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Cold Energy System Cascade Analysis for Waste Cold Energy Recovery from Liquid Nitrogen

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Waste cold energy generated from liquid nitrogen vaporization is usually abandoned when the gas supply system is pre-designed without cold integration. This study aims to investigate the potential for energy savings in a chiller system through the integration of waste cold recovery with thermal energy storage. The cold waste recovery system captures the waste cold generated during the operation of the liquid bulk nitrogen system and transfers it to a thermal energy storage system. This stored energy can then be utilized to supplement the chiller system during the targeted periods of peak demand, reducing its load and increasing its efficiency. A time-based cascade analysis, i.e., Cold Energy System Cascade Analysis (CESCA), is developed to determine the maximum peak shave load with the minimum capacity of the TES for liquified nitrogen (LN2) cold energy recovery system for a given peak shaving duration. The proposed methodology is applied to 3 cases, with different peak shaving durations, to examine the impacts of peak shaving duration on the design of the LN2 cold energy recovery system.

1. Introduction

The global climate changes are the key challenges to major environmental issues which have resulted in increased temperatures, escalating sea levels, and modifications in climate cycles. Without the additional efforts to reduce the global green-house gases, it can cause significant damage to livelihoods, businesses, and homes on this earth (Osman et al., 2023). Nitrogen gas is widely used in the process industrial and manufacturing plants which benefit from nitrogen's inert properties and employ them to prevent corrosion-causing interactions with oxygen, soiling, fire, explosion, and other detrimental effects (Ivanova and Lewis, 2012). Liquid nitrogen (LN2) is commonly produced by the separation and liquefaction of air. Liquid bulk nitrogen storage is commonly used to supply the gaseous nitrogen through the ambient air vaporizer (AAV) to provide reliable, consistent, and high purity gas needed in fabs. In recent advanced fabs, consumption of nitrogen can reach 50,000 m^3/h (Song et al., 2019). The waste cold energy generated from the vaporization is usually abandoned when the gas supply system is pre-designed by the supplier without considering the on-site heat integration opportunity. The recovery of LN2 cold energy can be maximized through the recovery of latent heat and sensible heat when the nitrogen gas demand is used at ambient temperature. A cold integration analysis is needed to determine the optimal equipment capacity, size, technology, and investment cost. Utilizing LNG cold energy results in appreciable savings in terms of the economy and environment. For example, according to cold utilization results in China, 2,356 Mt of standard coal can be saved, and 6.173 Mt of CO_2 can be reduced by 2020 (Ahmad et al., 2016). These are well-researched thermal storage techniques that are highly reliable, simple to install, and economically feasible (Hutty et al. 2020). Thermally layered storage vessels can have an efficiency of up to 90 %, according to experimental research (Facci et al., 2019). The measures to reduce mixing between the cold and hot layers are the main focus of the working limits for stratified storage tanks. The utilization of thermal energy storage (TES) with HVAC systems was demonstrated by Kamal et al. (2019) to be capable of shifting

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peak cooling electricity demand by up to 78 %, resulting in a reduction in operational expenses of up to 17 %. Similarly, Jebamalai et al. (2020) showed that TES could cut costs by over 7 % when using a district heating network powered by fossil fuels.

To minimize mixing and maintain high energy efficiency, it is generally accepted that lower intake velocities and greater temperature gradients between the hot and cold layers are optimal for stratified storage (Egging-Bratseth et al., 2020). Time-based pinch analysis (PA) is a numerical approach to analyze the supply chain aggregate planning using PA to satisfy the demand within a certain timeframe while making the most money (Linnhoff, 1993). Material flows, material holdup and time are three important indicators of a supply chain. Othman et al. (2017) proposed a Gas System Cascading Analysis (GASCA) for targeting a collection of biogas demand profiles for various biogas purity levels, subject to a minimum biogas transportation size. The original heat PA concept is comparable to the suggested PA for power systems. But both analyses disagree fundamentally in important ways. Heat PA is based on temperature vs. enthalpy, whereas power PA is dependent on time versus electricity usage (Ho et al., 2014).

