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Reliability based Redundancy Assessment of a Cogeneration Plant

Meseret Nasir* , Wan Mansor Wan Muhamad and Raja Aziz Raja Maarof

Mechanical Engineering Section, Universiti Kuala Lumpur, Malaysia France institute, 43650 UniKL, Bandar Baru Bangi, Selangor, Malaysia

ABSTRACT

Cogeneration systems are extensively used in Malaysia to produce power as a primary source. However, in the event of cogeneration system failure, the customer or the client are forced to use a redundancy to avoid power interruptions. There are two methods commonly used as a backup in the cogeneration systems which are Generator set and public utility. In order to choose the best redundancy for a particular cogeneration system, it is essential to evaluate the economic benefit analysis by considering several factors such as Maximum demand charge, installation cost and Discount interest. In the evaluation of economic benefit, this study identifies the number of failure and associated downtime using reliability and availability approach, and then present value method was applied. The result shows that the usage of public utility as redundancy is beneficial if the cogeneration system operates within five years period. However, if the cogeneration system operates more than five years, generator set option would be a better option to minimize the total cost. This research also addresses the effect of various factors such as installation cost, maximum demand charge, fuel cost, discount interest rate and production capacity. In general, the output of the research would be beneficial for the plant operator to select the appropriate redundancy option based on the economic advantages.

Keywords: Cogeneration, gas turbine, public utility, redundancy, reliability

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E-mail addresses:
meseret@unikl.edu.my/meseretreshid@gmail.com (Meseret Nasir)
drwmansor@unikl.edu.my (Wan Mansor Wan Muhamad)
azizmaarof@unikl.edu.my (Raja Aziz Raja Maarof)
* Corresponding author

INTRODUCTION

Cogeneration is a system using a single source of fuel to generate electricity and waste heat(Chen et al., 2018). This waste heat is useful to generate chilled water or steam depending on the customer need(s) (Reshid et al., 2017a, 2017b). The performance of cogeneration system is

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linked with availability. In the cogeneration system, high availability is the most important factor to avoid power interruption (Eti et al., 2007). In order to meet high availability, it is necessary that all equipment/subsystems of cogeneration plant remain in upstate condition for a longer duration of time. In other words, it is imperative for all subsystems to perform satisfactorily during their expected life span.

The performance of a cogeneration system relies on the availability and operating conditions of the equipment (Ramesh & Saravannan, 2011b). In a situation of a 1% reduction in availability for a macro cogeneration system, this results in unplanned shutdowns which causes about $500,000 loss of income (Meherwan, 2002). This economic loss has been estimated to be about 30% of the total cost of electricity generated by the cogeneration plant (Gräber, 2004; Lemma & Hashim, 2013). Such a proportion of expenditure is considered higher than what is encountered in other industries. One of the main reasons for the reduction of availability is failure. Failure is an unavoidable phenomenon which can occur unexpectedly. When failure occurs, efforts are needed to maintain the system and avert the associated risk due to it. The common practice to avert the associated risks due to failure is using redundancy or back up system. Generally cogeneration system uses two common redundancy options such as Generator set and public utility. Generator set (Genset) refers to a gas turbine driven generator as a redundancy used in a cogeneration plant. On the other hand, public utility refers to a cogeneration plant that taps electricity from the national power grid to avoid power interruptions. When the cogeneration system fails, the clients who are using the system as primary source of power are forced to use redundancy. However, the associated cost using redundancy is very high.

There are four major reasons for the need of redundancy (Pham & Wang, 1996). First is scheduled equipment maintenance. During the scheduled maintenance, the equipment will cease to function, for preventive maintenance or the Overhaul. Therefore, there is a need to have redundancy to continue supplying electric power to the user. The second reason is equipment failure. In such case, the equipment or the system needs to undergo corrective maintenance. During this time, the redundancy needs to supply the required demand to the client. Third is demand variations as the cogeneration plant is highly dependent on environmental conditions. The change in the environmental condition will cause fluctuation in demand. In order to cope with such circumstance, redundancy should be integrated. Finally, redundancy is needed due to special operating conditions. This condition refers to the startup and shutdown of plants which may cause trip or unexpected failure.

The economic analysis of power generating system is more closely linked to system availability and reliability analysis. This is because production interruption is one of the major worry for plant owners (Dougan & Reilly, 1993; Lewis & Lewis, 1987; Vega et al., 1998). The downtime cost in the power plant is very expensive apart from the maintenance cost of the equipment. During the plant outage, power is purchased from other sources to meet the demand of the utility system. Additionally, as Meherwan (2002) highlights, this can be very costly in terms of operation. Most power purchase agreements have articles which include maximum demand charge payments. This makes the power plant availability crucial for the power generation system (Meherwan, 2002). Unplanned outages may happen during peak generation seasons and usually result in significant losses. Richwine (2004) estimated that forced outages cost from 3 to 4.5 times as much as planned outages. Qiu et al. (2011) had established the failure cost model for power generating equipment in which it estimated the failure cost considering the probabilistic nature of failure. The probabilistic nature of failure was formulated using Weibull distribution. In their study, the cost of repair was only estimated, however; the failure cost should include the downtime cost which was caused by the failure.

Christiansen (2013) estimated unplanned outage events for 388 combined-cycle plants. The author collected 15-years data over 3000 units of the combined cycle power plant. The study identified the causes and durations of forced outages and unscheduled maintenance. Furthermore, reliability and availability were established for each class of plant. The costs to render the unit serviceable for each main outage were calculated, as were net revenues lost due to unplanned outages. Furthermore, Grace and Christiansen (2013) estimated the cost of unplanned outage events for combined-cycle systems. The study provided a detailed listing of events that caused forced and unscheduled maintenance outages in combined-cycle power plants, costs associated with such events and a quantified assessment of the economic impact that such outage events could have on overall maintenance costs and lost revenue.

Although several researches have been done on redundancy of power generating cogeneration plant, there still is lacking of research regarding the suitability of redundancy type to cogeneration plant. In fact, the choice of selecting the redundancy is normally left to the user. Thus, to avoid additional capital expenditure requirements, public utility is normally chosen to as redundancy, without considering the operation costs. From the experience of the cogeneration operators, the use of public utility can be expensive due to high cost of maximum demand charge that comes with, which is neglected in reviewed papers on redundancy. Thus, this paper analyses various redundancy options by considering several factors such as maximum demand charge, installation cost interest discount rate and failure frequency.

METHOD

In order to evaluate the redundancy options of the cogeneration power system, to the main requirement is to develop appropriate methodology which includes reliability, availability and economic assessment. The flow chart of the methodology is presented in Figure 1.

