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Optimal nuclear trigeneration system considering life cycle costing

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ABSTRACT

A nuclear reactor can generate a large amount of high-temperature waste heat, which can be recovered to produce simultaneous electricity, heating and cooling, known as a trigeneration system. Trigeneration System Cascade Analysis is a methodology based on Pinch Analysis to optimise a centralised trigeneration system in various energy ratings in demands. However, the previous study does not consider a complete life cycle costing in the Trigeneration System Cascade Analysis. The methodology consists of three main parts, which are data extraction, development of Trigeneration System Cascade Analysis, and calculations of the life cycle costing. In this analysis, a centralised Pressurised Water Reactor, which is the most commonly used nuclear reactor in the world, is applied in a trigeneration mode in three different industrial plants. Based on the results of the case study, an optimal Pressurised Water Reactor trigeneration system is obtained where the total thermal energy required is 1,102.25 MW or translated into 26.5 GWh/d. The Equivalent Annual Cost for the case study, on the other hand, showed the centralised Pressurised Water Reactor trigeneration system requires 1.89×10^{11} USD/y for maintaining, operating, constructing, and disposing of the overall Pressurised Water Reactor trigeneration system. The maintenance cost is the highest percentage which constitutes 51.3% of the overall cost. Comparisons between normal conditions, and planned and unplanned shutdowns are also conducted, and the results show that Equivalent Annual Costs of planned and unplanned shutdowns required an additional 1.4 MUSD and 0.5 MUSD to support the deficit energy during shutdowns. The implementation of the full life cycle costing during the normal conditions planned and unplanned shutdowns of the Pressurized Water Reactor trigeneration system gives a proper projection of the cash flows that can create an economic model that reflects all the project realisation conditions.

1. Introduction

Renewables and conventional power plants such as nuclear reactors typically have not fully utilised their potential to generate electricity. Around 30–40% of the total thermal energy are used to generate electricity, and the rest of it is dissipated into the surrounding (Wu and Wang, 2006). Many countries, including Malaysia, have taken actions to improve the efficiency of their renewables and conventional power plants. The Malaysian government, for instance, has taken the initiative to propose a comprehensive Energy Efficiency and Conservation Act to promote the effective utilisation of energy (Zulkifli, 2021). Cogeneration and trigeneration development are among the newest sectors that received special incentives from the government of Malaysia through the Green Technology Master Plan (GTMP) (Zailan et al., 2021). Implementation of a trigeneration system for renewables and conventional power plants can improve thermal efficiency by up to 90%. The trigeneration system is defined as a technology that can simultaneously generate power, heating, and cooling to improve thermal efficiency and help reduce the dependency on fossil fuels and mitigate climate change. As stated by Birol (2021), energy demands in the European Union are estimated to increase from 120 GW in 2019 to 270 GW in 2050 due to the increase in the deployment of heat pumps and air conditioners.

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Through a trigeneration system, waste heat from the power station can be reused to perform other applications such as district heating and district cooling. Reusing waste heat from the power station enables thermal energy to be fully utilised, reduces fuel usage and at the same time meets the required energy demands. An optimisation method for designing a trigeneration system has been widely applied to minimise cost and energy. Kavvadias and Maroulis (2010) have developed a multi-objective optimisation method considering technical, economic, environmental, and energetic performances to design optimal trigeneration plants. An amortisation period of networks and machines for the optimal trigeneration system is considered by Buoro et al. (2011) through the use of the Mixed Integer Linear Program. Piacentino et al. (2015) proposed an optimal trigeneration system considering layout, design, and operation parameters for hotel buildings. A methodology based on Pinch Analysis for designing an optimal trigeneration system in a continuous Total Site System (Klemeš et al., 1997) known as Trigeneration System Cascade Analysis (TriGenSCA) has been developed by Jamaluddin et al. (2019). The application of TriGenSCA was then extended by Jamaluddin et al. (2020) to include batch processes of the Total Site System to obtain an optimal size of a centralised trigeneration system. Lee et al. (2020) later merged the concept of a Locally Integrated Energy System (LIES) into a Total Site System to obtain savings of energy by reducing the conversion of energy in the trigeneration system. Recently, Jamaluddin et al. (2021) modified the TriGenSCA method by considering transmission and storage energy losses in the analysis. The study, however, does not consider a complete life cycle costing.

Pinch Analysis was initially proposed to design energy-efficient heat exchanger networks by analysing heat flow based on thermodynamics fundamentals (Linnhoff et al., 1982). Later, the Pinch Analysis has been progressively developed into a methodology that can optimise various kinds of resource networks such as water, heat, carbon, mass, power, and property. Implementing power applications based on Pinch Analysis has been initiated by Bandyopadhyay (2011) to design isolated renewable energy systems with storage based on the concept of the Grand Composite Curve (GCC) (developed by Linnhoff et al., 1982). The concept of the Power Pinch Analysis was then extended by Ho et al. (2012) to form a numerical approach called Electricity System Cascade Analysis (ESCA) for the optimal design and sizing of a non-intermittent power system with energy storage. A graphical approach known as Power Composite Curves (PCC) and Continuous PCC (CPCC) was developed by Wan Alwi et al. (2012) to obtain the available excess electricity for the next day (AEEND) and the minimum outsourced electricity supply (MOES) during start day and continuous 24 h operations for hybrid power systems (HPS). The AEEND and MOES are necessary for PCC and CPCC to enable users to downsize or upsize the HPS. Mohammad Rozali et al. (2012) then extended the PCC and CPCC in a numerical approach by proposing Storage Cascade Table (SCT) to consider energy losses due to charging and discharging in the storage as well as inverter and rectifier during electricity targets setting. A new graphical tool based on Pinch Analysis was developed by Wan Alwi et al. (2013) to visualise the current storage capacity, and the minimum outsourced electricity during start-up and continuous 24 h operation of HPS, known as Outsourced and Storage Electricity Curves (OSEC). The application of OSEC enables the users to shift loads for the HPS to reduce the maximum capacity of storage. Mohammad Rozali et al. (2014) then created three different scenarios for the reduction of capital and operating costs and used SCT to give directions on HPS to achieve technical and economic feasibility. Giaouris et al. (2014) developed a systemic approach by using Power GCC to adaptively adjust in short-term power needed for the system operation. Power Pinch Analysis was later extended by Esfahani et al. (2015) to obtain the lowest external electricity source needed and appropriate energy storage systems in renewable energy systems. Load shifting from peak to off-peak hours enables users to control the demand of electricity peak and allows them to optimise the electricity cost. The application of load shifting in the Power Pinch Analysis was proposed by Mohammad Rozali et al. (2015) to optimise the cost of electricity for an HPS. Norbu and Bandyopadhyay (2017) proposed a methodology based on Power Pinch Analysis to determine the minimum capacity of the HPS generator and the corresponding storage capacity by considering uncertainty constrained. The Power Pinch Analysis is then modified by Priya and Bandyopadhyay (2017) to address multi-objective problems for minimising the land and water footprints as well as capital cost with energy generation for the Indian power sector. Chaturvedi (2020) proposed a method to calculate the rating of power resources needed to satisfy power demands and minimise electricity cost in HPS. The latest study on the concept of Power Pinch Analysis was developed by Chaturvedi (2021) to set an optimal cost for a HPS.

A nuclear reactor is a type of power plant that can generate electricity from the splitting of atoms (from fission processes). The world is progressively shifting the fuel energy from fossil fuel to nuclear and renewables as the fossil fuel reserves are declining. Recently, at least 19% of the total annual electricity has been obtained from nuclear reactors in the US. However, e.g. in France, 70% of the total electricity generation comes from nuclear reactors (U.S. Energy Information Administration, 2021). Abe (2021) stated that in 2050, the capacity of the global nuclear electrical generation is expected to increase twice the current nuclear capacity. The rising development of nuclear reactors enhances the researchers to find opportunities to improve thermal efficiency for nuclear reactors (Khamis et al., 2013). Locatelli et al. (2017) proved that reducing the generation of nuclear power is economically insufficient, and then the study proposed options to reuse waste heat energy for district heating, desalination, and hydrogen production by implementing a cogeneration system to improve the thermal efficiency. The first commercial nuclear district heating is developed in Haiyang nuclear power plant, Shandong, to deliver heat to 700,000 m^3 of housing areas during winter and provide 20 TWh of electricity for a population of 300,000 (The Royal Society, 2020). Recently, several studies on the nuclear trigeneration system are proposed that the system is more beneficial in terms of improvement of thermal efficiency as compared with the cogeneration system. Zwierzchowski et al. (2019) introduced an innovative nuclear trigeneration system with thermal energy storage for the buildings by supplying useful heat for heating and cooling for air-conditioning. The results show a large significant reduction in energy usage, nuclear fuel consumption, and heat delivery losses. A recent study on evaluating the thermodynamic performance of a Supercritical Water Reactor as a nuclear trigeneration system was done by Marques et al. (2020), and the results present that the system has the potential to generate 5 kg/s of hydrogen, 960 kg/s of desalinated water, and 400 MW of electricity.

Jamaluddin et al. (2020) have developed a methodology based on Pinch Analysis to optimise a centralised trigeneration system based on variations of demands which is known as TriGenSCA. However, the development of the TriGenSCA does not consider a complete life cycle cost analysis in the calculation. This paper proposes an extended methodology based on Pinch Analysis to optimise a centralised nuclear trigeneration system with consideration of the life cycle cost calculation. Disposal of nuclear waste fuel requires a huge amount of cost as the radioactive materials need to cool down in spent fuel before the waste fuel is buried in a deep geological repository. The cost of radioactive management and disposal of the nuclear plant also need to be taken as considerations to complete the life cycle cost. The cost analysis is important for completing the life cycle analysis of a system to determine projections of future cash flows. The proper projection of the cash flows can create an economic model that reflects all the project realisation conditions. Comparisons of the costing between normal conditions planned and unplanned shutdowns are also presented in the discussion section.