From the above literature review, it can be concluded that there are a few key research gaps related to cold recovery from liquid bulk nitrogen and the use of thermal energy storage for waste cold recovery. Cold recovery from onsite liquid bulk nitrogen is presently lacking and less attractive due to the small volume and benefit constraints. Waste cold recovery without optimizing strategy leads to unpromising outcomes. Optimizing TES sizing using PA by time-based aggregation could be the alternative instead of energy-based PA. These research gaps highlight the need for further research and innovation in thermal energy storage and waste cold energy recovery, in order to maximize the benefits and reduce the constraints. In this work, Cold Energy System Cascade Analysis (CESCA) is proposed to determine the maximum peak shave load with the minimum capacity of the TES for LN2 cold energy recovery system for a given peak shaving duration. In the next section, the mathematical background and targeting algorithm are presented, which is followed by an illustrative example, and further analysis of the impact of peak shaving duration on the LN2 cold energy recovery system.

2. Mathematical Background and Targeting Algorithm

Figure 1 illustrates the superstructure of the CESCA. The cold energy generated from LN2 is being utilized to shave the peak load of cooling demand, and subsequently reduce the chiller load. In the proposed system, the cold energy can also be stored in the thermal energy storage (TES) for subsequent usage. The charging/discharging of TES is very much dependent on the targeted peak shave load. Thus, the given problem statement is stated as given a cooling demand profile (CD_t), and cold energy generation (R_t), to target the minimum capacity of thermal energy storage and the minimum chiller load, by adjusting the peak shaving duration.

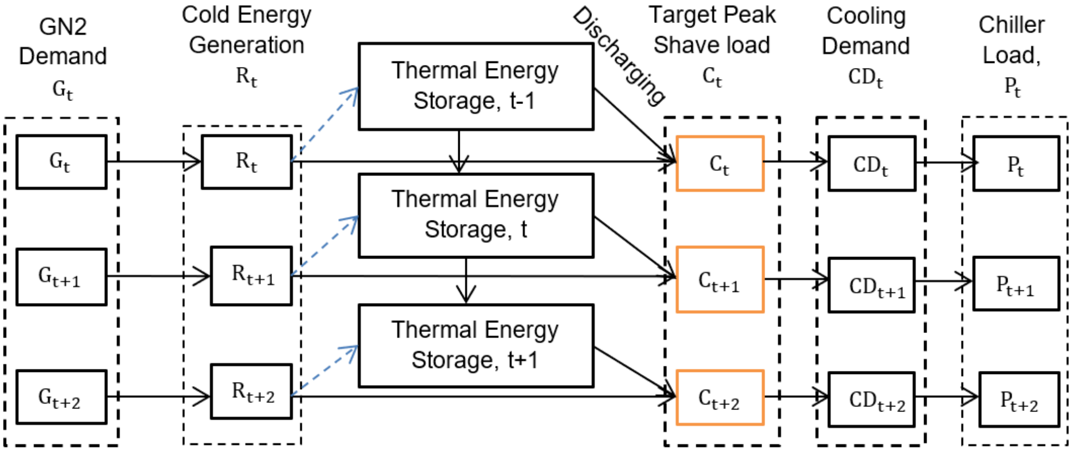


Figure 1: Super-structure of CESCA

Figure 2 illustrates the generic cascading procedure for CESCA framework. Time Slice t is arranged in ascending order in column 1. The time interval of each Time Slice could be arbitrarily adjusted. The cooling demand of each time slice (CD_t) is presented in column 2.