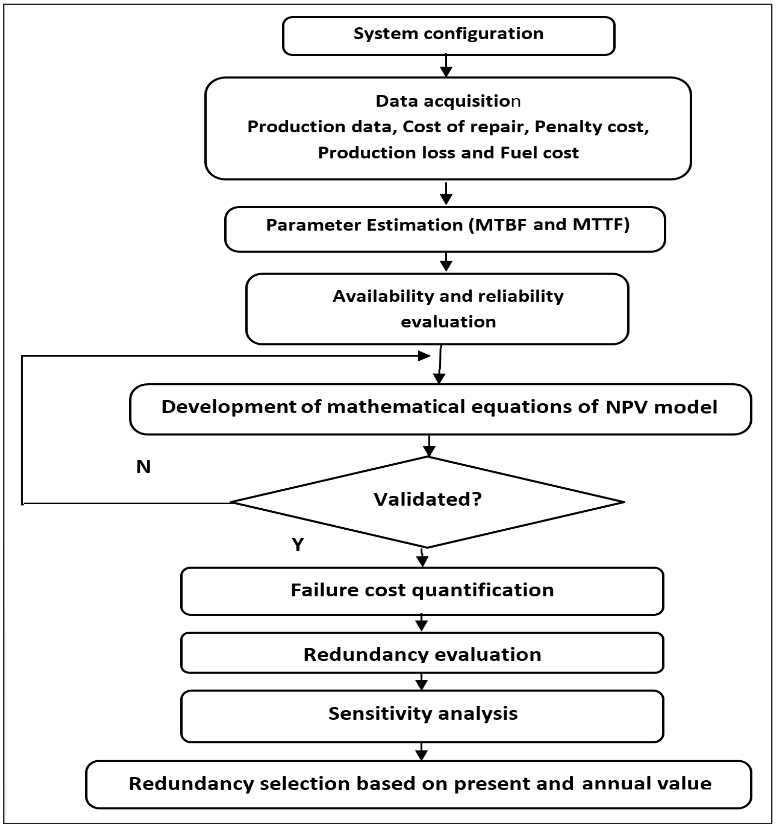

Figure 1. Methodology flow chart

Cogeneration System Configuration and Functional Block Diagram

A cogeneration system is a complex repairable system consisting of various subsystems such as gas turbine, heat recovery steam generator, steam absorption chillers, electric chillers and thermal energy storage systems which are linked in series, parallel or the combination of both (Arora & Kumar, 1997). The general network and configuration of the cogeneration system is depicted in Figure 3 Simulation block for power generation. The two main systems in the cogeneration system are gas-turbine (GT) and heat recovery steam generator (HRSG) (Shaaban et al., 2011; Soares et al., 2001). However, the configuration of cogeneration system differs depending on the consumer requirements and the site condition. Therefore, it is essential to integrate the cogeneration system with steam absorption chiller (SAC), auxiliary gas boiler (AGB), thermal energy storage (TES), and electrical chiller (EC) for the tropical region due to the need for high cooling loads. This fundamental configuration is useful to mitigate the wasted energy and increases the utilisation of the cogeneration system.

As observed in Figure 2, the gas turbine generates electric power and waste heat. The electric power goes to electric chillers and to the customer for electricity usage. The electric chiller uses electricity to produce the chilled water to supplement the high cooling load during the peak hour. This chilled water may also be reserved in the thermal storage. The waste heat generated from the gas turbine goes to heat recovery steam generator to produce steam. This steam is used for process heating in the steam absorption chillers. Finally, the chilled water will be supplied to the customer.

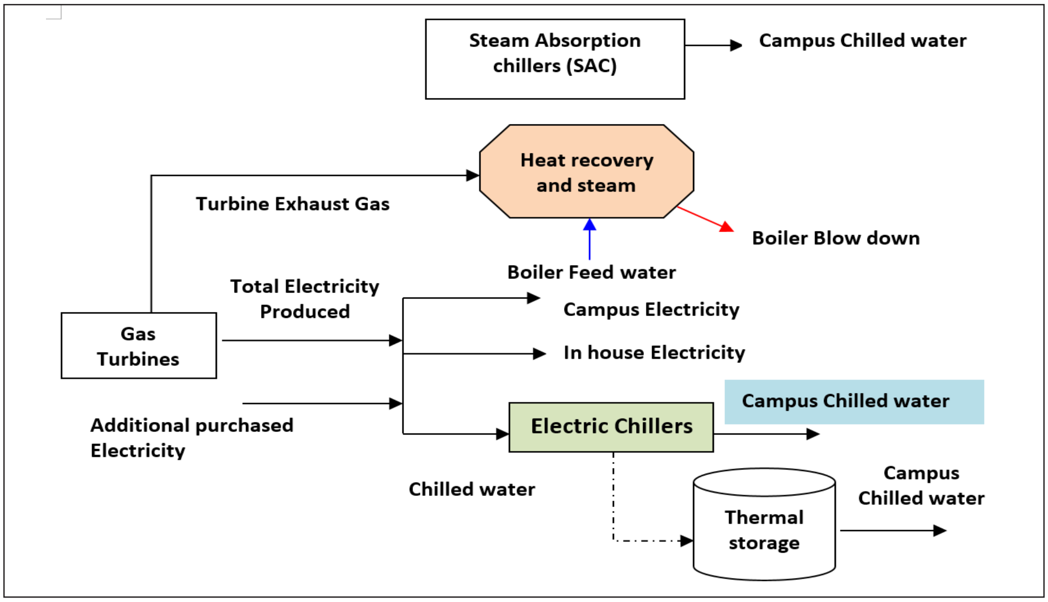

Figure 2. System configuration of cogeneration

Data Acquisition

The required data to develop the models are failure, repair and cost data. The failure and repair data are commonly used to develop the availability and reliability model. Unfortunately, the failure and repair data are scarce in many cases due to improper documentation of maintenance data (Louit et al., 2009). Therefore this study utilizes production data instead of maintenance data in the evaluation of availability and reliability. This is because production data is abundantly available. The operational hourly production data were collected from the plant historical production data and online observation to develop characterization of the cogeneration system for the period of five year. The collected data was filtered to exclude the holidays and schedule maintenance which was identified using calendar and the plant maintenance schedule. The reason is during the holiday or schedule maintenance, the system will be off or the generation capacity will be deliberately reduced. The performance data during this period does not reflect the characteristic of the system. Thus, this substantiates justification to regard the said period as irrelevant to the analysis. Furthermore, the performance data during start up and shutdown were also excluded from the analysis; because the system performance is low at these periods but most importantly, it is not due to the equipment problem.

