

# Development of Numerical Trigeration System Cascade Analysis with Transmission and Storage Energy Losses Consideration

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**Abstract.** Depletion and rising prices of fossil fuel, as well as environmental pollution, have led the world to find energy-efficient technologies such as improvement of efficiency of the current energy systems. The thermal efficiency of the current systems can be improved from 30 – 40 % to 80 – 90% through implementation of trigeneration system. Trigeration is a system which can improve the efficiency of the current energy systems by reusing the waste heat to produce power, heating and cooling from a single fuel. Pinch Analysis is a methodology which enables users to optimize the energy, water and other resources. Trigeration System Cascade Analysis (TriGenSCA) is developed to minimize power, heating and cooling energies as well as obtain optimal sizing of the trigeneration system. In the previous TriGenSCA, transmission energy losses which contribute significantly to the final amount of energy arrived at the demand was not considered. This leads to an optimistic target for energy reduction. The objective of this work is to develop an extension of numerical insight-based Pinch Analysis methodology for optimal trigeneration system which considers energy losses in the transmission lines and storage systems. There are three major steps on developing TriGenSCA, which are data extraction, construction of TriGenSCA with transmission and storage energy losses, and comparison of TriGenSCA with and without transmission energy losses consideration. The transmission energy losses are included in the TriGenSCA where energy depleted due to the transportation of energy from the trigeneration system to the demand load, separated by 10 km of distances. Aluminium cable steel, carbon and stainless steel pipelines are used to transfer power and thermal energies to the demands. Based on the case study, the energy difference of TriGenSCA with and without transmission energy losses is 76.83 MWh/d. This shows huge energy is lost due to the transmission process. The development of this systematic methodology can give benefits to engineers, designers and power plant managers in order to determine the exact value of utility and thus, perform the optimal design of a trigeneration system.



## 1. Introduction

Rising prices of fossil fuels and environmental pollution have led to serious problems in the world. The problems, however, can be catered by the development of energy-efficient technologies. Trigeneration is an alternative technology that can improve the efficiency of the current energy systems by reusing waste heat for other applications such as district heating and cooling. The construction of power and thermal suppliers such as nuclear power stations and geothermal field, however, are far away from the commercial and residential buildings [1]. The plants need to be located near a ready supply of cooling water, which not necessarily correspond to the location of the population centre [2]. Conventional heat transportation processes are normally limited within a small range of temperature and short distance (less than 10km) [3]. Han et al. [4] proposed a novel combined heat driven absorption cooling with energy storage and long distance heating and cooling systems without heat preservation. Han et al. [4] proved that a long transmission distance of 14.9 km could create 13.1 MW of heat loss.

Pinch Analysis is a part of Process Integration which combines several parts of processes or whole processes to minimize consumption of resources or harmful emission into the environment. In the late 1970s, the Pinch Analysis has been introduced by Linnhoff and Flower [5] which was called Heat Recovery Pinch to improve heat recovery in the industry. Since then, the development of Pinch Analysis has been continuously evolving in heat exchanging networks, mass exchanging networks, utility systems, water networks and production planning (see details on Klemeš et al. [6]). Recent studies of Total Site Cooling, Heating and Power methodology has been developed by Jamaluddin et al. [7] involving trigeneration system for minimising cooling, heating and power requirements in total site energy system. However, the TriGenSCA method developed by Jamaluddin et al. [7] does not consider transmission energy losses. The energy losses in the heat and cool transmission are due to the friction resistance along the pipelines and dissipation heat loss between pipelines and surroundings. Meanwhile, the energy loss in power transmission is due to the resistance in the conductor. The consideration of transmission energy losses in the methodology can give an actual value of utility needed in a trigeneration system. The objective of this work is to develop an extension of numerical insight-based Pinch Analysis methodology, which considers transmission energy losses in the pipelines for the demand buildings. The development of this systematic methodology can give benefits to engineers, designers and power plant managers in order to determine the exact value of utility and thus, perform optimal design of a trigeneration system.