Cold energy generated (R_t) by nitrogen gas flow(G_t) is determined for each Time Slice t using Eq(1) and arranged in column 6, where CL is the specific cooling load of nitrogen (TR/kg N_2) and f_{HEX} is the efficiency of the heat exchanger.

$$R_t = G_t \times CL \times f_{HEX} \tag{1}$$

In the first iteration, the target peak shave cooling demand (C_t) is then derived from the cold energy generation (R_t), utilization factor (u) with the initial value of 100% and peak shave duration (m) by using Eq(2) and presented in column 3.

$$C_t = C = \sum_t R_t \times (u/m) \qquad \forall\, t \tag{2}$$

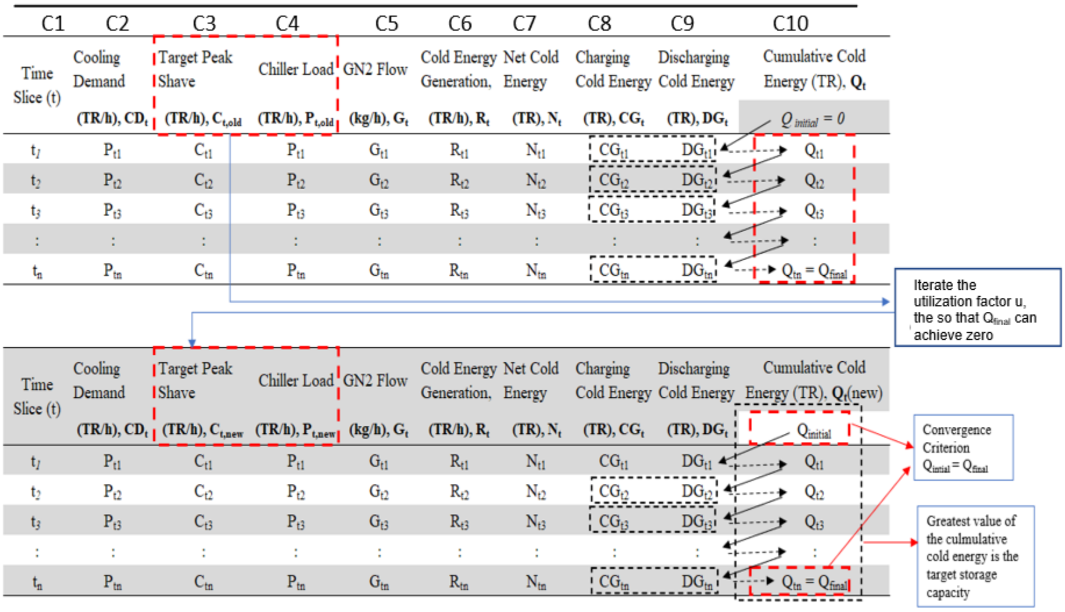


Figure 2 Generic Cascading Procedure for CESCA Framework

The final chiller load (P_t) is tabulated using Eq(3) and presented in column 4.

$$P_t = CD_t - C_t \qquad \forall\, t \tag{3}$$

Net cold energy (N_t) is referring to the difference between R_t and C_t, calculated using Eq(3) are presented in column 7.

$$N_t = R_t - C_t \qquad \forall\, t \tag{4}$$

Based on the sign indicators, the charging and discharging LN2 data are calculated. Since the net cold energy (N_t) is positive, the charging LN2 (CG_t) is determined using Eq(4) and presented in column 8, by considering the charging efficiency (f_{chg}) of LN2 storage.

$$CG_t = N_t\, f_{chg} \qquad \forall\, t \tag{4}$$

If the net gas demand N_t is negative, Eq(5) is used to compute the discharging cold energy (DG_t) and presented in column 9, by considering the charging efficiency (f_{chg}).

$$DG_t = \frac{N_t}{f_{chg}} \qquad \forall\, t \tag{5}$$

Eq(6) is used to determine cumulative cold energy at every Time Slice t (Q_t), by considering the cumulative cold energy at previous Time Slide (Q_{t-1}), charging and discharging of cold energy. The value is then presented in column 10.