The system operation and maintenance cost data were also gathered from the plant and literature to evaluate the redundancy options.

Parameter Estimation

Without reliability and availability assessment, it is difficult to predict the number of failures and downtimes which is used as an input for consequences assessment. In binary system performance evaluation, the equipment is characterized into two states such as working and failed state. These two states of the system can be determined by analysis of the mean time between failure (MTBF) and the mean time to repair (MTTR). MTBF estimates how frequently the system will fail. MTBF is also a basic parameters for reliability (Wang & Sivazlian, 1997). This can be represented by;

$$MTBF = \frac{Accumulated\ \ operating\ time}{Frequency\ \ of\ failure} \tag{1}$$

MTTR gauges how quickly the system is back to service. This can be represented by;

$$MTTR = \frac{Accumulated\ \ down\ time}{Frequency\ of\ \ failure} \tag{2}$$

In this study, exponential distribution can be used to evaluate the system or equipment reliability and availability for useful period of the bathtub curve (Rausand & Høyland, 2003). The exponential distribution is a good estimation for repairable system as most of the repairable component or system lies in the useful period of the bathtub curve. The useful period of the bathtub curve uses a constant failure rate which means that it can be approximated by the average actual changing rate during the respected time duration.

Equations (3) and (4) are used to define the system or equipment reliability and availability respectively.

$$R(t) = e^{-\lambda \cdot t} \tag{3}$$

$$A(t) = \frac{\mu}{\lambda + \mu} + \frac{\mu}{\lambda + \mu}.e - \left(\lambda + \mu\right)t \tag{4}$$

where λ is the failure rate and μ is repair rate of the equipment. λ and μ can be defined as Equation (5) and (6) respectively.

$$\lambda = \frac{1}{MTBF} \tag{5}$$

$$\mu = \frac{1}{MTTR} \tag{6}$$

The system reliability of series and parallel system configuration which contain n equipment can be represented by Equation (7) and (8) respectively (Rausand & Høyland, 2003).

$$R_s(t) = \prod_{i=1}^{n} \exp[\lambda_i t] = \exp\left(\sum_{i=1}^{n} \lambda_i t\right) \tag{7}$$

$$R_s(t) = 1 - \prod_{i=1}^{n} [1 - \exp \lambda_i t] \tag{8}$$

Similarly, the availability of the series and parallel system can be defined using Equation (9) and (10).

$$A_s(t) = A_1(t) A_2(t) \ldots\ldots A_n(t) = \prod_{i=1}^{n} A_i(t) \tag{9}$$

$$\begin{aligned} A_s(t) &= 1 - (1 - A_1(t))(1 - A_2(t)) \ldots (1 - A_n(t)) \\ &= 1 - \prod_{i=1}^{n} [1 - A_i(t)] \end{aligned} \tag{10}$$

Using Equations (7)-(10) depending on the configuration of the system, the cumulative number of failure and down time can be found using Equation (11) and (12) respectively.

$$N(t) = \lambda \cdot t \tag{11}$$

$$D(t) = [1 - A(t)] \cdot t \tag{12}$$

where $N(t)$ is the cumulative expected number of failure, $D(t)$ is the cumulative expected down time and λ is the constant system failure rate.

Estimation of Cost of Redundancy

In this section, the associated cost of public utility and Genset were formulated mathematically. Each redundancy options depend on various factors.

Cost of using Public Utility as Redundancy

When the cogeneration system used public utility as redundancy, the operator need to consider maximum demand charge due to hookup electricity from the grid, cost of repair and opportunity loss. Thus, the total expected cost can be estimated by Equation (13)

$$\begin{bmatrix} \textit{Total Expected} \\ \textit{cost of failure} \end{bmatrix} = \begin{bmatrix} \textit{Expected} \\ \textit{cost of repair} \end{bmatrix} + \begin{bmatrix} \textit{Expected cost of electricity supplied} \\ \textit{by redundancy} \end{bmatrix} + \begin{bmatrix} \textit{Expected cost of} \\ \textit{opportunity loss} \end{bmatrix} - \begin{bmatrix} \textit{Expected} \\ \textit{fuel save} \end{bmatrix} \tag{13}$$

Cost of Repair

When the system failed, corrective maintenance is applied to bring back the system into functional state. The cost of corrective maintenance (C_{cm}) can be defined as Equation (14).

$$C_{cm} = NC_r \tag{14}$$

where N is the frequency of failure per year and C_r is cost of repair per failure.

Maximum Demand Charge

Public utility supplies to a Co-generator in the incident that the Co-generator does not produce electricity due to plant failure. The Co-generator has an option of firm or non-firm supply. Non-firm standby means that public utility does not guarantee that supply can be given when the Co-generator fails. Due to its connection to public utility, maximum demand charge cost is imposed when the system fails. This cost is highly dependent on the frequency of the failure. The maximum demand charge cost per year (Cp) can be estimated using Equation (15)

$$C_P = NC_{Max}KZ \tag{15}$$

where C_{Max} is the Maximum demand charge cost per kw, K is the capacity in kw required per connection, and Z is the percentage ratio of the system hook-up of electricity from redundancy. This means only certain failures which get higher restore time will be hooked up with electricity from redundancy. The minimum waiting time to hook up electricity from redundancy system is based on the contract agreement between the cogeneration plant and the user. Thus, Z can be defined by applying Equation (16) based on the historical data of a cogeneration system.

$$Z = \frac{\textit{Number of hook up redundancy due to failure}}{\textit{Total failure frequency}} \tag{16}$$

Cost of Supplied Power by Public Utility

During system outage, the plant needs to purchase power from the public utility to avoid the customer damaging cost. This cost can be calculated using Equation (17)

$$C_s = D_t C_R E_R \tag{17}$$

where D_t is the total amount of time the plant would be out of service per year as a result of failure, C_R is cost of electricity rate per kw from public utility and E_R is the amount of energy supplied by the redundancy per hour.

Loss of Opportunity

Whenever the failure occurs, the system is down for repair action. This unavailability of the system will cause opportunity loss. This loss can be represented by

$$C_{Lp} = D_t CL \tag{18}$$

where C is cost per kw charged to clients and L is the possible amount of power delivered to clients during the service outage.

Fuel Save

When the system uses the public utility as redundancy in the event of failure, it is not required to supply the fuel for the cogeneration system as the system is down for maintenance action. This fuel save F_S can be estimated using Equation (15)

$$F_S = C_f D_t Y \tag{19}$$

where C_f is the cost of fuel per GJ and Y is the amount fuel required to operate cogeneration per hour.