## 2. Methodology and Case Study

This paper applies the insight-based numerical approach via TriGenSCA with transmission and storage energy losses consideration. The development of TriGenSCA is necessary to minimize the power, heating and cooling targeting as well as to optimize sizing of the utility. In this case study, the centralized trigeneration system is implemented in order to supply power, heating and cooling applications to the demands. Production of Very High-Pressure Steam (VHPS) from the boiler is used to generate power, and lower pressure steams such as High-Pressure Steam (HPS) through a double extracting steam turbine. The HPS can be directly supplied to the demand or condensed by using the condensing turbine to generate more power or by using a condensation system to generate Hot Water (HW). The HW can be used either directly to the demand or converted to cooling utilities such as Chilled Water (ChW) through absorption chiller. The lead acid battery is used as a storage system for power, whereas the thermochemical energy storage system is used for storing heating and cooling energies. The usage of storage systems is required to get rid of the problem of insufficient coincidence between energy supply and demand.

In the first step, data for energy supply and demand are extracted to demonstrate the extended methodology of Trigeneration Pinch Analysis. Figure 1 shows the hourly energy source and demand patterns during the summer season. The data of hospital and hotel buildings as energy demands are extracted from [8] since these buildings consumed a high amount of power, heating and cooling, especially during summer. Energy supply, on the other hand, is formed based on the average total

demands as calculated by using Equation (1). In this case study, the HPS is summarized as a heating utility, whereas ChW is summarized as a cooling utility. The data required for transmission and storage energy losses are presented in Table 1.

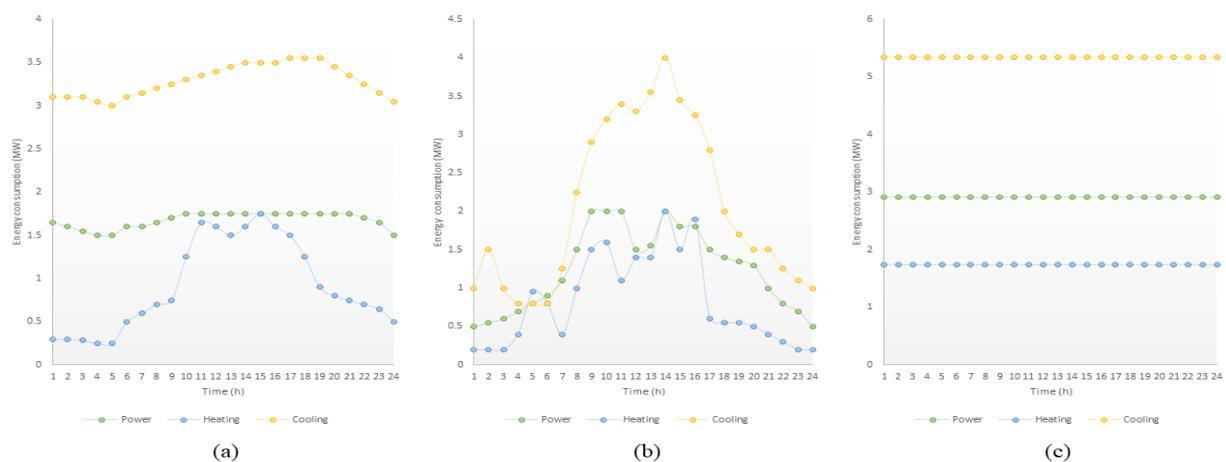
$$E_{ave} = \frac{\sum E_{demand}}{T} \quad (1)$$

Where;

$E_{ave}$  = Average energy in MW

$\sum E_{demand}$  = Total energy demand of a day in MWh

$T$  = Time in h



**Figure 1.** Data energy patterns in a day during the summer season for (a) hospital building [8], (b) hotel building [8] and (c) trigeneration system.