$$Q_t = Q_{t-1} + CG_t + DG_t \qquad \forall\, t \tag{6}$$

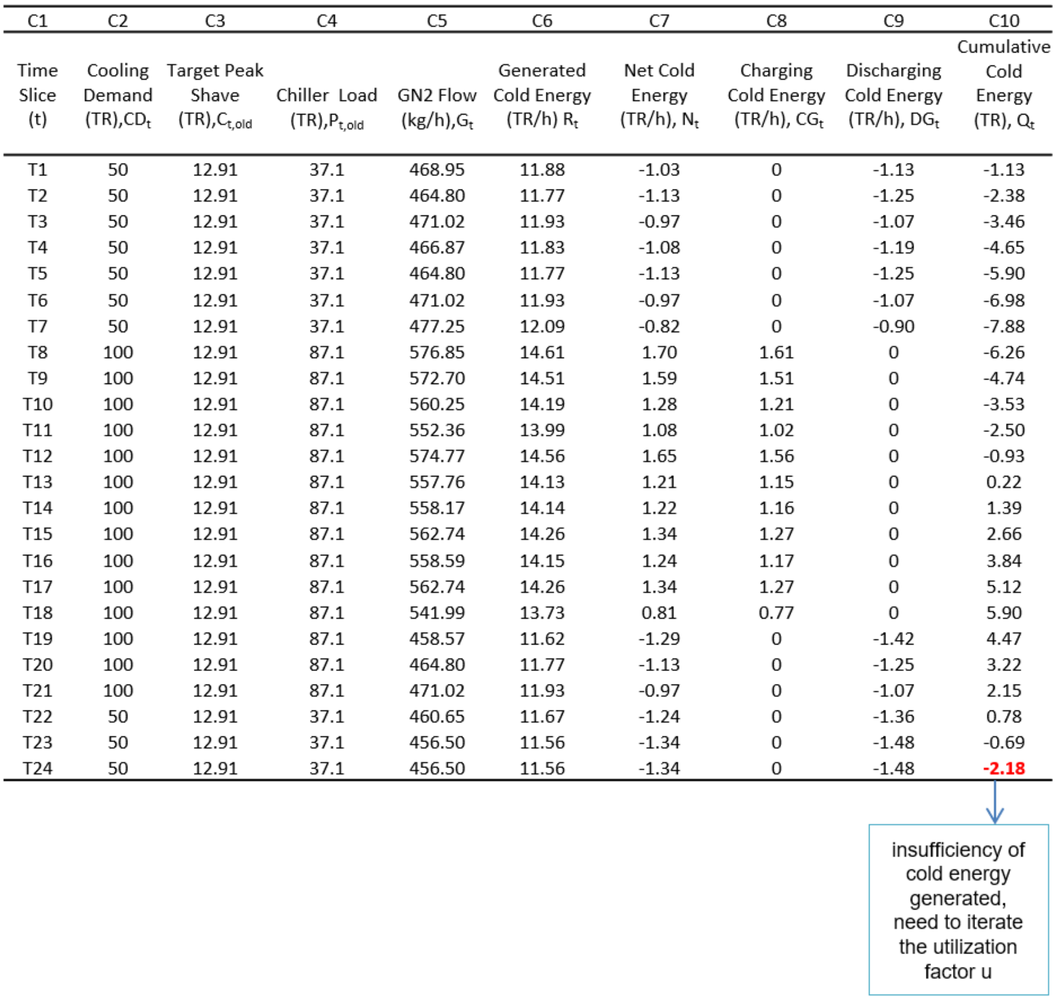
In the case of final cumulative cold energy (Q_{final}) showing negative value, it implies that the initial utilization factor u, is not realistic, where the available energy from the TES is not able cater for the targeted peak demand.

With that, “Goal Seek” function in Excel is utilized to target the new utilization factor (u), to ensure the Q_{final} is positive.

With the new utilization factor (u), the target peak shave value is then recalculated using Eq (2), and the subsequent cumulative energy profile is tabulated. The most negative cold energy in cumulative cold energy is then became the initial storage capacity of the new cumulative cold energy (the new $Q_{initial,}$). The minimum capacity of TES is determined by selecting the maximum value in the Column 10 of new cumulative cold energy.