2. Conceptual design of PWR as nuclear trigeneration system

In this paper, Pressurised Water Reactor (PWR) is applied as a centralised nuclear trigeneration system. The PWR, which is the most commonly used nuclear reactor in the world, contributes to 301 out of 454 nuclear power plants, or 66% of all operating nuclear reactors (Ho et al., 2019). Fig. 1 shows the conceptual design of the PWR as a centralised nuclear trigeneration system supplying electricity, heating, and cooling to three different demands, namely Plants A, B, and C. The PWR generates steam from thermal energy that is used to drive a turbine for electricity generation. Some of the waste heat is dissipated to the surroundings while others are recovered from heat recovery to supply heating and pass-through refrigeration system to generate cooling. The Heat Recovery Steam Generator is used for heat recovery to reuse excess heat after the steam is supplied to the power turbine (Khaliq et al., 2009). The absorption chiller is chosen to be implemented as a refrigeration system. The details of the absorption chiller operation can be found in Jamaluddin et al. (2019). As for the electricity and thermal storage systems, a lead-acid battery is applied for storing electricity, whereas thermochemical storage is used to store heating and cooling energy.

To demonstrate the analysis, the assumptions of the nuclear trigeneration system design are as follows:

(i) The thermal efficiency of the centralised nuclear trigeneration system is assumed to be 90% (Wu and Wang, 2006). The thermal efficiency presents the useful energy over the total energy in the centralised nuclear trigeneration system.

(ii) The charging and discharging efficiencies of lead-acid batteries (Dunn et al., 2011) and thermochemical storage (Hauer, 2011) are the same, which is 80%. The value of inverter efficiency is estimated to be 90% (Park et al., 2020). The charging and discharging efficiencies represent energy losses due to storing and discharging from and to the energy storage. Inverter, on the other hand, is included as the electricity is converted from Alternating Current (AC) to Direct Current (DC) and vice versa.

(iii) The coefficient of performance (COP) for the refrigerant system is 1.0. The COP is defined as a ratio of useful cooling energy generated to work or energy needed. The value of COP is equal to 1.0, showing that the useful cooling energy generated from the refrigerant is equivalent to the heating energy needed (Deng et al., 2011).

(iv) Energy losses due to transmission are not accounted for in this analysis.

(v) The analysis does not consider the fluctuations of demands due to weather changes and topology in the industrial plants.

(vi) The energy supply from PWR as a nuclear trigeneration system is consistent in 24-h operations.

3. Methodology

TriGenSCA is a methodology developed by Jamaluddin et al. (2020) to optimise the sizing of the centralised trigeneration system and can minimise the targeting of electricity, heating, and cooling energy. However, the development of TriGenSCA has not considered the complete life cycle cost. The previous study only considers initial investment cost, as well as operational and maintenance costs. In this case study, PWR uses Uranium-235 as a fuel to generate thermal energy for heating water to form steam. The radioactive waste fuel, also known as spent fuel, needs to be cooled down in the spent fuel pool since the spent fuel continues to generate heat due to the decaying of the radioactive elements inside the fuel. The nuclear waste disposal is then buried down under a deep geological repository. The process of disposing of waste fuel requires a huge cost. The process of waste fuel disposal is required for every 5 y. Moreover, the cost of radioactive management and disposal of the overall power plant also needs to be considered as well since it requires a large amount of cost to handle the effluent emissions of the radioactive in the water. In this paper, the overall life cycle cost from PWR as a nuclear trigeneration system is considered to give directions for energy providers to restructure the financial calculation. The overall methodology in this analysis consists of three main steps, which are data extraction, construction of TriGenSCA, and calculation of life cycle cost. The details of every step are shown in the below subsection.

3.1. Data extraction

The first step of the methodology involves the extraction of the energy supply data from the PWR nuclear trigeneration system and energy demand data. In this data extraction step, energy rating in MW and time in h are needed to show a consistency of energy supply and energy demand variations. Fig. 2 presents the maximum energy required from three different demands, and Fig. 3 shows the total energy supply from the PWR trigeneration system and total maximum energy demands based on a summation of three different industries. Based on the demand

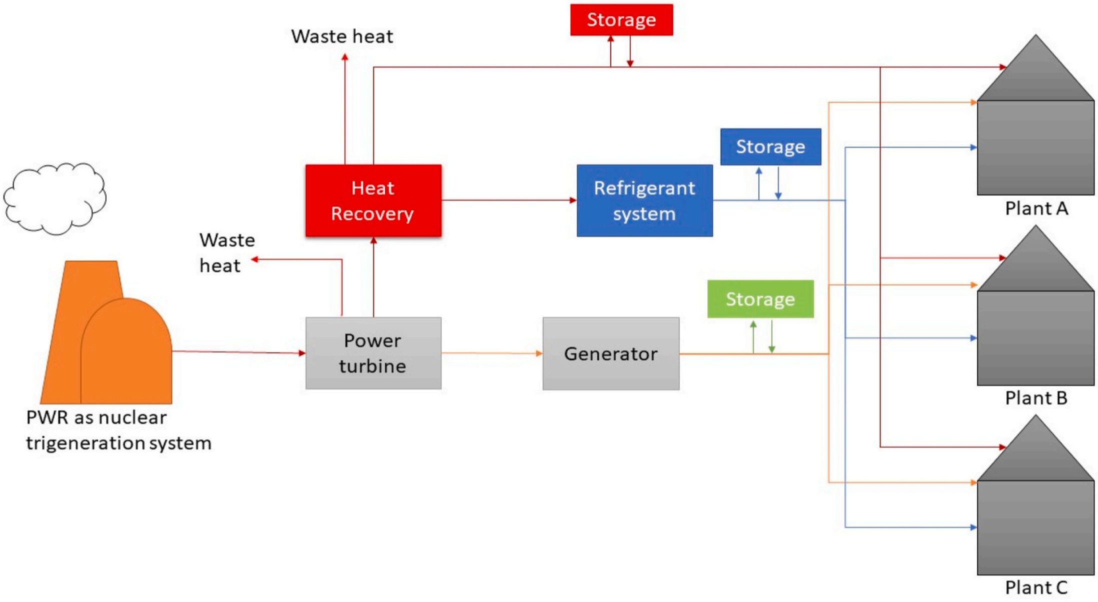

Fig. 1. Conceptual Design of PWR as a nuclear trigeneration system with energy storage (adapted and modified from Jradi and Riffat, 2014).

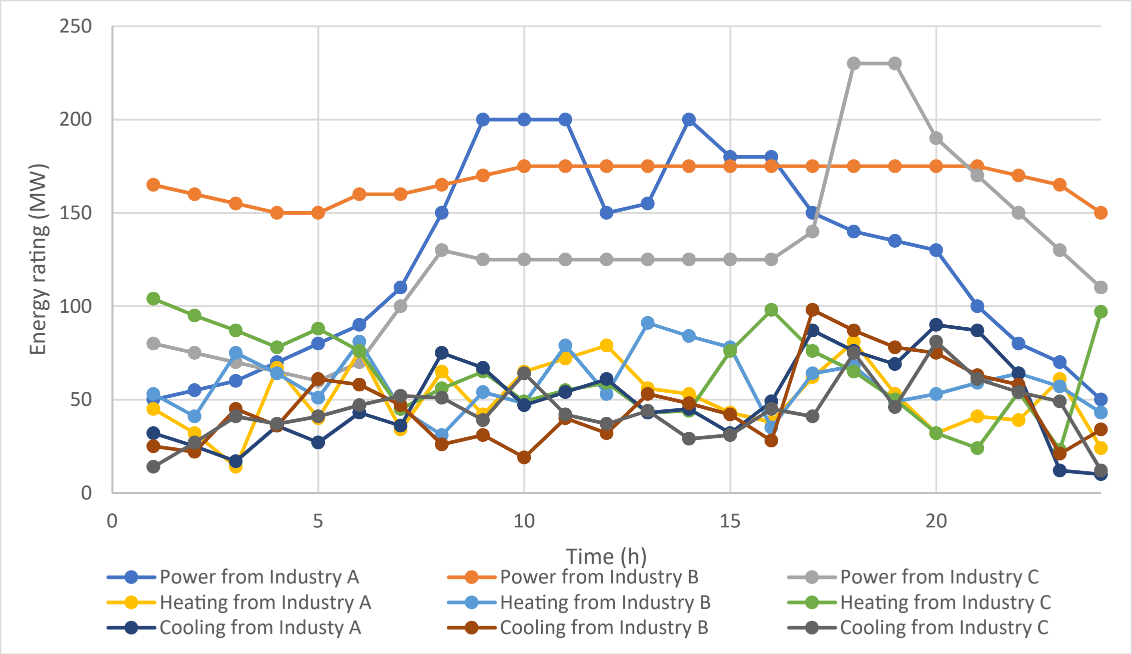

Fig. 2. Maximum energy needed from three industries, namely Industry A, B and C.

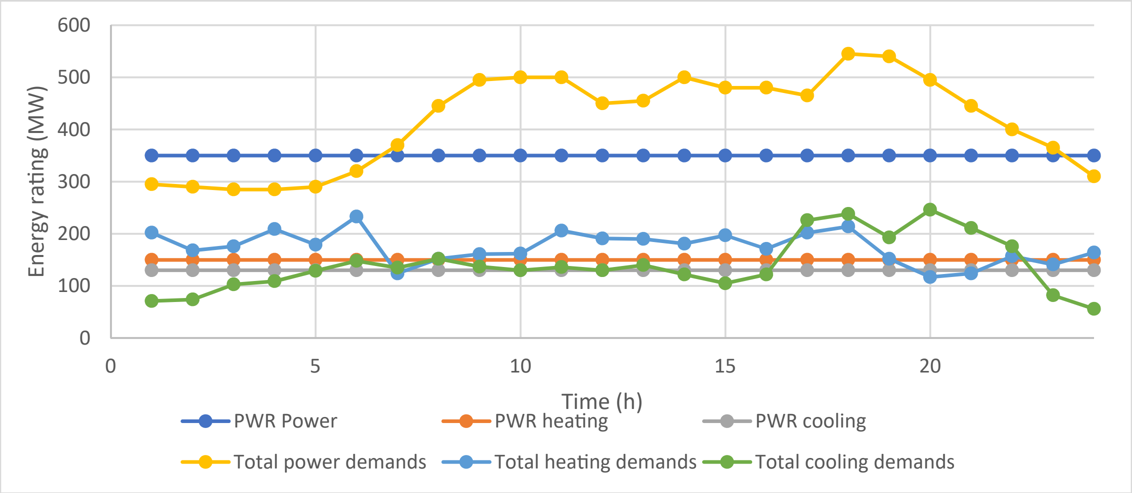

Fig. 3. The total energy supply from the PWR trigeneration system and total maximum energy demands based on the summation of three different industries.

variations, the energy supply is in deficit. External energy or upsizing the reactor is required to reduce the energy gaps between supply and demand. The data obtained from this step are used for the next step. As for the lead-acid battery and thermochemical storage, charging and discharging efficiencies are required to show the energy losses during storing and discharging of power and thermal energy. Inverter efficiency is also required for the power to convert from AC to DC and vice versa. Table 1 shows the data needed for the energy losses during charging and discharging to and from the storage systems.