Therefore, the annual expected cost of failure (AECF) can be obtained using equation (20)

$$AECF = NC_r + NC_{Max}KZ + D_t CL + D_t C_R E_R + C_f D_t Y \tag{20}$$

Cost of using Gen Set

If the plant uses a Gen set as redundancy, three main cost need to be considered, namely capital which is related to installation cost, cost of repaired which is related to maintenance and fuel cost which is related to operation cost. All these costs can be represented by Equation (21)

$$AECF_{Genset} = [C_i Q][A/P, i, m] + NC_r + D_t C_f L \tag{21}$$

where Q is the capacity of redundancy, C_i is the cost of installation per KW and C_f is the cost of fuel to operate the Gen set.

The annual expected cost of failure can also be represented by the net present value (PV) using Equation (22) (Sullivan et al., 2000). The present value means the monetary amount that should be deposited at a certain rate to pay outlay after n years. This means that all the annual costs are recalculated to the equivalent value of the present time.

$$PV = AECF(P/A, i, m) \tag{22}$$

where $(P/A, i, m)$ is the present worth factor, m is number of years and i is the interest rate.

RESULTS AND DISCUSSION

Case Study

Universiti Teknologi PETRONAS (UTP) power generation cogeneration was taken as a case study. The availability and reliability of the power generation was linked to the operation of the two parallel gas turbines installed in the plant. The failure of any one of the two gas turbines would cause reduction of power being generated. If both turbines failed, no power will be generated to be supplied to the client. To avoid this occurrence, the system needs to have back up power supply. For the case of this plant, the backup is obtained from the national grid. This similar case is being practiced by other cogeneration plants (Haghifam & Manbachi, 2011; Ramesh & Saravannan, 2011a, 2011b; Shaaban et al., 2011). One of the main disadvantages of using the national grid as back up is the high cost of maximum demand charge. This, in turn, leads to high cost charged for any hook up to the national grid when turbine(s) failed. The configuration of power generation system is indicated in Figure 3. In this research, a cogeneration plant which consists of two gas turbines is taken as a case study. The turbines are connected using parallel configuration to produce electricity for the university area as shown in Figure 3. This simulation block diagram is developed using BlockSim software. When both turbines fail, the system used public utility as redundancy. To determine MTBF and MTTR, five years of historical performance data of Gas turbine were used. In order to capture the failure event and MTBF from gas turbine performance, the minimum acceptable performance of the gas turbine was determine based five years daily historical and technical data. Thus, 1497KW is considered as minimum acceptable performance for both turbines. Any performance of gas turbine below the minimum level is considered as the gas turbine in failed state. Based on this assumption, the MTTF, MTBF, downtime, operating hours, and failure event are estimated as shown Table 1.

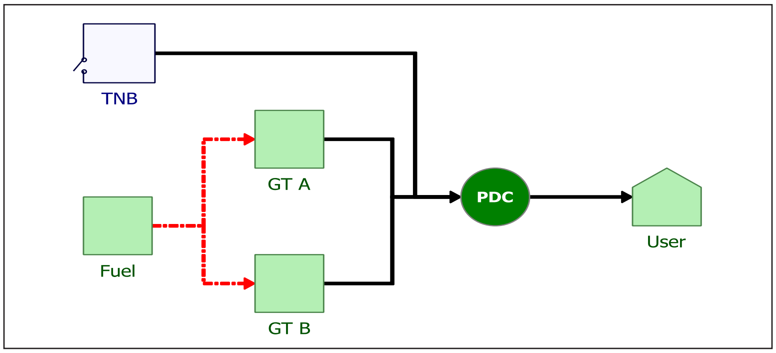

Figure 3. Simulation block for power generation

Table 1
Reliability and availability parameters

Parameters	Unit	Value
Accumulated Operating Hours	Hr	14270
Accumulated Downtime Hours	Hr	594
Failure Frequency	Number of failure	54
MTBF	Hr	264.3
MTTR	Hr	11

Estimation of Availability and Reliability

The availability and reliability analysis were performed using BlockSim software. Figure 4 illustrates the availability of power generation system. The plot reflects that the use of redundancy may enhance the performance of the system. The mean availability of the system with redundancy was about 98% while the mean availability of power generation without redundancy is about 85%. The increment of performance obviously will enhance the profitability of the system and create conducive working environment for the utility plant, even though the cost of redundancy is expensive.

Figure 5 shows the reliability of the system with and without the effect of redundancy. The reliability of the system working without redundancy is less than the system working with reliability. If the system was working without redundancy, there is a high probability that the system may experience a failure compared to the system working with redundancy.

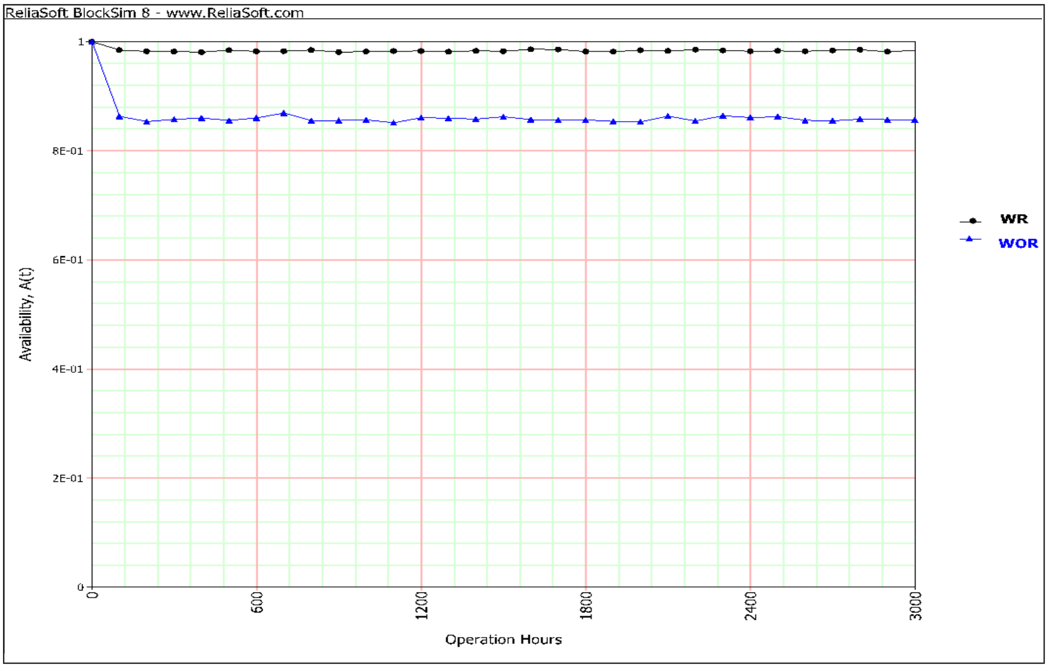

Figure 4. Binary system availability of power generation with redundancy (WR) and without redundancy (WRO)