3. Case Study

The developed method is applied in a case study. The cooling demand and available GN2 flow of the facilities can be observed in the Cooling Demand and GN2 Flow column 5 of Figure 3. The heat exchanger efficiency is assumed at 95% with an overall heat transfer coefficient of 0.67 for cryogenic liquid. The heat loss for TES charging and discharging (f_{chg}) is both assumed at 5 %. The peak shaving duration of 24 h. Figure 3 and Figure 4 present the initial and final iteration results for CESCA.

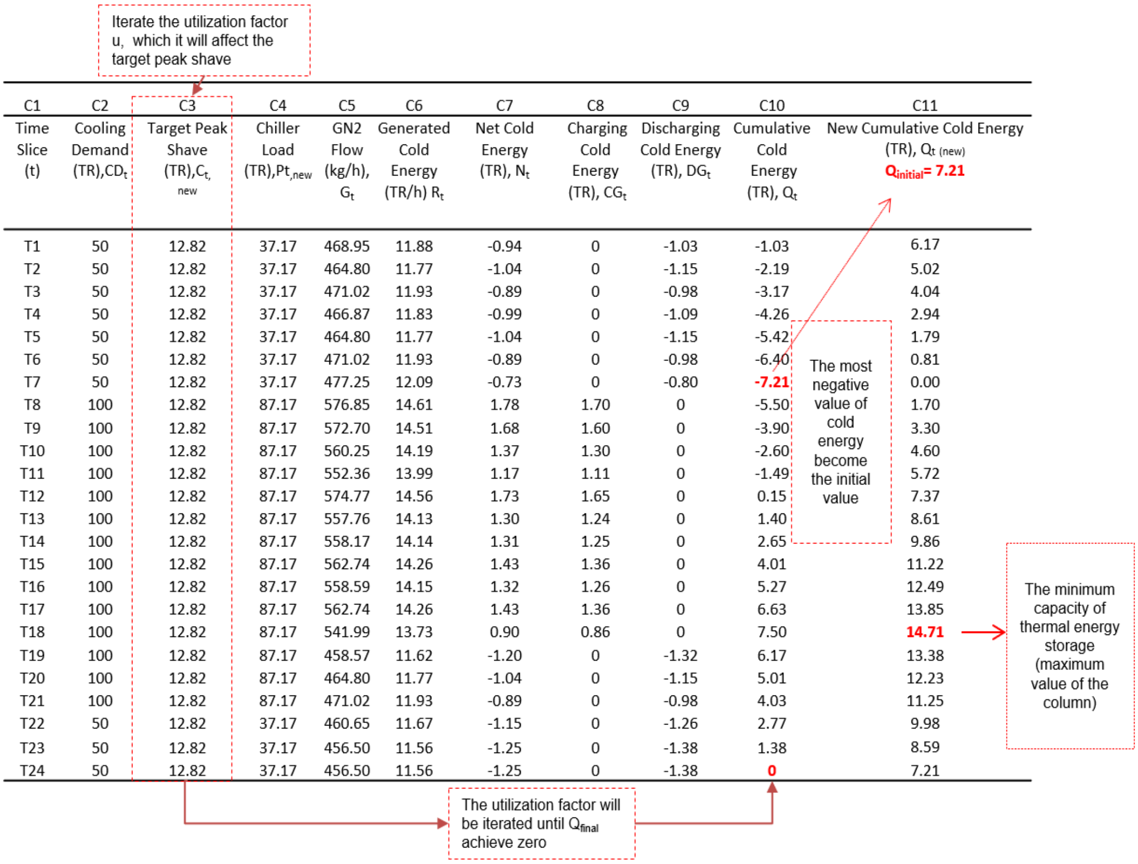


C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
Time Slice (t)	Cooling Demand (TR),CD_t	Target Peak Shave (TR),$C_{t,old}$	Chiller Load (TR),$P_{t,old}$	GN2 Flow (kg/h),G_t	Generated Cold Energy (TR/h) R_t	Net Cold Energy (TR/h), N_t	Charging Cold Energy (TR/h), CG_t	Discharging Cold Energy (TR/h), DG_t	Cumulative Cold Energy (TR), Q_t
T1	50	12.91	37.1	468.95	11.88	-1.03	0	-1.13	-1.13
T2	50	12.91	37.1	464.80	11.77	-1.13	0	-1.25	-2.38
T3	50	12.91	37.1	471.02	11.93	-0.97	0	-1.07	-3.46
T4	50	12.91	37.1	466.87	11.83	-1.08	0	-1.19	-4.65
T5	50	12.91	37.1	464.80	11.77	-1.13	0	-1.25	-5.90
T6	50	12.91	37.1	471.02	11.93	-0.97	0	-1.07	-6.98
T7	50	12.91	37.1	477.25	12.09	-0.82	0	-0.90	-7.88
T8	100	12.91	87.1	576.85	14.61	1.70	1.61	0	-6.26
T9	100	12.91	87.1	572.70	14.51	1.59	1.51	0	-4.74
T10	100	12.91	87.1	560.25	14.19	1.28	1.21	0	-3.53
T11	100	12.91	87.1	552.36	13.99	1.08	1.02	0	-2.50
T12	100	12.91	87.1	574.77	14.56	1.65	1.56	0	-0.93
T13	100	12.91	87.1	557.76	14.13	1.21	1.15	0	0.22
T14	100	12.91	87.1	558.17	14.14	1.22	1.16	0	1.39
T15	100	12.91	87.1	562.74	14.26	1.34	1.27	0	2.66
T16	100	12.91	87.1	558.59	14.15	1.24	1.17	0	3.84