Table 1
Data needed for the energy losses during charging and discharging to and from the storage systems.

Types of storage	Types of efficiency	Value of efficiency (%)	Literatures
Lead-acid battery	Charging	80	Dunn et al. (2011)
	Discharging	80	Dunn et al. (2011)
	Inverter	90	Park et al. (2020)
Thermochemical	Charging	80	Hauer (2011)
	Discharging	80	Hauer (2011)

3.2. Development of Trigeneration System Cascade Analysis (TriGenSCA)

The development of the TriGenSCA requires three steps to optimise the utility sizing in the trigeneration system, which are a development of the cascade analysis of the TriGenSCA, calculation of the sizing of the utility, and calculation of the percentage change between previous and current sizing of the utility.

3.2.1. Development of the cascade analysis of the TriGenSCA

The TriGenSCA was developed by Jamaluddin et al. (2020) to optimise the sizing of PWR as a nuclear trigeneration system as well as to target minimum electricity, heating, and cooling to be supplied to the demands. Tables 2 and 3 show the initial and final iterations of the TriGenSCA. The development of the TriGenSCA is presented below:

(i) Column 1 shows time in 1 h. The period is for 24 h

(ii) Electricity, heating and cooling energy supply on each time interval are shown in Column 2. On the other hand, maximum electricity, heating and cooling energy from demands are presented in Column 3. The energy supply and energy demands are taken directly from the data extraction in Step 1. The energy supply is obtained from the PWR as a nuclear trigeneration system, and the maximum energy demands are obtained from the total summation of the three industries.

(iii) Column 4 presents the net energy requirement in the system. The net energy requirement in the system is an indicator to show the energy is in excess or deficit in each time interval. If the value shows negative values, the energy is in deficit, and if the value shows positive values, the energy is in excess.

(iv) Column 5 shows the new net energy requirement. The new net energy requirement indicates energy shifting from heating energy in heat recovery to cooling energy in an absorption chiller as a refrigerant system. Since the COP of the absorption chiller is 1.0, the value of heating energy needed is the same as the value of cooling energy produced. For example, 33 MW of excess heat energy at the time interval of 20 h in Table 2 is converted to the same amount of cooling energy. The value of the deficit cooling energy is changed from −116 MW to −83 MW.

(v) Energy losses during charging and discharging from and to the energy storage systems are presented in Column 6. The charging and discharging efficiencies from Table 1 are used to show energy losses during the charging and discharging of the storage systems. To include the energy losses during charging of heating and cooling energy in the thermochemical storage system, the heating and cooling energy from Column 5 are multiplied with charging efficiency. As for the energy losses considered during discharging of the heating and cooling energy from the thermochemical storage system, the heating and cooling energy in Column 5 is divided by discharging efficiency of the thermochemical storage. The energy losses for the charging electricity to the lead-acid battery are considered by multiplying the electricity energy with charging and inverter efficiencies, whereas the electricity energy losses during the discharging process are divided by discharging and inverter efficiencies.

(vi) The cumulative energy in Column 7 is presented to show the total values of the respective energy produced. The initial value of the cumulative energy is zero to show no energy is produced in the system. The initial value is then added with the value from the first interval of the energy losses in Column 6, and the list goes on until the summation reaches the 24th interval.

(vii) The procedure of the new cumulative energy in Column 8 is the same as in Column 7. However, the initial value of the new cumulative energy is taken from the lowest value in Column 7 and changed as a positive value. For example, in Table 3, the lowest value of the electricity in Column 7 is at the interval of 21st, which is −178.7 MW. The value of −178.7 MW is then changed to the positive value of the 178.7 MW, and the value would be at the initial value of Column 8. The initial values in Column 8 present the minimum outsourced energy supply, while the final values in Column 8 show the available excess energy for the next day. The maximum storage systems can also be obtained from the maximum value of this column. For example, in Table 3, the maximum storage system for electricity is 863.8 MWh, heating is 106.5 MWh, and cooling is 330.8 MWh.

Based on Table 2, the minimum outsourced electricity, heating and cooling energy supply are 2,508.8 MWh, 809.8 MWh and 478.5 MWh. The available excess electricity, heating and cooling for the next day are 28.8 MWh, 0 MWh and 97.6 MWh. The differences between the minimum outsourced energy supply and the available excess energy for the next day in Table 3 show the utilities still need to be upsized. The values of minimum outsourced electricity, heating and cooling supply in Table 3, on the other hand, are 178.7 MWh, 76.7 MWh and 109.8 MWh. For the available excess electricity, heating and cooling energy are 178.4 MWh, 76.0 MWh and 110.8 MWh.

3.2.2. Utility sizing calculations

Initially, the sizes of the electricity, heating and cooling utilities are obtained directly from Step 1. However, the initial sizes of the utilities may not be optimal since the centralised trigeneration system is undersized and the utility sizes need to be recalculated to obtain optimal energy so that the excess and outsourced energy can be minimised. Equation (1) shows the calculation to obtain the new utility sizes. In this equation, the minimum outsourced energy supply and excess available energy for the next day are needed to present whether the energy supplied is in surplus or deficit.

$$U_{new} = U_{previous} - \frac{(E_{final} - E_{initial})}{T} \tag{1}$$

U_{new} = New sizing utilities in the PWR trigeneration system
$U_{previous}$ = Previous sizing utilities in the PWR trigeneration system
E_{final} = Available excess energy for the next day
$E_{initial}$ = Minimum energy outsourced supply
T = time

In Table 2, the results show that the minimum outsourced electricity, heating and cooling energy supply are 2,508.8 MWh, 809.8 MWh and 478.5 MWh. The available excess electricity, heating and cooling for the next day are 28.8 MWh, 0 MWh and 97.6 MWh. This shows that the utility needs to be changed, either upsized or downsized, since the electricity, heating, and cooling energy are imbalanced. The utility sizes need to be changed to minimise the energy gaps between the available excess energy for the next day and the minimum outsourced energy supply. Based on the calculations from Equation (1), the newly estimated sizes of the electricity, heating and cooling utilities are 453.3 MW, 183.7 MW and 145.9 MW.

3.2.3. Percentage change between the previous and current sizing of the utility

Cascade analysis using TrigenSCA is repeated in the next iteration by using a new estimated sizing of the utilities obtained from the previous step. The percentage change between the previous and current sizing of the utility is calculated by using Equation (2) to get an optimal sizing of the utility. The iteration method is performed to minimise the energy differences between the minimum outsourced energy supply and the available excess energy for the next day. The target of the iteration method is set as 0.01% to get accurate results of the sizing of the utility. By using Equation (2), the calculations on the percentage change for electricity is 29.5%, heating is 22.5%, and cooling is 4.4%. Since all of the percentage changes for all of the utilities are more than 0.01%, the calculations of the sizing of the new utility and percentage change between the previous and current sizing of the utility are repeated until the percentage change has reached below or equal to 0.01%. The calculations are stopped at the 7th iteration since all of the utilities are below or equal to 0.01%. Table 4 shows the lists of the sizing of utility and its percentage change.

$$P = \frac{|U_{new} - U_{previous}|}{U_{previous}} \times 100\% \tag{2}$$

P = Percentage change between the previous and current sizing of the utility

Table 2a
Initial iteration of the TriGenSCA.

1	2			3			4		
Time (h)	Source (MW)			Demand (MW)			Net energy requirement (MWh)		
	Power	Heating	Cooling	Power	Heating	Cooling	Power	Heating	Cooling
1	350	150	130	295	202	71	55	−52	59
2	350	150	130	290	168	74	60	−18	56
3	350	150	130	285	176	103	65	−26	27
4	350	150	130	285	209	109	65	−59	21
5	350	150	130	290	179	129	60	−29	1
6	350	150	130	320	233	148	30	−83	−18
7	350	150	130	370	124	135	−20	26	−5
8	350	150	130	445	152	152	−95	−2	−22
9	350	150	130	495	161	137	−145	−11	−7
10	350	150	130	500	162	130	−150	−12	0
11	350	150	130	500	206	136	−150	−56	−6
12	350	150	130	450	191	130	−100	−41	0
13	350	150	130	455	190	140	−105	−40	−10
14	350	150	130	500	181	122	−150	−31	8
15	350	150	130	480	197	105	−130	−47	25
16	350	150	130	480	171	122	−130	−21	8
17	350	150	130	465	202	226	−115	−52	−96
18	350	150	130	545	214	238	−195	−64	−108
19	350	150	130	540	152	193	−190	−2	−63
20	350	150	130	495	117	246	−145	33	−116
21	350	150	130	445	124	211	−95	26	−81
22	350	150	130	400	157	176	−50	−7	−46
23	350	150	130	365	141	82	−15	9	48

(*continued on next page*)

Table 2a (*continued*)

1	2			3			4		
Time (h)	Source (MW)			Demand (MW)			Net energy requirement (MWh)		
	Power	Heating	Cooling	Power	Heating	Cooling	Power	Heating	Cooling
24	350	150	130	310	164	56	40	−14	74

Table 2b
Initial iteration of the TriGenSCA.