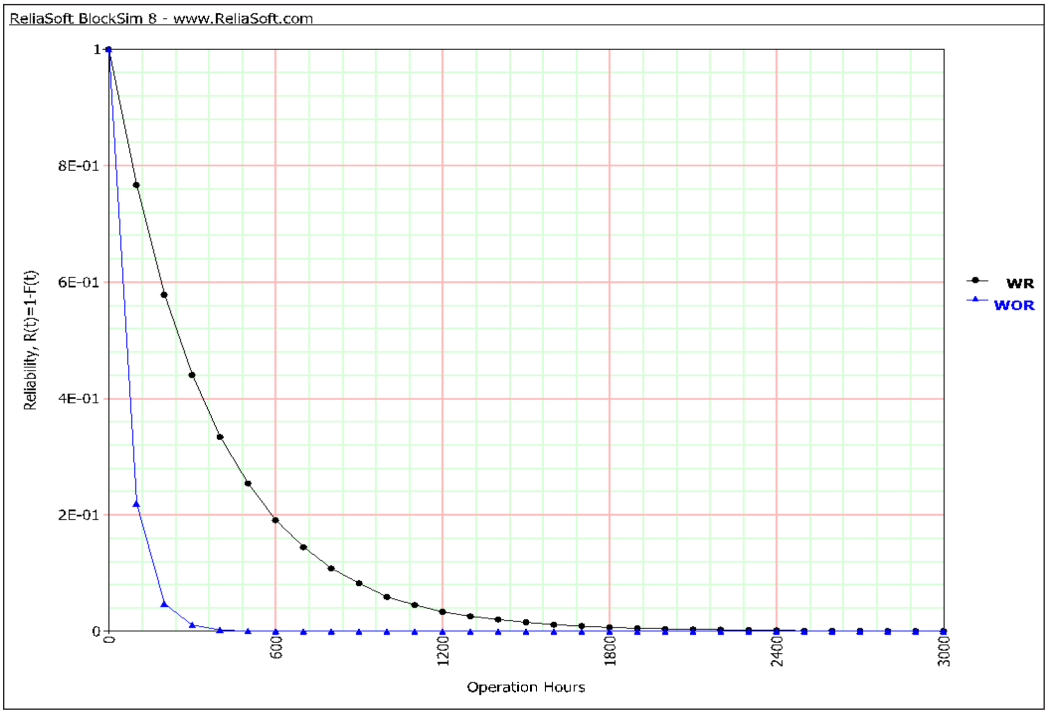

Figure 5. Binary system reliability of power generation system with redundancy (WR) and without redundancy (WRO)

Estimation of Cumulative Number of Failure and Downtimes

Figure 6 and 7 show that cumulative number of failure and downtime of power generation through time respectively. As indicated in the plots, the model predicted value was compared with actual failure frequency and downtime. The validation results show that the model prediction was closer to actual data. This validation results were further confirmed using t-test by considering five years observation data. Table 2 shows that the summary of statistical results using cumulative downtime hours. The statistical results indicate that there is no statistical difference between the predicted and actual downtime and number of failure. The P value results indicate 0.095 and 0.062 for cumulative failure and down time. This mean that statistically no significant different between the model and actual data as the significance value (p) is greater than 0.05 with 95% confidence level.

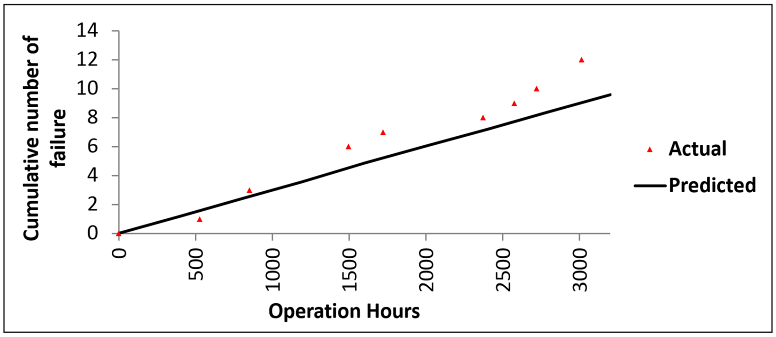

Figure 7. Cumulative downtime hours

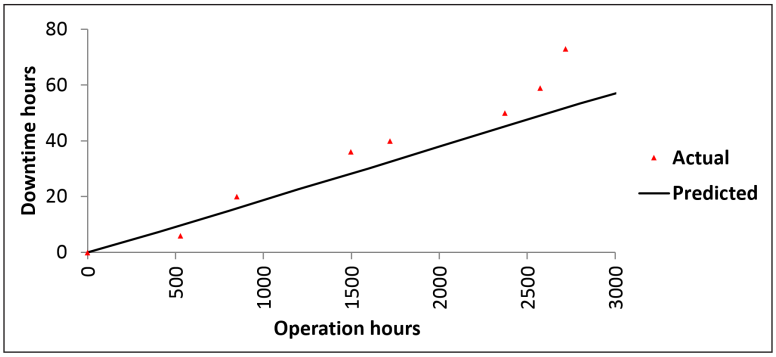

Figure 6. Cumulative number of failures

Table 2
Statstical validation with cumulative number of failures and downtime hours

Statistical Parameters	Cumulative Number of failure	Cumulative downtime hours
P value	0.095	0.062
t critical value	2.2622	2.30600

Validation and Sensitivity Analysis of Redundancy Cost

The system operation and maintenance cost data were also gathered from the plant and literature to evaluate the cost of redundancy. The sample costs data considered in this study are shown in Table 3.