T17	100	12.91	87.1	562.74	14.26	1.34	1.27	0	5.12
T18	100	12.91	87.1	541.99	13.73	0.81	0.77	0	5.90
T19	100	12.91	87.1	458.57	11.62	-1.29	0	-1.42	4.47
T20	100	12.91	87.1	464.80	11.77	-1.13	0	-1.25	3.22
T21	100	12.91	87.1	471.02	11.93	-0.97	0	-1.07	2.15
T22	50	12.91	37.1	460.65	11.67	-1.24	0	-1.36	0.78
T23	50	12.91	37.1	456.50	11.56	-1.34	0	-1.48	-0.69
T24	50	12.91	37.1	456.50	11.56	-1.34	0	-1.48	**-2.18**

insufficiency of cold energy generated, need to iterate the utilization factor u

Figure 3: Initial iteration result of CESCA

The CESCA begins with the initial iteration Figure 3, the target peak shave is being estimate by 100% the total daily generated cold energy of GN2 and constraint by the duration of peak shave. The initial hourly target peak shave load is the average of total daily generated cold energy divide by the total hours of peak shave duration, i.e., 12.91 TR. The cumulative cold energy, Q_t at T24 observed at negative value (-2.18 TR) explained that the insufficiency of cold energy generated daily. The cumulative cold energy Q_{24} is then iterated to become zero by manipulating the target peak shave utilization load percentage (u). At final iteration, the target peak shave utilisation percent is reduced from the original assumed 100 % to 99.32 %, and the resulted target peak shave is now 12.81 TR. With that, in the new cumulative energy profile, the most negative cold energy (- 7.21 TR) became the initial storage capacity of the new cumulative cold energy (the new $Q_{initial}$,). The minimum capacity of thermal energy storage is determined by selecting the maximum value in the Column 11 of new cumulative cold energy, i.e., 14.71 TR.