1	5			6			7		
Time (h)	New net energy requirement (MWh)			Charging and discharging energy (MWh)			Cumulative energy (MWh)		
	Power	Heating	Cooling	Power	Heating	Cooling	Power	Heating	Cooling
							0	0	0
1	55	−52	59	39.6	−65	47.2	39.6	−65	47.2
2	60	−18	56	43.2	−22.5	44.8	82.8	−87.5	92
3	65	−26	27	46.8	−32.5	21.6	129.6	−120	113.6
4	65	−59	21	46.8	−73.75	16.8	176.4	−193.75	130.4
5	60	−29	1	43.2	−36.25	0.8	219.6	−230	131.2
6	30	−83	−18	21.6	−103.75	−22.5	241.2	−333.75	108.7
7	−20	21	0	−27.78	16.8	0	213.42	−316.95	108.7
8	−95	−2	−22	−131.94	−2.5	−27.5	81.478	−319.45	81.2
9	−145	−11	−7	−201.39	−13.75	−8.75	−119.91	−333.2	72.45
10	−150	−12	0	−208.33	−15	0	−328.24	−348.2	72.45
11	−150	−56	−6	−208.33	−70	−7.5	−536.58	−418.2	64.95
12	−100	−41	0	−138.89	−51.25	0	−675.47	−469.45	64.95
13	−105	−40	−10	−145.83	−50	−12.5	−821.3	−519.45	52.45
14	−150	−31	8	−208.33	−38.75	6.4	−1,029.63	−558.2	58.85
15	−130	−47	25	−180.56	−58.75	20	−1,210.19	−616.95	78.85
16	−130	−21	8	−180.56	−26.25	6.4	−1,390.74	−643.2	85.25
17	−115	−52	−96	−159.72	−65	−120	−1,550.47	−708.2	−34.75
18	−195	−64	−108	−270.83	−80	−135	−1,821.3	−788.2	−169.75
19	−190	−2	−63	−263.89	−2.5	−78.75	−2,085.19	−790.7	−248.5
20	−145	0	−83	−201.39	0	−103.75	−2,286.58	−790.7	−352.25
21	−95	0	−55	−131.94	0	−68.75	−2,418.52	−790.7	−421
22	−50	−7	−46	−69.44	−8.75	−57.5	−2,487.97	−799.45	−478.5
23	−15	9	48	−20.83	7.2	38.4	−2,508.8	−792.25	−440.1
24	40	−14	74	28.8	−17.5	59.2	−2,480	−809.75	−380.9

U_{new} = New sizing utilities in the PWR trigeneration system
$U_{previous}$ = Previous sizing utilities in the PWR trigeneration system

The final iteration shows that the minimum requirement of utility for producing electricity is 440.9 MW, heating is 186.5 MW, and cooling is 138.2 MW. Fig. 4 shows the final results of the PWR as a trigeneration system supplying the demands. As results are shown in Table 3, the minimum outsourced energy supply for electricity is 178.4 MWh, heating is 76.5 MWh, and cooling is 110.5 MWh. The available excess energy for the next day for electricity is 178.4 MWh, heating is 76 MWh, and cooling is 110.8 MWh. The differences between the minimum outsourced energy supply and the available excess energy for the next day show the heat energy is in a deficit of 0.5 MWh whereas, for the cool energy, 0.3 MWh is in excess. The deficit of heat energy can be tackled by buying from the other company or increasing the heat recovery. The excess cool energy, on the other hand, can be directly dissipated to the surroundings or sell it to the other industry.

Table 2c
Initial iteration of the TriGenSCA.

1	8		
Time (h)	New cumulative energy (MWh)		
	Power	Heating	Cooling
	2,508.8	809.75	478.5
1	2,548.4	744.75	525.7
2	2,591.6	722.25	570.5
3	2,638.4	689.75	592.1
4	2,685.2	616	608.9
5	2,728.4	579.75	609.7
6	2,750	476	587.2
7	2,722.22	492.8	587.2
8	2,590.28	490.3	559.7
9	2,388.89	476.55	550.95
10	2,180.56	461.55	550.95
11	1,972.22	391.55	543.45
12	1,833.33	340.3	543.45
13	1,687.5	290.3	530.95
14	1,479.17	251.55	537.35
15	1,298.61	192.8	557.35
16	1,118.06	166.55	563.75
17	958.33	101.55	443.75
18	687.5	21.55	308.75
19	423.61	19.05	230
20	222.22	19.05	126.25
21	90.28	19.05	57.5
22	20.83	10.3	0
23	0	17.5	38.4
24	28.8	0	97.6

3.3. *Life cycle cost calculation*

The life cycle cost of the overall PWR trigeneration system consists of initial investment cost, operational and maintenance costs, replacement cost, waste disposal cost, radioactive wastewater management cost and decommissioning cost of the overall PWR trigeneration system. In this study, the life cycle cost is calculated in the form of Equivalent Annual Cost (EAC), which presents the life cycle cost in a year. The EAC that is proposed by Jamaluddin et al. (2020) is calculated to show an annual estimated cost of owning, operating and maintaining the centralised trigeneration system in a Total Site system within its useful lifetime. However, the waste and overall PWR trigeneration disposal cost, as well as replacement cost and radioactive management cost, were not considered in the analysis. In this study, the calculation includes initial investment cost, operational and maintenance costs, replacement cost, waste disposal cost, radioactive management cost and decommissioning of the overall PWR trigeneration system and details on each cost is presented below.

3.3.1. *Initial investment cost*

The initial investment cost is defined as the amount needed by an energy provider to start the construction of the PWR trigeneration system. The initial investment cost consists of several assets such as a PWR reactor, storage power and thermal systems, desalination plant, electric grid and thermal pipelines. The desalination plant is needed to generate freshwater for cooling purposes and the production of steam to be supplied to the turbine. Usage of the seawater in the nuclear plant can cause corrosion on the carbon steel piping (Yokoyama et al., 2015). In the nuclear reactor, approximately 1,100 gallons ~4.17 m^3 of water are required to produce 1 MWe/h (Green, 2019). Based on the case study, the desalination plant needs to cover 110,500 m^3 for a day to cool down the Uranium fuel and heat the water for the production of the turbine. The Arabian Gulf Fujairah F1 Extension SWRO was developed in 2009 and is taken as an example of a desalination plant because the plant can generate 136,000 m^3/d (Intelligence et al., 2011). The total initial investment cost for the plant is 200 MUSD. As for the PWR reactor and storage power and thermal systems, the sizing is considered in the initial investment cost, where the PWR initial investment is 770 USD/kW (Woite, 1978). The initial investment in storage power and thermal systems, on the other hand, is 100 USD/kWh for lead-acid batteries and 70 USD/kWh for thermochemical storage (Zhang et al., 2016). The initial investment costs for the electric grid and thermal pipelines are also considered, where the length of 100 km is estimated to supply power and thermal energy to the demands. In the initial investment of the electric grid, transmission and distribution lines are taken into consideration, where the investment cost is 2 MUSD/km for the transmission line and 1 MUSD/km for the distribution line (SCMO, 2019). Carbon steel pipelines are used for the thermal pipelines and based on Yildirim et al. (2010), the investment cost of the thermal pipelines is estimated to be 25 USD/m, considering 1 m of diameter and 115 °*C* of fluid temperature. Table 5 shows a summary of the initial investment cost, taking into consideration the average inflation rate of 2.3% (Hung, 2021). The total investment cost of the overall plant is 5.79×10^{11} USD.

3.3.2. *Operational and maintenance costs*

The operational and maintenance costs in this calculation are the cost of operating and maintaining involvement in the overall plant. There is a diverse methods to calculate the operational and maintenance cost in the literature. Recently, Zailan et al. (2021a,b) have considered outage losses and resource costs in their cogeneration optimisation model. Whereby, the detail operational and maintenance costs involved in this study are the costs for a nuclear plant, desalination plant, storage power and thermal systems, thermal pipelines and the electric grid. The operational and maintenance costs of the nuclear plant consist of fuel and non-fuel parts. The fuel part is considered in the nuclear core, and others are considered non-fuel parts. Table 6 presents the total operational and maintenance costs of the overall system. The operational and maintenance of the system are considered to be involved every year until the system is disposed of (Takashima et al., 2007). Based on the case study, the total operational and maintenance costs for the overall system are 110.27 M USD/y.

3.3.3. *Replacement cost*

The replacement cost added in the calculation represents a change in the major equipment that is disrupted. The replacement of the equipment is necessary to ensure the overall system is operating at optimal conditions. Table 7 shows the replacement cost of each major part of the PWR in a trigeneration system. As stated by Yokoyama et al. (2015), the replacement of the major equipment needs to be done every 5 years to avoid a shutdown of the overall system due to disruption of the equipment. Hence, the total replacement of the major equipment is 6 times as the lifetime of the PWR trigeneration system is 30 years. The number of failure equipment is obtained from Bond et al. (2003), where the results are extracted from Columbia Generating Station, operated by Energy Northwest in Richland, Washington. The case study shows that the total

Table 3a
Final iteration of the TriGenSCA.

1	2			3			4		
Time (h)	Source (MW)			Demand (MW)			Net energy requirement (MWh)		
	Power	Heating	Cooling	Power	Heating	Cooling	Power	Heating	Cooling
1	440.93	186.46	138.25	295	202	71	145.93	−15.54	67.25
2	440.93	186.46	138.25	290	168	74	150.93	18.46	64.25
3	440.93	186.46	138.25	285	176	103	155.93	10.46	35.25
4	440.93	186.46	138.25	285	209	109	155.93	−22.54	29.25
5	440.93	186.46	138.25	290	179	129	150.93	7.46	9.25
6	440.93	186.46	138.25	320	233	148	120.93	−46.54	−9.745
7	440.93	186.46	138.25	370	124	135	70.93	62.46	3.25
8	440.93	186.46	138.25	445	152	152	−4.07	34.46	−13.75
9	440.93	186.46	138.25	495	161	137	−54.07	25.46	1.25
10	440.93	186.46	138.25	500	162	130	−59.07	24.46	8.25
11	440.93	186.46	138.25	500	206	136	−59.07	−19.54	2.25
12	440.93	186.46	138.25	450	191	130	−9.07	−4.54	8.25
13	440.93	186.46	138.25	455	190	140	−14.07	−3.54	−1.75
14	440.93	186.46	138.25	500	181	122	−59.07	5.46	16.25
15	440.93	186.46	138.25	480	197	105	−39.07	−10.54	33.25
16	440.93	186.46	138.25	480	171	122	−39.07	15.46	16.25
17	440.93	186.46	138.25	465	202	226	−24.07	−15.54	−87.75
18	440.93	186.46	138.25	545	214	238	−104.07	−27.54	−99.75
19	440.93	186.46	138.25	540	152	193	−99.07	34.46	−54.75
20	440.93	186.46	138.25	495	117	246	−54.07	69.46	−107.75
21	440.93	186.46	138.25	445	124	211	−4.07	62.46	−72.75
22	440.93	186.46	138.25	400	157	176	40.93	29.46	−37.75
23	440.93	186.46	138.25	365	141	82	75.93	45.46	56.25
24	440.93	186.46	138.25	310	164	56	130.93	22.46	82.25

replacement cost in a 26.5 GWh/d of the PWR trigeneration system requires 25.33 × 10^6 USD/y to replace the major equipment.

