

[1]) Unsuitable due to operation time < 72 hours

3.7 Fuel cells

The suitability of fuel cells in different applications is seen in table 7. They have in total too many shortcomings and doubts to be deemed suitable for any application. Their availability and dynamic behavior is insufficient and the diversification gains are small.

Table 7. The suitability of fuel cells

Fuel cells			
Application	**Suitable**	**Suitable under certain preconditions**	**Unsuitable**
Onsite emergency AC source			X
Onsite emergency DC source			X
Alternate AC source, small			X
Alternate AC source, large			X
Alternate AC source, mobile			X

3.8 Stirling engines

The suitability of stirling engines in different applications is seen in table 8. Stirling engines would require higher temperatures than what is available in a nuclear power plant to function satisfactorily, they are therefore deemed unsuitable for all applications.

Table 8. The suitability of stirling engines

Stirling engines			
Application	**Suitable**	**Suitable under certain preconditions**	**Unsuitable**
Onsite emergency AC source			X[1]
Onsite emergency DC source			X[1]
Alternate AC source, small			
Alternate AC source, large			X[1]
Alternate AC source, mobile			X[1]

[1]) Unsuitable since the available heat in the process is not sufficient

3.9 Thermoelectric generators

The suitability of thermoelectric generators in different applications is seen in table 9. Thermoelectric generators can only be implemented as a single unit due to lack of power.

The concept with thermoelectric generators is characterized by:

- Relatively large diversification gains due to resilience to low temperature and absence of gas formation.
- Hard to create a robust and simple solution that can supply a sufficient amount of elements with heat.
- Creates heat losses in the process.

- Cannot be charged during times with available AC power.
- Only available when process heat is available, not during outages for example.

Table 9. The suitability of thermoelectric generators

Thermoelectric generators			
Application	**Suitable**	**Suitable under certain preconditions**	**Unsuitable**
Onsite emergency AC source			X[1]
Onsite emergency DC source		X[2]	
Alternate AC source, small			X[1]
Alternate AC source, large			X[1]
Alternate AC source, mobile			X[3]

[1]) Unsuitable due to lack of available power

[2]) Suitable provided sufficient access to heating and cooling and that it is acceptable that it is only available when process heat is available.

[3]) Unsuitable due to lack of available power and that it is not suitable for mobility.

3.10 Flywheels

The suitability of flywheels in different applications is seen in table 10. Flywheels can only cope with short discharge times and are therefore not suitable for any of the stated applications, the minimum required discharge time is 8 hours.

The concept with flywheels is characterized by:

- Potential for high power discharges. Resilience to large number of discharges of different magnitudes.
- Only viable for short discharge times due to losses.

Table 10. The suitability of flywheels

Flywheels			
Application	**Suitable**	**Suitable under certain preconditions**	**Unsuitable**
Onsite emergency AC source			X[1]
Safety class DC source			X[1]
Alternate AC source, small			X[1]
Alternate AC source, large			X[1]
Alternate AC source, mobile			X[1]

[1]) Unsuitable due to insufficent discharge time.

5. Conclusions

Out of the 10 power sources, diesel generators, batteries and to some extent gas turbines are seen as conventional technology at the nuclear power plants. In relation to them the other power sources have been assessed regarding diversification gains, foremost with regards to external events. The power sources with the largest diversification gains are:

- Internal steam turbine
- Hydro power
- Thermoelectric generators

Of these three hydro power is the only one that can be available during reactor outages and accidents where steam is not available in the main process.

References

[1] Magnus Lenasson, "Comparison between different power sources for emergency power supply at nuclear power plants", Elforsk, Report no 13:87. Available 2014-02-26 at http://elforsk.se/Rapporter/?rid=13_87_

Comparison between Different Power Sources for Emergency Power Supply at Nuclear Power Plants

Solvina
Energy Excellence

Background

- Fukushima
- Common Cause Failure due to External Event
- Increased focus on diversification?
- In that case, which power sources should be used?

Solvina
Energy Excellence

Method

- Define different applications
- Identify essential parameters
- Identify acceptance criteria for the parameters
- Evaluate a number of power sources with respect to these parameters

Solvina
Energy Excellence

Applications

- Defined applications:
  - Onsite emergency AC Source
    - The ordinary emergency AC source, today mainly diesel generators, ≈ 2 MW
  - Onsite emergency DC Source
    - The ordinary emergency DC source, today mainly batteries , ≈ 200 kW
  - Alternate AC source, small
    - An alternate AC source designed to replace one of the ordinary emergency AC sources , ≈ 2 MW
  - Alternate AC source, large
    - An alternate AC source designed to supply half of the internal grid, both safety, safety related and non-safety equipment , ≈ 20 MW
  - Alternate AC source, mobile
    - An alternate AC source with tasks equal to "Alternate AC source, small" except it is mobile.

Solvina
Energy Excellence

Essential parameters

- Parameters used for evaluation:
  - Available power
  - Available energy and energy density
  - Maximum operation time
  - Dynamic operation
  - Starting time
  - Realizability of power sources within or outside the protected area
  - Availability and reliability
  - Possibilty to classify as safety equipment
  - Sensitivity to external events
  - Additional risks of challenging existing equipment
  - Aspects of maintenance and operational readiness
  - Mobility
  - Investment and operational costs

Solvina

Power Sources

- Investigated power sources:
  - Diesel generators
  - Gas turbines
  - Internal steam turbine
  - External steam turbine
  - Hydro power
  - Batteries
  - Fuel cells
  - Stirling engines
  - Thermoelectric generators
  - Flywheels

Solvina

Results

√=Suitable, X=Suitable under certain preconditions, -=Not suitable

Power source	Application				
	Onsite emergency AC source	Onsite emergency DC source	Alternate AC source, small	Alternate AC source, large	Alternate AC source, mobile
Diesel generators	√	-	√	X	√
Gas turbines	-	-	√	√	X
Internal steam turbine	-	-	X	-	-
External steam turbine	X	-	X	-	-
Hydro power	X	-	X	X	-
Batteries	-	√	-	-	-
Fuel cells	-	-	-	-	-
Stirling engines	-	-	-	-	-
Thermoelectric generators	-	X	-	-	-
Flywheels	-	-	-	-	-

Results continued

- Power sources with large diversification gains:
  - Internal steam turbine
  - Hydro power
  - Thermoelectric generators
- Hydro power does not require any specific operation mode in the NPP to work.