Table 3
Input parameters for redundancy cost evaluation

Parameters	Unit	Values
Cost of Maximum demand	RM / KW	48.6
Cost of Electricity	RM/ KW	0.22
Cost of repair	RM/failure	100000
Cost of fuel	RM/GJ	6.066
Fuel flow	RM/GJ/Hr	49.74
Investment Cost for Gen set	RM/ KW	999
Production cost of Gen set	RM/set	0.17
Current demand of the campus	KW/day	5000
Maximum demand	KW	8400

The expected cost of failure were estimating the cost of failure caused by the actual downtime and failure frequency, and then compared with the cost calculated with the predicted failure and down time using Equation (20) and (21). The results are shown in Table 4 and 5. The estimated present value of failure cost for the actual failure and down time is -RM 7,722,356 while the present cost of failure for predicted failure and down time is RM 7,338,172. The annual value for five years using the actual down time and number of failure is RM 2,545,317 while the annual cost of failure for predicted failure and down time is RM 2,582,199. Based on the present and annual cost of failure, the deviation between the actual and predicted value is 1.43% which falls within acceptable margin. Thus, the developed failure cost model is useful to predict the impact of failure in monetary value.

Table 4
Cumulative failure cost based on actual number of failure and downtimes

Year	Expected Cost of production loss (RM)	Expected Penalty cost	Expected Cost of supplied power	Expected Cost of repair	Fuel cost saving	Total Expected cost of failure
0	0	0	0	0	0	0
1	-53,391	-1,270,353	-69,095	-777,945	18,952	-2,151,833
2	-97,884	-2,328,981	-126,674	-1,426,233	34,746	-3,945,026
3	-134,962	-3,211,171	-174,656	-1,966,473	47,907	-5,439,354
4	-165,859	-3,946,329	-214,641	-2,416,672	58,875	-6,684,628
5	-191,607	-4,558,961	-247,963	-2,791,839	68,015	-7,722,356

Note: The unit of all costs used in this study is Malaysian Ringgit (RM)

Table 5
Cumulative failure cost based on predicted number of failure and downtime

Year	Expected Cost of production loss	Expected Penalty cost	Expected Cost of supplied power	Expected Cost of repair	Fuel cost saving	Total Expected cost of failure
0	0	0	0	0	0	0
1	-73,333	-1,071,630	-56,667	-583,333	-20,115	-1,764,848
2	-128,333	-2,474,955	-99,167	-1,347,222	-35,201	-4,014,476
3	-184,988	-3,325,455	-142,946	-1,810,185	-49,215	-5,414,359
4	-228,095	-4,122,799	-175,845	-2,244,213	-61,039	-6,709,913
5	-265,229	-4,647,799	-204,539	-2,565,715	-71,224	-7,612,057

Note: The unit of all costs used in this study is Malaysian Ringgit (RM)

As can be seen in Figure 8, 58.5% of the failure cost was due to penalty cost (maximum demand charge) of failure, 35.8% was the cost incurred to restore the system, 3.2 % was contributed by the electricity used during downtime of the cogeneration systems and 2.5% was the estimated loss of power due to cogeneration system failure. It can be observed that Maximum demand charge contributes to the high cost of using public utility as a redundancy system for cogeneration plant. Public utility is a power supplied by the national electricity. Basically the use of redundancy is associated with number of failure. This means that it relates further with reliability and availability. Hence, predicting the number of failure and down time will support the development of maintenance strategy, thus reducing the frequency of occurrence for redundancy to be utilized. This also helps in reducing the cost of maximum demand charge to be borne by the client. Essentially, the reliability and availability of the power generation system is enhanced. It also minimizes the cost of failure associated with redundancy.

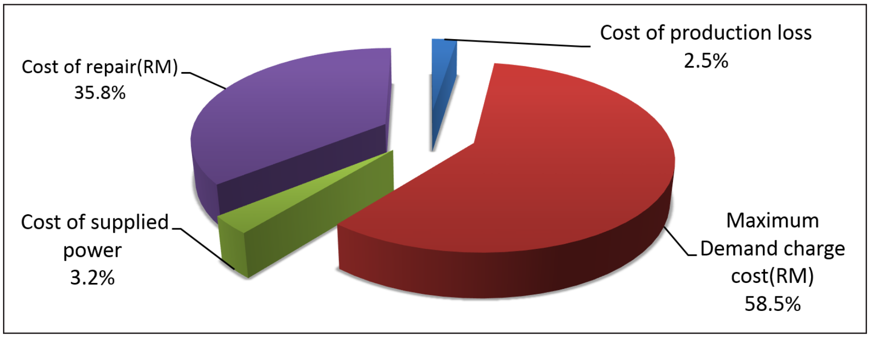

Figure 8. Contribution of failure cost

Spider Plot Analysis

The redundancy selection is affected by several factors such as Maximum demand charge, installation cost and Discount interest. These factors are not constant from place to place and through time as well. In order to analyse the effect of each parameter, the spider plot analysis was used. Figure 9 and 10 showed the effect of various parameters for both redundancy possibilities such as public utility and Gen set respectively. The intersection of each curve with the abscissa shows the decision reversal point - the percentage change from each factor's most likely value at which the PW is zero. As shown in Figure 9, the slop of Maximum demand charge and MARR steeper compare to other factors which means that the PV for public utility is more sensitive to Maximum demand charge and MARR. Similarly, Figure 10 shows the installation cost is more sensitive to Gen set compared to other factors. Thus, the cogeneration operator need to look closely on Maximum demand charge, MARR and installation cost to choose the best redundancy options.