3.3.4. *Waste disposal cost*

An optimised PWR trigeneration system in this case study is obtained, and based on the analysis, the final sizing of electricity, heating and cooling utilities are 440.9 MW, 186.5 MW and 138.2 MW. The total thermal energy of 1,102.25 MW or 26.5 GWh/d is needed to meet the energy demand requirements. Nuclear fuel is classified as a high-level radioactive waste since most of the radioactivity remains in the fuel even after it has been used. The full capacity of the fuel needs to remove every 5 years (one-third of the reactor core is changed every one to two years) (Energy International Agency, 2021). As stated by the European Nuclear Society (2021), the complete fission of 1 kg of Uranium-235 produces 24 GWh of thermal energy. Based on this case study, approximately 1.1 kg of Uranium-235 is needed by the PWR trigeneration system to meet the demand requirements in a day. In the 5 years' time, around 2,015 kg or translating to 2.015 tons of the weight of Uranium-235 are needed before the fuel has been disposed of. The radioactive waste of the uranium fuel is classified as Class C, which requires isolation that it is buried at least 5 m below the surface and requires an engineered barrier (Baisden and Choppin, 2007). Equation (3) presents the cash flows of disposal cost calculation in the PWR trigeneration system. The calculation of the disposal cost is necessary for the energy providers to determine projections of future cash flows. The proper projection of the cash flows can create an economic model that reflects all the project implementation conditions. The disposal and expenses costs are obtained from OECD Nuclear Energy Agency (1993) and Woite (1978). The disposal cost includes processing waste and the waste in the spent fuel before the processing is started. The expenses cost, on the other hand, considers equipment, labour and transportation for the waste disposal. Based on the literature, the disposal cost is 100,000 USD/t, and the expense cost is 50 MUSD. Considering the average inflation rate of 2.3% (Hung, 2021), the current disposal and expense costs are 192,352 USD/t and 213 MUSD. The calculations show that the future cash flow for waste disposal in 5 y in the PWR trigeneration system is 213,387,590 USD.

Table 3b
Final iteration of the TriGenSCA.

1	5			6			7		
Time (h)	New net energy requirement (MWh)			Charging and discharging energy (MWh)			Cumulative energy (MWh)		
	Power	Heating	Cooling	Power	Heating	Cooling	Power	Heating	Cooling
							0	0	0
1	145.93	−15.54	67.25	105.07	−19.42	53.80	105.07	−19.42	53.80
2	150.93	18.46	64.25	108.67	14.77	51.40	213.74	−4.66	105.20
3	155.93	10.46	35.25	112.27	8.37	28.20	326.02	3.71	133.40
4	155.93	−22.54	29.25	112.27	−28.17	23.40	438.29	−24.46	156.80
5	150.93	7.46	9.25	108.67	5.97	7.40	546.96	−18.49	164.21
6	120.93	−46.54	−9.75	87.07	−58.17	−12.19	634.03	−76.67	152.02
7	70.93	62.46	3.25	51.07	49.97	2.60	685.11	−26.70	154.62
8	−4.07	20.71	0	−5.65	16.57	0	679.46	−10.13	154.62
9	−54.07	25.46	1.25	−75.09	20.37	1.00	604.37	10.24	155.62
10	−59.07	24.46	8.25	−82.04	19.57	6.60	522.33	29.81	162.22
11	−59.07	−19.54	2.25	−82.04	−24.42	1.80	440.29	5.39	164.02
12	−9.07	−4.54	8.25	−12.59	−5.67	6.60	427.70	−0.29	170.63
13	−14.07	−3.54	−1.75	−19.54	−4.42	−2.19	408.17	−4.71	168.44
14	−59.07	5.46	16.25	−82.04	4.37	13.01	326.13	−0.34	181.44
15	−39.07	−10.54	33.25	−54.26	−13.17	26.60	271.87	−13.51	208.04
16	−39.07	15.46	16.25	−54.26	12.369	13.01	217.61	−1.15	221.04
17	−24.07	−15.54	−87.75	−33.425	−19.42	−109.69	184.19	−20.57	111.36
18	−104.07	−27.54	−99.75	−144.54	−34.42	−124.69	39.65	−55.00	−13.33
19	−99.07	0	−20.29	−137.59	0	−25.36	−97.94	−55.00	−38.69
20	−54.07	0	−38.29	−75.09	0	−47.86	−173.03	−55.00	−86.55
21	−4.07	0	−10.29	−5.65	0	−12.86	−178.68	−55.00	−99.41
22	40.93	0	−8.29	29.47	0	−10.36	−149.21	−55.00	−109.77
23	75.93	45.46	56.25	54.67	36.37	45.00	−94.53	−18.63	−64.77
24	130.93	22.46	82.25	94.27	17.97	65.80	−0.26	−0.66	1.04

$$C_{flow} = c_{min,5} Q_5 + E_t \tag{3}$$

C_{flow} = Future cash flows for waste disposal in 5 y (USD).
$c_{min,5}$ = Disposal costs (USD/t).
Q_5 = Physical waste volume produced in 5 y (t).
E_t = Expense cost (USD).

3.3.5. Radioactive wastewater management cost

Radioactive wastewater management is needed to be considered in the life cycle costing to decontaminate the radioactive waste in the water. The decontamination of the radioactive wastewater management covered in this study is the process of removing hazardous materials in the water. The amounts of waste produced in a nuclear reactor depend on the type of reactor and the capacity of the power generated (Efremenkov, 1989). The waste evaporator is commonly used to emit radioactive wastewater in water through the evaporation process. Based on Straub (1956), around 528.34 USD/ m^3 of radioactive waste management costs are needed for the waste evaporator to operate to get rid of radioactive waste in the water. The case study shows the generation of freshwater in the PWR trigeneration system needs 110,500 m^3/d to operate, and the total radioactive wastewater management cost requires 58 MUSD d.

3.3.6. Decommissioning cost of nuclear power plant

A decommissioning term includes all radioactive clean-up and progressive dismantling of the nuclear power plant. Decommissioning starts with refuelling in the core and the removal of coolant. Next, the radioactive is cleaned up, and the nuclear power plant is dismantled before a license is terminated and decontamination is verified. The overall decommissioning cost is expected to be 0.73 MUSD/MWe (Neri et al., 2016). The final optimised PWR trigeneration system shows the electricity produced is 1,102.25 MWe, and the total decommissioning cost is 804.64 MUSD to decommission the overall plant.

The calculation of the EAC in this paper is based on Net Present Value (NPV). The NPV is the basic criterion for investment project financial analysis. Equation (4) shows the overall calculation of EAC by including

Table 3c
Final iteration of the TriGenSCA.

1	5		
Time (h)	New cumulative energy (MWh)		
	Power	Heating	Cooling
	178.68	76.67	109.77
1			
	283.75	57.24	163.57
2			
	392.42	72.01	214.97
3			
	504.70	80.38	243.17
4			
	616.97	52.21	266.57
5			
	725.64	58.17	273.97
6			
	812.71	0	261.79
7			
	863.79	49.97	264.39
8			
	858.14	66.54	264.39
9			
	783.05	86.91	265.39
10			
	701.01	106.48	271.99
11			
	618.97	82.05	273.79
12			
	606.38	76.38	280.39
13			
	586.85	71.95	278.21
14			
	504.81	76.32	291.21
15			
	450.55	63.15	317.81
16			
	396.29	75.52	330.81
17			
	362.87	56.09	221.12
18			
	218.33	21.67	96.44
19			
	80.74	21.67	71.08
20			
	5.65	21.67	23.22
21			
	0	21.67	10.36
22			
	29.47	21.67	0
23			
	84.14	58.04	45.00
24			
	178.42	76.01	110.80

initial investment cost, operational and maintenance costs, replacement cost, waste disposal cost, radioactive management cost and decommissioning cost of the overall PWR trigeneration system (modified from Jamaluddin et al., 2020). The overall calculation of the EAC is 1.89 × 10^{11} USD/y considering the discount rate is 10% (Energy International Agency, 2021), the growth of price rate is 1% (Takashima et al., 2007), and the coefficient correlation is 0.025 (Takashima et al., 2007). Fig. 5 shows the distributions of the EAC in the PWR trigeneration system in a year, and most of the costs that contribute to the overall calculation are the operational and maintenance costs which present more than half of the overall cost (53.1%).

$$EAC = IC_{initial} \times \frac{i(1+i)^{n_1}}{(1+i)^{n_1-1}} + \frac{OM}{30}\int_1^{30} e^{(i-\mu+\delta)t_1} dt_1 + \frac{T}{30}\int_1^{6} e^{(i-\mu+\delta)t_2} dt_2 + c_{flow} \times \frac{i(1+i)^{n_2}}{(1+i)^{n_2-1}} + DC_{end} \times \frac{(1+i)^{n_1-1}}{i(1+i)^{n_1}} + c_{radioactive\ management} \times 365\ d \tag{4}$$

EAC = Equivalent Annual Cost (USD).
$IC_{initial}$ = Initial investment cost (USD).
i = discount rate.
n_1 = lifetime of the PWR as a trigeneration system (y).
OM = Operational and maintenance costs (USD).
μ = growth of price rate.
δ = coefficient correlation.
t_1 = time for operational and maintenance (y).
T = Replacement cost (USD).
t_2 = number for replacement of equipment in lifetime.
C_{flow} = Cash flow of the disposal costs (USD).
n_2 = time for every fuel disposal (y).
DC_{end} = Decommissioning cost of overall plant cost (USD).
$c_{radioactive\ management}$ = Cashflow of the radioactive wastewater management (USD).