**Table 1.** Data required for transmission and storage energy losses

Parameters	Data	
Estimated length of transmission for power and thermal energies	10 km	
Type of insulator for thermal pipeline	Calcium silicate	
Diameter for carbon steel for heat pipeline [9]	0.1 m	
Diameter for stainless steel for cool pipeline [9]	0.1 m	
Heat dissipating capacity of heating pipeline per unit area [4]	350 W/m <sup>2</sup>	
Heat dissipating capacity of cooling pipeline per unit area [4]	420 W/m <sup>2</sup>	
Inverter efficiency [7]	90%	
Thermochemical storage system [7]	Charging efficiency	58%
	Discharging efficiency	58%
Lead-acid battery [7]	Charging efficiency	90%
	Discharging efficiency	90%
Aluminum Cable Steel (Code: Starling) [10]	Resistance	98.1 mΩ/km
	Carrying current capacity	840 A
	Temperature	75°C

The development of cascade analysis in TriGenSCA is necessary to verify the estimated size of utilities in a trigeneration system. Table 2 shows simplified cascade analysis of the trigeneration system after iteration. Construction of cascade analysis can be constructed as shown below:

1. Column 1 shows time for 24 h operations with 1 h interval.
2. Column 2 shows the power, heating and cooling source from the trigeneration system (obtained from Figure 1).
3. Column 3 presents the availability of energy after transmission energy losses. The available power after considering transmission energy losses is calculated by using Equation (2) to show energy depleted due to the transportation of power from the trigeneration system to the demand load, separated by long distances. Available heat and cool energy after the transmission process, on the other hand, is calculated by using Equation (3). Transmission heat energy uses carbon steel pipeline to transfer the energy source from the trigeneration system to the demand load. Transmission of cool energy, on the other hand, uses a stainless steel pipeline to transfer the cool energy to the demand load.

$$W_{power} = E_{power} - (R_T \times I^2 \times L \times 1h) \quad (2)$$

Where;

$W_{power}$  = Availability of power energy after transmission energy loss in MWh

$E_{power}$  = New net power energy requirement in MWh

$R_T$  = Resistance in  $m\Omega/km$

$I$  = Carrying current capacity in Ampere

$L$  = Length of transmission in m

$$W_{hot/cool} = E_{hot/cool} - (\pi \times D \times L \times q_c) \quad (3)$$

Where;

$W_{hot/cool}$  = Availability of hot/cool energy after transmission energy loss in MWh

$E_{hot/cool}$  = New net hot/cool energy requirement in MWh

$D$  = Diameter of pipelines in m

$L$  = Length of transmission in m

$q_c$  = Heat dissipating capacity per unit area in  $MWh/m^2$

4. Column 4 shows energy demands from hotel and hospital buildings (data can be obtained from Figure 1).
5. Column 5 presents the net energy requirement where the available energy from Column 3 is subtracted with energy demands from Column 4. This indicates that the availability of energy generations are supplied to the energy demands at the respective time intervals. Surplus energy is represented as a positive value, where deficit energy is represented as a negative value.
6. The new net energy requirement in Column 6 shows the conversion of surplus energy at the higher utility temperature to deficit energy at lower utility temperature. The energy conversion, however, requires energy lost due to the efficiency of utility. The example is given in the table where power has a deficit of 0.14 MWh at an 8th-time interval. Hence, surplus heating utility consists of HPS is condensed into a condensing turbine to form additional power. However, 0.03 MWh of heat energy is lost due to the efficiency of a condensing turbine.
7. Column 7 shows the energy losses due to the charging and discharging of storage systems based on the available energy after transmission energy losses. Surplus energy is charged and stored into the storage systems (positive values) whereas deficit energy shows insufficient energy which requires energy in the storage systems to discharge to provide an additional source of

energy (negative values). The charging and discharging efficiencies are considered in order to indicate energy losses due to charging and discharging of energies into and out of storage systems (obtained from Step 1).

8. Column 8 presents the cumulative energy of the system. This indicates that the excess energy at the time interval is stored into the storage systems and will be further used in the following time interval. A start-up for initial energy is assumed to be zero. Surplus energy is accumulated from the highest to the lowest time intervals. Equation (4) is used to calculate the cumulative energy. Negative values in Column 8 show deficit energy where positive values show surplus energy. The highest negative value in this column represents the most deficits of energy required in the system.

$$E_{i+1} = E_i + E_{\text{charg/discharg}} \quad (4)$$

Where;

$E_{i+1}$  = Cumulative energy for the next time interval in MWh

$E_i$  = Cumulative energy for the current time interval in MWh

$E_{\text{charg/discharg}}$  = Charging and discharging energy in MWh

9. Column 9 presents the new cumulative energy, which also calculated by using Equation (4). The highest negative value in Column 8 is converted as a positive value and make it as the initial cumulative energy to represents the external energy needed in the storage tank to supply the demand. The excess energy available in the storage tank can be obtained from the last row of this column.