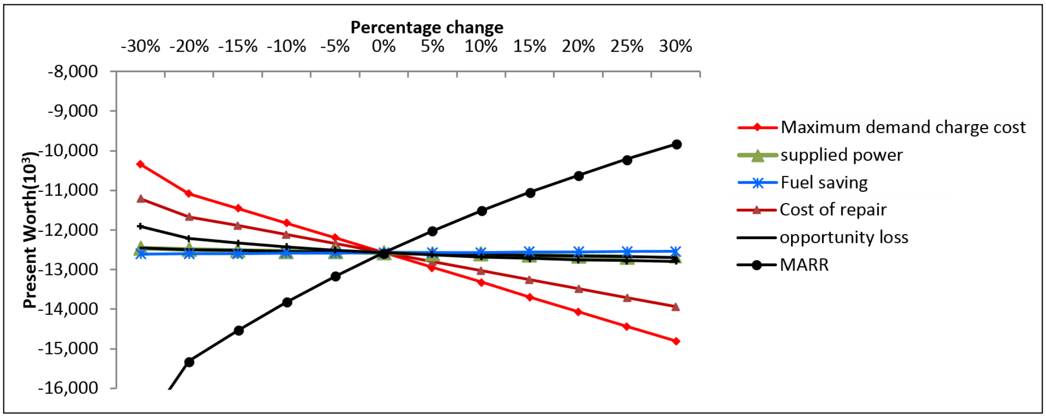

Figure 9. Sensitivity analysis for public utility

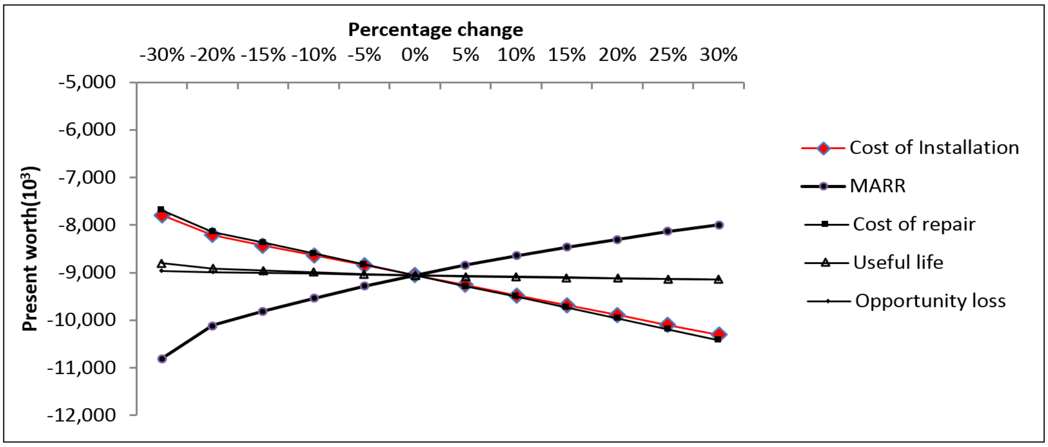

Figure 10. Sensitivity analysis for Gen set

Redundancy Evaluation of Power Generation System

Redundancy is essential for power generation to improve the performance of the system but it is very expensive to operate as it incurs maximum demand charge penalty. To avoid the redundancy totally from the system is difficult because the customer damaging cost of the utility system is substantial. However, one can minimize the effect of redundancy by selecting the suitable type. Currently, the campus electricity generation system uses public utility as redundancy, but it can alternately install Gen set as redundancy options. In order to compare these two redundancy options, Equation (22) were used to estimate the associated present of each redundancy option for a 20 years' life span. The results of present value of each redundancy are presented in Figure 11. This result shows that in the first 5 years, the present value of public utility is less than Gen set which means that it is a better option than Genset if the useful period of cogeneration is less than 5 years. However, when the useful period of cogeneration is greater than five years, Gen set would serve well as the present value is less than public utility. The present value for public utility and Genset redundancy at the end of 20 years were RM11, 948,611 and RM8,721,946 respectively. Thus, by the end of year 20, using Gen set would minimise 24% of the redundancy cost compared to Public utility.

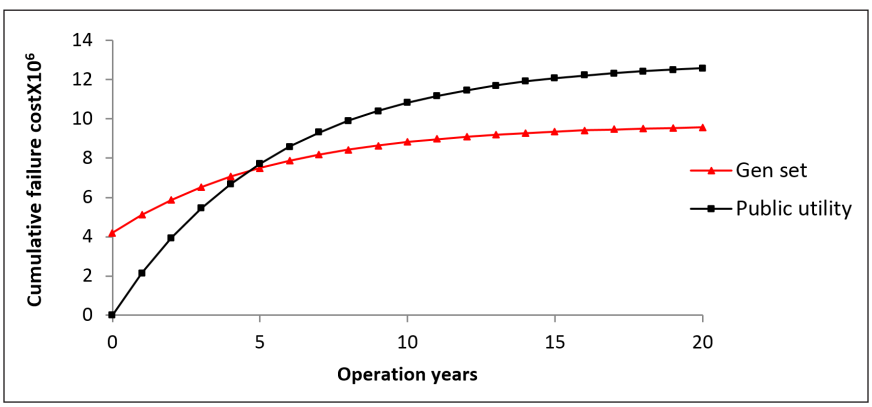

Figure 11. Comparison of Gen set and public utility based on failure cost evaluation

Effect of Installation Cost, Maximum Demand Charge and Discount Interest On Redundancy Selection

There are certain factors which can affect the failure cost of Gen set and public utility such as installation cost, capacity, maximum demand charge, and interest rate. These parameters may vary from time to time or place to place. Thus, there is a need for sensitivity analysis in order to identify the breakeven point for decision making. Regarding installation cost, the information taken from gas turbine hand book (Farmer & De Biasi, 2010) infers that Gen set installation range from approximately \$300 per kW for very large utility-scale plants to $1,000 per kW for small industrial cogeneration installation. However, the prices of construction can vary as a result of local labour market conditions and the geographic conditions of the site. Figure 12 shows the effect of cost of installation on annual cost for different redundancy options. The variation in installation cost affect the Gen set redundancy than public utility because the public utility redundancy is already installed and functions with the existing system. The plot result indicates that if the cost of installation was less than RM1714.73 per kW, Gen set would be preferable to public utility. However, if the cost of installation for Gen set is higher than RM1714.73, public utility would be a better option.

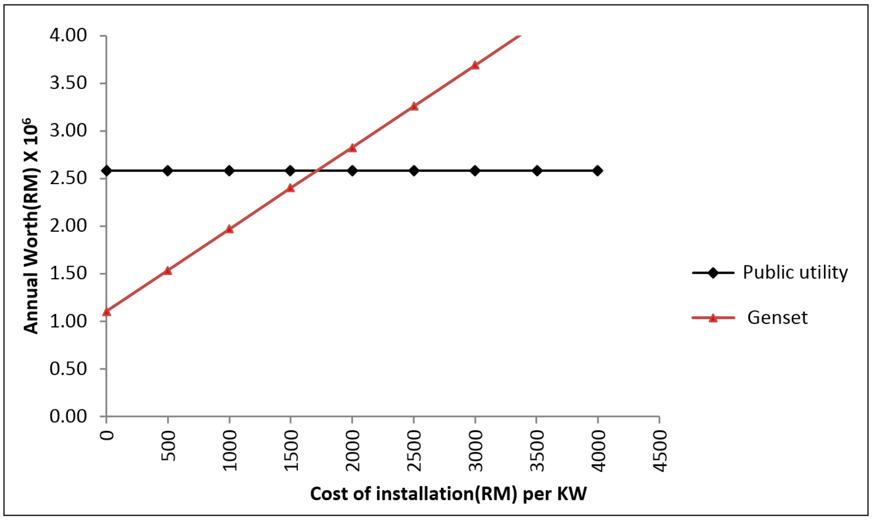

Figure 12. Effect of installation cost on redundancy evaluation

The second factor is the maximum demand charge. The maximum demand costs may vary depending on the plant's location. In areas where electricity costs are high, for a base-load cogeneration system, its costs can account for up to 70% of the total plant consequence costs. The sensitivity was done by varying the maximum demand charge from RM0 to RM60 per kW. Figure 13 shows that the breakeven value for maximum demand charge cost is RM28.92 per kw. If the maximum demand charge is less that 28.92 kW per hour, using public utility as redundancy could be a better option. On the contrary, if the penalty cost is higher than RM28.92 per kW, Gen set could be a better option.