4. Discussions

The final iteration of the TriGenSCA shows the total thermal energy of 1,102.25 MW or translated into 26.5 GWh/d is needed to cover three industrial plants. On the other hand, the maximum storage system obtained for electricity is 863.8 MWh, heating is 106.5 MWh, and cooling is 330.8 MWh. Comparison of the calculation for EAC during the normal condition planned and unplanned shutdowns are made to assist the energy providers in rerouting the pathway of the projections of future cash flows. Based on the study presented by World Nuclear Association (2022), 94% of the unavailable capacity of the nuclear reactor in the global (68% is due to planned shutdown and 26% is due to unplanned shutdown) is within plant management control. However, these shutdowns reduce the overall capacity of the PWR trigeneration system. The planned shutdown was able to reduce the capacity of the overall nuclear reactor by 18.7%, while the unplanned shutdown reduced the overall nuclear reactor capacity by 6%. Fig. 6 shows the reduction of the capacity due to planned and unplanned shutdowns. The average of all nuclear reactors constitutes around 50 days to overcome these shutdowns. The major reason for the event of a planned shutdown is caused a combined maintenance and refuelling outage, while for the unplanned shutdown, the major reason for the event is an extension of planned outages and an immediate, controlled shutdown. Tables in Appendices A and B show the cascade analysis of the TriGenSCA after consideration of planned and unplanned shutdowns. In Appendices A and B, an

Table 4
Summary of percentage changes for the iteration in the TriGenSCA.

Iteration	Electricity (MW)	Percentage change for electricity (%)	Heating (MW)	Percentage change for heating (%)	Cooling (MW)	Percentage change for cooling (%)
1	350	29.52	150	22.49	130	12.21
2	453.33	2.91	183.74	1.11	145.87	4.35
3	440.14	0.20	185.79	0.29	139.52	0.76
4	441.03	0.02	186.34	0.07	138.45	0.15
5	440.93	0.01	186.46	0.02	138.25	0.03
6	440.94	0.01	186.49	0.01	138.21	0.01
7	440.94		186.49		138.2	

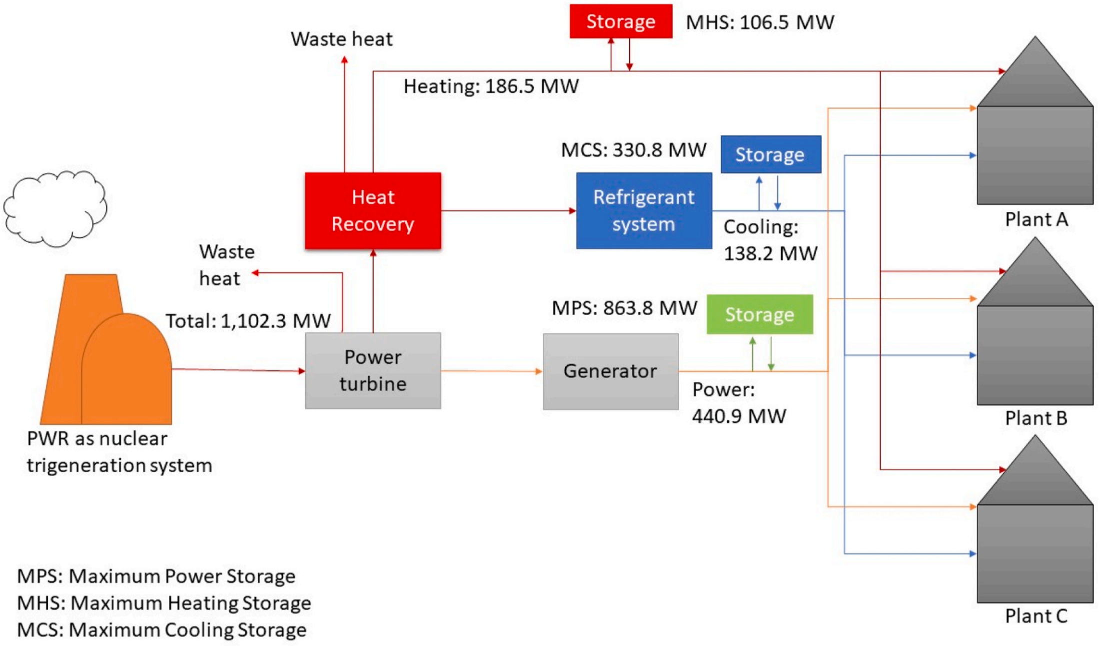

Fig. 4. Final results on energy supply and maximum storage systems of the PWR as a trigeneration system.

Table 5
Summary of the total initial investment costs on each type of investment involved.

Type of investment		Initial investment cost	Initial investment cost in 2022	Criteria for case study	Total investment cost (USD)	Literature
PWR reactor		770 USD/kW	3,292.60 USD/kW	1,102.25 MW	3.63×10^9	Woite (1978)
Energy storage	Power	100 USD/kWh	116.16 USD/kWh	863.8 MWh	0.1×10^9	Zhang et al. (2016)
	Thermal	70 USD/kWh	81.31 USD/kWh	106.5 MWh (heating) 330.8 MWh (cooling)	8.66×10^6 (heating) 26.9×10^6 (cooling)	Zhang et al. (2016)
Desalination plant		200 MUSD	247.89 MUSD	110,500 m^3	247.89 M	Intelligence et al. (2011)
Electric grid	Transmission	2 MUSD/km	2.18 MUSD/km	100 km	218 M	SCMO (2019)
	Distribution	1 MUSD/km	1.09 MUSD/km	100 km	109 M	SCMO (2019)
Thermal pipelines		25,000 USD/km	31,964.50 USD/km	100 km	3.2×10^6	Yildirim et al. (2010)
Total initial investment cost (USD)					5.79×10^{11}	

Table 6
Total operational and maintenance costs of the overall system.

Type of instrument		Operational and maintenance cost	Operational and maintenance costs in 2022	Criteria for the case study	Total operational and maintenance costs (USD)	Literature
Nuclear plant	Fuel	0.49 USD/kWh	0.53 USD/kWh	26.5 GWh	14.05×10^6	Jamaluddin et al. (2020)
	Non-fuel	1.37 USD/kWh	1.48 USD/kWh	26.5 GWh	39.22×10^6	Jamaluddin et al. (2020)
Storage system	Power	50 USD/kWh	55.49 USD/kWh	863.8 MWh	47.93×10^6	Sarbu and Sebarchievici (2018)
	Thermal	10 USD/kWh	11.10 USD/kWh	106.5 MWh (heating) 330.8 MWh (cooling)	1.18×10^6 (heating) 3.67×10^6 (cooling)	Sarbu and Sebarchievici (2018)
Desalination plant		1.07 USD/m^3	1.33 USD/m^3	110,500 m^3	0.15×10^6	Intelligence et al. (2011)
Thermal pipelines		6.41 USD/kWh	7.29 USD/kWh	106.5 MWh (heating) 330.8 MWh (cooling)	0.78×10^6 (heating) 2.41×10^6 (cooling)	Andika et al. (2017)
Electric grid		0.9 USD/kWh	1.02 USD/kWh	863.8 MWh	0.88×10^6	Fares and King (2017)
Total operational and maintenance cost (USD)					110.27×10^6	

additional column is added to the third column to show the reduction of the capacity of energy production due to planned and unplanned shutdowns. Columns 4 until 9 follow the same step as Columns 3 until 8 in cascade analysis of the TriGenSCA.

Based on the results shown in Tables in Appendices A and B, the overall PWR trigeneration system needed additional external energy as power, heating, and cooling are in deficits due to shut down (minimum outsourced energy supply is subtracted with available excess energy for the next day). During the planned shutting down of the PWR trigeneration system, the power, heating, and cooling require additional values of 2,236.83 MWh, 712.87 MWh and 927.00 MWh. As for the unplanned shutting down of the PWR trigeneration system, the respective external

Table 7
Replacement cost of the major equipment in the PWR trigeneration system (Bond et al., 2008).

Equipment	Number of equipment	Failure rate (failure/y)	Replacement cost (USD/MWh)	Replacement cost in 2022 (USD/MWh)
Motor	198	0.0438	66.90	86.63
Centrifugal pump	9	0.0042	30.00	38.85
Heat exchanger	436	0.0120	30.00	38.85

power, heating and cooling energy needed are 704.93 MWh, 96.91 MWh and 463.27 MWh. Since the energy is deficit during shut down, the EAC requires additional cost as the penalty energy cost is included. The penalty cost is the cost that considers factors such as late deliveries and bid adjustment. Based on the study done by Carvalho et al. (2018), the value of the penalty function due to energy deficit is 7.205 USD/MWh. The EAC, which includes shutdown, is shown in Equation (5). Based on the calculation of the equation, the additional cost of the EAC for planned and unplanned shutdowns are 1.4 MUSD and 0.5 MUSD. Table 8 presents a summary of the comparison between the PWR trigeneration system in normal conditions, and planned and unplanned conditions.

$$EAC_{shutdown} = EAC + \left[50\, d \times \left(c_{ip} \times E_{deficit}\right)\right] \tag{5}$$

$EAC_{shutdown}$ = Equivalent Annual Cost that includes a shutdown (USD).

EAC = Equivalent Annual Cost (USD).

c_{ip} = Penalty function due to energy deficit (USD/MWh).

$E_{deficit}$ = Deficit energy (MWh).

5. Conclusions

In this paper, an extended TriGenSCA has been developed to include the overall life cycle cost in the PWR as a trigeneration system. The analysis contributes to a complete life cycle analysis of the trigeneration system to determine cash flow projection. The proper cash flow projection creates an economic model that reflects all the project realisation conditions. Based on this case study, 1.89×10^{11} USD/y is required by the energy provider for the PWR trigeneration system to construct, operate, maintain, dispose, and clean up. An additional cost of 1.4 MUSD and 0.5 MUSD due to penalty cost during the incapability of the system to generate energy during planned, and unplanned shutdowns are also calculated and included in the analysis. The latest TriGenSCA has several benefits, such as:

a) Application of an extended TriGenSCA methodology to obtain an optimal sizing of the PWR trigeneration system and to generate minimum total energy for the demands.
b) Consideration of energy losses during charging and discharging in the storage systems.
c) Inclusion of overall life cycle cost in the EAC to determine cash flow projection.