The new size of utility in a trigeneration system needs to be calculated so that energy gaps between initial energy and final energy could be minimized. The minimization of energy gaps between initial energy and final energy can reduce costs as well as energy dissipation to the environment. The new size of utility in a trigeneration system is calculated, as shown in Equation (5). Based on the analysis, there are two conclusions that can be drawn. Firstly, the capacity of utility needs to be increased if the final energy is less than the initial energy. Secondly, the capacity of utility is in oversized if the final energy is more than the initial energy. By using Equation (5), power, heating and cooling utilities are increased from 2.92 MW, 1.74 MW and 5.34 MW to 3.78 MW, 3.66 MW and 7.64 MW.

$$S_{eq(new)} = S_{eq} - \frac{(E_{final} - E_{initial})}{T} \quad (5)$$

Where;

$S_{eq(new)}$  = New estimated utility sizing in a trigeneration system in MW

$S_{eq}$  = Previous estimated utility sizing in a trigeneration system in MW

$E_{final}$  = Available energy for the next day in MWh

$E_{initial}$  = Minimum outsourced energy supply in MWh

$T$  = Time in h

The percentage change which is derived by using Equation (6) used to reduce the energy gaps between minimum outsourced energy supply to start up the system and available energy for the next day. The reduction of energy gaps can give an optimal size of utilities in the trigeneration system. Ho et al. [10] have set a value of 0.05% as a tolerance for the accuracy of the results. An iteration method is involved in this step and will stop as the values of percentage change of power, heating and cooling are below or at 0.05%. Based on the first iteration, percentage changes for power, heating and cooling are 22.82%, 52.4% and 30.09%. The calculation stops at 6th iteration since all percentage changes of utilities are less than 0.05%.

$$P = \frac{|S_{eq(new)} - S_{eq}|}{S_{eq}} \times 100\% \quad (6)$$

Where;

$P$  = Percentage change between the previous and new size of utility in a trigeneration system

$S_{eq(new)}$  = New estimated utility sizing in a trigeneration system in MW

$S_{eq}$  = Previous estimated utility sizing in a trigeneration system in MW

**Table 2a.** Simplified cascade analysis after final iterations.

1 Time (h)	2 Energy source (MW)			3 Available energy (MW)			4 Energy demand (MWh)			5 Net energy requirement (MWh)		
	Power	Heat	Cool	Power	Heat	Cool	Power	Heat	Cool	Power	Heat	Cool
1	3.69	3.37	7.26	3.01	2.27	5.94	2.15	0.5	4.1	0.85	1.77	1.84
24	3.69	3.37	7.26	3.01	2.27	5.94	2	0.7	4.05	1.01	1.57	1.89

**Table 2b.** Simplified cascade analysis after final iterations.

1 Time (h)	6 New net energy requirement (MWh)			7 Charging and discharging energy (MWh)			8 Cumulative energy (MWh)			9 New cumulative energy (MWh)		
	Power	Heat	Cool	Power	Heat	Cool	Power	Heat	Cool	Power	Heat	Cool
							0	0	0	1.95	4.18	4.73
1	0.85	1.77	1.84	0.69	1.02	1.07	0.69	1.02	1.07	2.64	5.21	5.80
24	1.01	1.57	1.89	0.81	0.91	1.09	-0.01	0.01	0.01	1.95	4.19	4.73

### 3. Conclusion

An extension of the numerical method based on Pinch Analysis called TriGenSCA by considering transmission and storage energy losses has been developed to determine the exact value of energy required by a trigeneration system to supply to the demands. Energy losses due to frictional force in the transmission lines as well as charging and discharging of energy into and out of storage systems are considered. more energy is needed by the trigeneration system to supply sufficient energy to the demands. The TriGenSCA can offer an optimal sizing of utilities in the trigeneration system by reducing energy gaps between final and initial energy contents in the trigeneration system. The development of this tool can offer benefits to engineers, designers and power plant managers in order to determine the exact value of utility and thus, perform optimal design of a trigeneration system.

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