The installed capacity of the Gen set varies based on the demand of customer and interest of the owner to make a decision on the redundancy. So, one needs to see the effect of installed capacity by comparing with the existing installed public utility. Figure 14 shows the comparison of public utility redundancy with Gen set when the capacity is increasing. The breakeven capacity is 7.43 MW. If the plant installed the Gen set capacity at less than 7.43 MW, the public utility option should be rejected. If the plant installed more than 7.43 MW, it is better to use public utility as redundancy than Gen set.

The minimum attractive rate of return (MARR) is one of the factors that may affect the consequence of failure, which also varies through time. The effect of MARR on redundancy selection is shown in Figure 15. As it can be seen from the graph, if the MAAR is less than 35%, Gen set can be chosen as redundancy. If discount rate is greater than 35%, public utility is the better redundancy option. Spacing is different for this section.

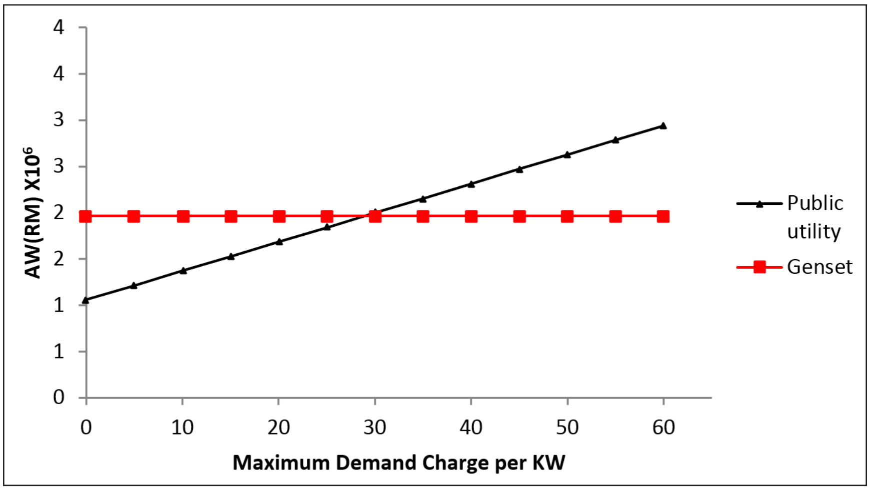

Figure 13. Effect of maximum demand charge on redundancy evaluation

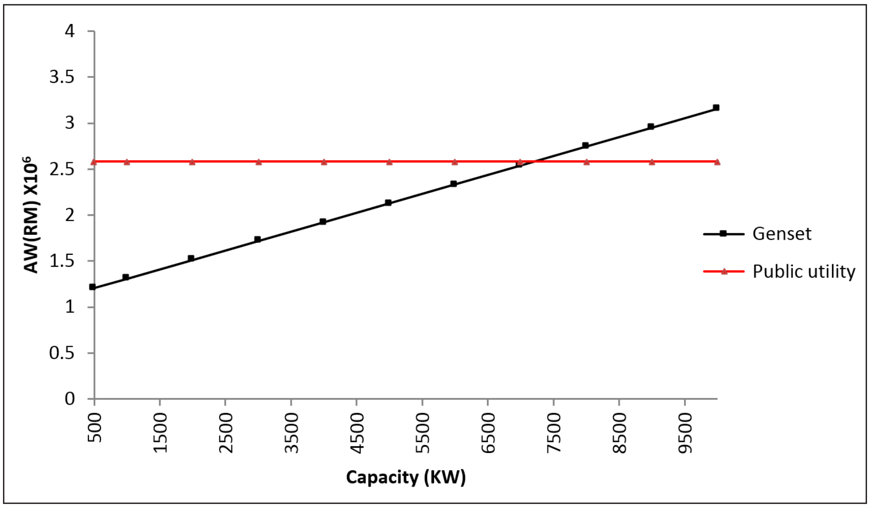

Figure 14. Effect of capacity on redundancy evaluation

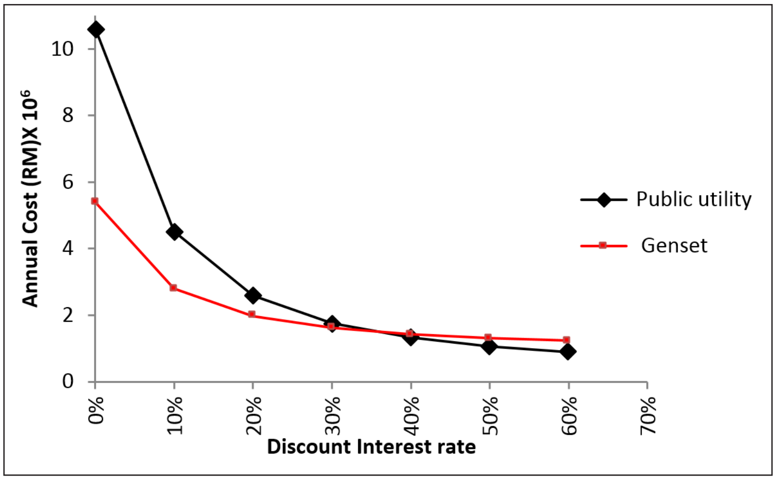

Figure 15. Effect of interest rate on redundancy evaluation

CONCLUSION

This study is very useful as it analyses various redundancy options for cogeneration system from an economic perceptive. Furthermore, it developed a reliability based cost model which included reliability and availability concept to analyse the economic benefits on the selection of redundancy for cogeneration plants. This paper also examines various factors which can affect the selection of redundancy. The case study findings indicated that gen set redundancy is better if the cogeneration plant operates for a period of more than five years. However, in short term cogeneration operations which accounts for less than five years, the public utility would be a better options. The sensitivity analysis also indicated Maximum demand charge, MARR and installation cost have significant effect on the selection of redundancy. In general, this study is very useful for cogeneration operators to select the best redundancy option which incurs minimum cost.

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