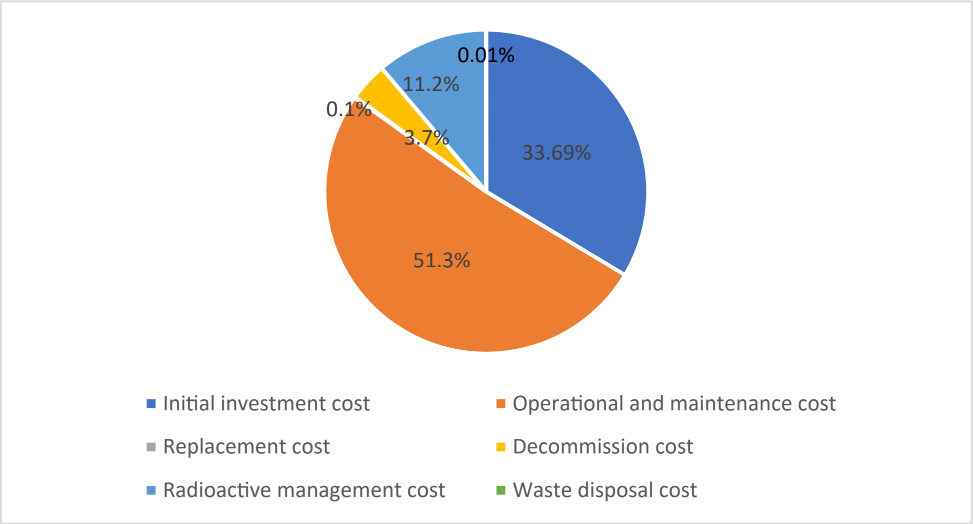

Fig. 5. Distribution of each cost in the Equivalent Annual Cost.

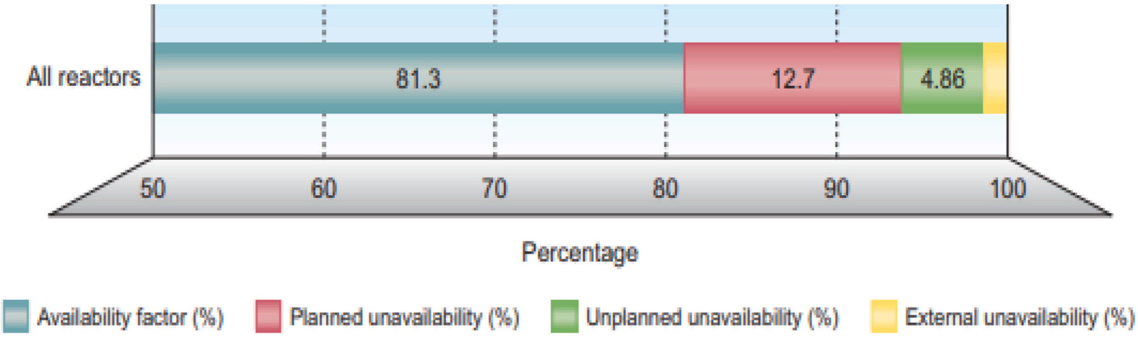

Fig. 6. Available capacity of nuclear reactor plants due to planned and unplanned shutdowns (World Nuclear Association, 2022).

Table 8

Comparison between PWR trigeneration in a normal condition, planned and unplanned conditions.

		Normal condition	Planned shutdown	Unplanned shutdown
Utility sizing (MW)	Power	440.94	358.49	414.49
	Heating	186.49	151.62	175.31
	Cooling	138.20	112.36	129.91
Storage system (MWh)	Power	863.79	2,549.61	1,378.03
	Heating	106.48	748.96	254.37
	Cooling	330.81	1,070.31	691.55
Minimum outsourced energy supply (MWh)	Power	178.68	2,271.74	926.22
	Heating	76.67	748.96	254.37
	Cooling	109.77	996.37	560.72
Available excess energy for the next day (MWh)	Power	178.42	34.91	121.29
	Heating	76.01	36.09	157.46
	Cooling	110.80	69.37	97.45
Additional cost due to shutdown (MUSD)		–	1.4	0.5

d) Comparison of cost and energy between normal operations with planned and unplanned shutdowns of the PWR trigeneration system.

The current work of extended TriGenSCA methodology is only applicable for analysing the complete life cycle costing of the PWR as a trigeneration system. It is envisioned that the TriGenSCA methodology can be extended to the life cycle costing of the other types of trigeneration systems. The TriGenSCA methodology can be further developed to include the effects of climate variations that may cause fluctuations in energy demands and influence the performance of the trigeneration system.

CRediT authorship contribution statement

Khairulnadzmi Jamaluddin: Conceptualization, Methodology, Investigation, Writing – original draft, Funding acquisition. **Sharifah Rafidah Wan Alwi:** Conceptualization, Writing – review & editing, Funding acquisition, Supervision. **Zainuddin Abd Manan:** Writing – review & editing, Supervision. **Khaidzir Hamzah:** Writing – review & editing, Supervision. **Jiří Jaromír Klemeš:** Writing – review & editing, Supervision, Funding acquisition. **Roziah Zailan:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Nomenclatures

AC – Alternating Current
AEEND – Available Excess Electricity for the Next Day
COP – Coefficient of Performance
CPCC – Continuous Power Composite Curves
DC – Direct Current
EAC – Equivalent Annual Cost
ESCA – Electricity System Cascade Analysis
GCC – Grand Composite Curve
GTMP – Green Technology Master Plan
HPS – Hybrid Power Systems
LIES – Locally Integrated Energy System
MOES – Minimum Outsourced Electricity Supply
NPV – Net Present Value
OSEC – Outsourced and Storage Electricity Curves
PCC – Power Composite Curves
PWR – Pressurised Water Reactor
SCT – Storage Cascade Table
SWRO – Seawater Reverse Osmosis
TriGenSCA – Trigeneration System Cascade Analysis

APPENDIX A

Table A.1
TriGenSCA after planned shutdown

1	2			3			4		
Time (h)	Source (MW)			Source after shutdown (MW)			Demand (MW)		
	Power	Heating	Cooling	Power	Heating	Cooling	Power	Heating	Cooling
1	440.93	186.46	138.25	358.49	151.62	112.36	295	202	71
2	440.93	186.46	138.25	358.49	151.62	112.36	290	168	74
3	440.93	186.46	138.25	358.49	151.62	112.36	285	176	103
4	440.93	186.46	138.25	358.49	151.62	112.36	285	209	109
5	440.93	186.46	138.25	358.49	151.62	112.36	290	179	129
6	440.93	186.46	138.25	358.49	151.62	112.36	320	233	148
7	440.93	186.46	138.25	358.49	151.62	112.36	370	124	135
8	440.93	186.46	138.25	358.49	151.62	112.36	445	152	152
9	440.93	186.46	138.25	358.49	151.62	112.36	495	161	137
10	440.93	186.46	138.25	358.49	151.62	112.36	500	162	130
11	440.93	186.46	138.25	358.49	151.62	112.36	500	206	136
12	440.93	186.46	138.25	358.49	151.62	112.36	450	191	130
13	440.93	186.46	138.25	358.49	151.62	112.36	455	190	140
14	440.93	186.46	138.25	358.49	151.62	112.36	500	181	122
15	440.93	186.46	138.25	358.49	151.62	112.36	480	197	105
16	440.93	186.46	138.25	358.49	151.62	112.36	480	171	122
17	440.93	186.46	138.25	358.49	151.62	112.36	465	202	226
18	440.93	186.46	138.25	358.49	151.62	112.36	545	214	238
19	440.93	186.46	138.25	358.49	151.62	112.36	540	152	193
20	440.93	186.46	138.25	358.49	151.62	112.36	495	117	246
21	440.93	186.46	138.25	358.49	151.62	112.36	445	124	211
22	440.93	186.46	138.25	358.49	151.62	112.36	400	157	176
23	440.93	186.46	138.25	358.49	151.62	112.36	365	141	82
24	440.93	186.46	138.25	358.49	151.62	112.36	310	164	56

Table A.2
TriGenSCA after planned shutdown

1	5			6			7		
Time (h)	Net energy requirement (MWh)			New net energy requirement (MWh)			Charging and discharging energy (MWh)		
	Power	Heating	Cooling	Power	Heating	Cooling	Power	Heating	Cooling
1	63.49	−50.38	41.36	63.49	−50.38	41.36	45.71	−62.98	33.08
2	68.49	−16.38	38.36	68.49	−16.38	38.36	49.31	−20.48	30.68
3	73.49	−24.38	9.36	73.49	−24.38	9.36	52.91	−30.48	7.48
4	73.49	−57.38	3.36	73.49	−57.38	3.36	52.91	−71.73	2.68
5	68.49	−27.38	−16.64	68.49	−27.38	−16.64	49.31	−34.23	−20.81

(*continued on next page*)

Table A.2 (*continued*)

1	5			6			7		
Time (h)	Net energy requirement (MWh)			New net energy requirement (MWh)			Charging and discharging energy (MWh)		
	Power	Heating	Cooling	Power	Heating	Cooling	Power	Heating	Cooling
6	38.49	−81.38	−35.64	38.49	−81.38	−35.64	27.71	−101.73	−44.56
7	−11.51	27.62	−22.64	−11.51	27.62	−22.64	−15.99	22.096	−28.31
8	−86.51	−0.38	−39.64	−86.51	−0.38	−39.64	−120.16	−0.475	−49.56
9	−136.51	−9.38	−24.64	−136.51	−9.38	−24.64	−189.60	−11.73	−30.81
10	−141.51	−10.38	−17.64	−141.51	−10.38	−17.64	−196.55	−12.98	−22.06
11	−141.51	−54.38	−23.64	−141.51	−54.38	−23.64	−196.55	−67.98	−29.56
12	−91.51	−39.38	−17.64	−91.51	−39.38	−17.64	−127.10	−49.23	−22.06
13	−96.51	−38.38	−27.64	−96.51	−38.38	−27.64	−134.05	−47.98	−34.56
14	−141.51	−29.38	−9.64	−141.51	−29.38	−9.64	−196.55	−36.73	−12.06
15	−121.51	−45.38	7.36	−121.51	−45.38	7.36	−168.77	−56.73	5.88
16	−121.51	−19.38	−9.64	−121.51	−19.38	−9.64	−168.77	−24.23	−12.06
17	−106.51	−50.38	−113.64	−106.51	−50.38	−113.64	−147.94	−62.98	−142.06
18	−186.51	−62.38	−125.64	−186.51	−62.38	−125.64	−259.05	−77.98	−157.06
19	−181.51	−0.38	−80.64	−181.51	−0.38	−80.64	−252.10	−0.48	−100.81
20	−136.51	34.62	−133.64	−136.51	34.62	−133.64	−189.60	27.70	−167.06
21	−86.51	27.62	−98.64	−86.51	27.62	−98.64	−120.16	22.10	−123.31
22	−41.51	−5.38	−63.64	−41.51	−5.38	−63.64	−57.66	−6.73	−79.56
23	−6.51	10.62	30.36	−6.51	10.62	30.36	−9.05	8.50	24.28
24	48.49	−12.38	56.36	48.49	−12.38	56.36	34.91	−15.48	45.08

Table A.3
TriGenSCA after planned shutdown

1	8			9		
Time (h)	Cumulative energy (MWh)			New cumulative energy (MWh)		
	Power	Heating	Cooling	Power	Heating	Cooling
	0	0	0	2,271.75	748.96	996.37
1	45.71	−62.98	33.08	2,317.46	685.98	1029.45
2	95.02	−83.45	63.77	2,366.77	665.51	1060.14
3	147.93	−113.93	71.25	2,419.68	635.03	1067.62
4	200.84	−185.65	73.94	2,472.59	563.31	1070.31
5	250.15	−219.88	53.13	2,521.90	529.08	1049.50
6	277.86	−321.60	8.578	2,549.61	427.36	1004.95
7	261.87	−299.51	−19.73	2,533.62	449.45	976.64
8	141.72	−299.98	−69.28	2,413.46	448.98	927.08
9	−47.88	−311.71	−100.09	2,223.86	437.25	896.28
10	−244.43	−324.68	−122.14	2,027.32	424.28	874.22
11	−440.98	−392.66	−151.70	1,830.77	356.30	844.67

(*continued on next page*)

Table A.3 (*continued*)

1	8			9		
Time (h)	Cumulative energy (MWh)			New cumulative energy (MWh)		
	Power	Heating	Cooling	Power	Heating	Cooling
12	−568.08	−441.88	−173.75	1,703.67	307.08	822.61
13	−702.12	−489.86	−208.31	1,569.62	259.10	788.06
14	−898.67	−526.58	−220.37	1,373.08	222.38	776.00
15	−1067.44	−583.31	−214.48	1,204.31	165.65	781.89
16	−1236.20	−607.53	−226.54	1,035.54	141.43	769.83
17	−1384.14	−670.51	−368.59	887.61	78.45	627.78
18	−1643.18	−748.48	−525.65	628.56	0.48	470.72
19	−1895.28	−748.96	−626.45	376.46	0	369.92
20	−2084.89	−721.26	−793.51	186.86	27.70	202.86
21	−2205.04	−699.17	−916.81	66.70	49.79	79.56
22	−2262.70	−705.89	−996.37	9.05	43.07	0
23	−2271.74	−697.40	−972.08	0	51.56	24.28
24	−2236.83	−712.87	−927.00	34.91	36.09	69.37

APPENDIX B

Table B.1
TriGenSCA after an unplanned shutdown

1	2			3			4		
Time (h)	Source (MW)			Source after shutdown (MW)			Demand (MW)		
	Power	Heating	Cooling	Power	Heating	Cooling	Power	Heating	Cooling
1	440.93	186.46	138.25	414.49	175.30	129.91	295	202	71
2	440.93	186.46	138.25	414.49	175.30	129.91	290	168	74
3	440.93	186.46	138.25	414.49	175.30	129.91	285	176	103
4	440.93	186.46	138.25	414.49	175.30	129.91	285	209	109
5	440.93	186.46	138.25	414.49	175.30	129.91	290	179	129
6	440.93	186.46	138.25	414.49	175.30	129.91	320	233	148
7	440.93	186.46	138.25	414.49	175.30	129.91	370	124	135
8	440.93	186.46	138.25	414.49	175.30	129.91	445	152	152
9	440.93	186.46	138.25	414.49	175.30	129.91	495	161	137
10	440.93	186.46	138.25	414.49	175.30	129.91	500	162	130
11	440.93	186.46	138.25	414.49	175.30	129.91	500	206	136
12	440.93	186.46	138.25	414.49	175.30	129.91	450	191	130
13	440.93	186.46	138.25	414.49	175.30	129.91	455	190	140
14	440.93	186.46	138.25	414.49	175.30	129.91	500	181	122
15	440.93	186.46	138.25	414.49	175.30	129.91	480	197	105
16	440.93	186.46	138.25	414.49	175.30	129.91	480	171	122
17	440.93	186.46	138.25	414.49	175.30	129.91	465	202	226

(*continued on next page*)

Table B.1 (*continued*)

1	2			3			4		
Time (h)	Source (MW)			Source after shutdown (MW)			Demand (MW)		
	Power	Heating	Cooling	Power	Heating	Cooling	Power	Heating	Cooling
18	440.93	186.46	138.25	414.49	175.30	129.91	545	214	238
19	440.93	186.46	138.25	414.49	175.30	129.91	540	152	193
20	440.93	186.46	138.25	414.49	175.30	129.91	495	117	246
21	440.93	186.46	138.25	414.49	175.30	129.91	445	124	211
22	440.93	186.46	138.25	414.49	175.30	129.91	400	157	176
23	440.93	186.46	138.25	414.49	175.30	129.91	365	141	82
24	440.93	186.46	138.25	414.49	175.30	129.91	310	164	56

Table B.2
TriGenSCA after an unplanned shutdown

1	5			6			7		
Time (h)	Net energy requirement (MWh)			New net energy requirement (MWh)			Charging and discharging energy (MWh)		
	Power	Heating	Cooling	Power	Heating	Cooling	Power	Heating	Cooling
1	119.49	−26.70	58.91	119.49	−26.70	58.91	86.03	−33.37	47.13
2	124.49	7.30	55.91	124.49	7.30	55.91	89.63	5.84	44.73
3	129.49	−0.70	26.91	129.49	−0.70	26.91	93.23	−0.87	21.53
4	129.49	−33.70	20.91	129.49	−33.70	20.91	93.23	−42.12	16.73
5	124.49	−3.70	0.91	124.49	−3.70	0.91	89.63	−4.62	0.73
6	94.49	−57.70	−18.09	94.49	−57.70	−18.09	68.03	−72.12	−22.62
7	44.49	51.30	−5.09	44.49	51.30	−5.09	32.03	41.04	−6.37
8	−30.51	23.30	−22.09	−30.51	23.30	−22.09	−42.38	18.64	−27.62
9	−80.51	14.30	−7.09	−80.51	14.30	−7.09	−111.82	11.44	−8.87
10	−85.51	13.30	−0.09	−85.51	13.30	−0.09	−118.77	10.64	−0.12
11	−85.51	−30.70	−6.09	−85.51	−30.70	−6.09	−118.77	−38.37	−7.62
12	−35.51	−15.70	−0.09	−35.51	−15.70	−0.09	−49.32	−19.62	−0.12
13	−40.51	−14.70	−10.09	−40.51	−14.70	−10.09	−56.27	−18.37	−12.62
14	−85.51	−5.70	7.91	−85.51	−5.70	7.91	−118.77	−7.12	6.33
15	−65.51	−21.70	24.91	−65.51	−21.70	24.91	−90.99	−27.12	19.93
16	−65.51	4.30	7.91	−65.51	4.30	7.91	−90.99	3.44	6.33
17	−50.51	−26.70	−96.09	−50.51	−26.70	−96.09	−70.16	−33.37	−120.12
18	−130.51	−38.70	−108.09	−130.51	−38.70	−108.09	−181.27	−48.37	−135.12
19	−125.51	23.30	−63.09	−125.51	23.30	−63.09	−174.32	18.64	−78.87
20	−80.51	58.30	−116.09	−80.51	58.30	−116.09	−111.82	46.64	−145.12
21	−30.51	51.30	−81.09	−30.51	51.30	−81.09	−42.38	41.04	−101.37
22	14.49	18.30	−46.09	14.49	18.30	−46.09	10.43	14.64	−57.62
23	49.49	34.30	47.91	49.49	34.30	47.91	35.63	27.44	38.33
24	104.49	11.30	73.91	104.49	11.30	73.91	75.23	9.04	59.13

Table B.3
TriGenSCA after an unplanned shutdown

1	8			9		
Time (h)	Cumulative energy (MWh)			New cumulative energy (MWh)		
	Power	Heating	Cooling	Power	Heating	Cooling
	0	0	0	826.22	254.37	560.72
1	86.03	−33.37	47.13	912.25	221.00	607.85
2	175.66	−27.53	91.85	1,001.88	226.84	652.57
3	268.89	−28.39	113.38	1,095.12	225.97	674.10
4	362.12	−70.51	130.10	1,188.34	183.85	690.82
5	451.75	−75.13	130.83	1,277.97	179.24	691.55
6	519.78	−147.25	108.21	1,346.00	107.13	668.93
7	551.81	−106.21	101.85	1,378.03	148.16	662.57
8	509.44	−87.57	74.23	1,335.65	166.80	634.95
9	397.61	−76.12	65.36	1,223.83	178.25	626.09
10	278.84	−65.48	65.25	1105.06	188.89	625.97
11	160.08	−103.85	57.63	986.29	150.52	618.35
12	110.75	−123.47	57.51	936.97	130.90	618.24
13	54.48	−141.84	44.90	880.70	112.53	605.62
14	−64.28	−148.96	51.22	761.93	105.41	611.95
15	−155.28	−176.07	71.15	670.94	78.29	631.87
16	−246.27	−172.63	77.489	579.95	81.73	638.20
17	−316.42	−206.00	−42.64	509.79	48.37	518.08
18	−497.69	−254.37	−177.76	328.53	0	382.96
19	−672.01	−235.73	−256.62	154.20	18.64	304.10
20	−783.84	−189.08	−401.74	42.38	65.29	158.98
21	−826.22	−148.04	−503.11	0	106.33	57.62
22	−815.786	−133.39	−560.72	10.43	120.97	0
23	−780.156	−105.95	−522.40	46.06	148.42	38.33
24	−704.925	−96.91	−463.27	121.29	157.46	97.45

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