Iterate the utilization factor u, which it will affect the target peak shave

C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
Time Slice (t)	Cooling Demand (TR),CD_t	Target Peak Shave (TR),$C_{t,new}$	Chiller Load (TR),$Pt_{,new}$	GN2 Flow (kg/h), G_t	Generated Cold Energy (TR/h) R_t	Net Cold Energy (TR), N_t	Charging Cold Energy (TR), CG_t	Discharging Cold Energy (TR), DG_t	Cumulative Cold Energy (TR), Q_t	New Cumulative Cold Energy (TR), $Q_{t\ (new)}$ **$Q_{initial}$= 7.21**
T1	50	12.82	37.17	468.95	11.88	-0.94	0	-1.03	-1.03	6.17
T2	50	12.82	37.17	464.80	11.77	-1.04	0	-1.15	-2.19	5.02
T3	50	12.82	37.17	471.02	11.93	-0.89	0	-0.98	-3.17	4.04
T4	50	12.82	37.17	466.87	11.83	-0.99	0	-1.09	-4.26	2.94
T5	50	12.82	37.17	464.80	11.77	-1.04	0	-1.15	-5.42	1.79
T6	50	12.82	37.17	471.02	11.93	-0.89	0	-0.98	-6.40	0.81
T7	50	12.82	37.17	477.25	12.09	-0.73	0	-0.80	**-7.21**	0.00
T8	100	12.82	87.17	576.85	14.61	1.78	1.70	0	-5.50	1.70
T9	100	12.82	87.17	572.70	14.51	1.68	1.60	0	-3.90	3.30
T10	100	12.82	87.17	560.25	14.19	1.37	1.30	0	-2.60	4.60
T11	100	12.82	87.17	552.36	13.99	1.17	1.11	0	-1.49	5.72
T12	100	12.82	87.17	574.77	14.56	1.73	1.65	0	0.15	7.37
T13	100	12.82	87.17	557.76	14.13	1.30	1.24	0	1.40	8.61
T14	100	12.82	87.17	558.17	14.14	1.31	1.25	0	2.65	9.86
T15	100	12.82	87.17	562.74	14.26	1.43	1.36	0	4.01	11.22
T16	100	12.82	87.17	558.59	14.15	1.32	1.26	0	5.27	12.49
T17	100	12.82	87.17	562.74	14.26	1.43	1.36	0	6.63	13.85
T18	100	12.82	87.17	541.99	13.73	0.90	0.86	0	7.50	**14.71**
T19	100	12.82	87.17	458.57	11.62	-1.20	0	-1.32	6.17	13.38
T20	100	12.82	87.17	464.80	11.77	-1.04	0	-1.15	5.01	12.23
T21	100	12.82	87.17	471.02	11.93	-0.89	0	-0.98	4.03	11.25
T22	50	12.82	37.17	460.65	11.67	-1.15	0	-1.26	2.77	9.98
T23	50	12.82	37.17	456.50	11.56	-1.25	0	-1.38	1.38	8.59
T24	50	12.82	37.17	456.50	11.56	-1.25	0	-1.38	**0**	7.21

The most negative value of cold energy become the initial value

The minimum capacity of thermal energy storage (maximum value of the column)

The utilization factor will be iterated until Q_{final} achieve zero

Figure 4: Final iteration result of CESCA

4. Impact of Leak Shaving Duration on The LN2 Cold Energy Recovery System

To analyse the impact of peak shaving duration on the cooling system, the case study in Section 3 is expanded by considering 2 additional cases, i.e., Case 2 and Case 3. The detailed description of scenarios is given as:

- Case 1: Peak shaving duration of 24 h (described in Section 3)
- Case 2: Peak shaving duration of 14 h by considering the peak electricity period which is 14 h from 8 am to 10 pm. This is the period when the utility provider charges the maximum demand.
- Case 3: Peak shaving duration of 8 h by considering office hours from 8 am to 5 pm.

Table 1 shows the key results of applying CESCA on the above describe scenarios, whereas Figure 1 presents the chiller load before and after cold energy recovery from LN2. From Figure 1, it can be observed that in Case 1, the entire chiller load profile is shifted downward, due to the 24 h peak shaving duration. In Case 2, the magnitude of peak shaving is now increased from 12.8 TR to 21.0 TR, due to shorter peak shaving duration. And to cater for the greater magnitude of peak shave, TES capacity has to be increased from 14.71 TR to 112.16 TR. Similar observation can be found between Case 2 and Case 3, where the magnitude of peak shaving is increased to 28.7, when the peak shaving duration is limited to 8 h.

Table 1: Results of CESCA

Results	Case 1	Case 2	Case 3
Initial target peak shave at 100% (TR)	12.9	22.1	31.0
Target utilization factor (%)	99.32 %	94.81 %	92.65 %
Final target peak shave at the target utilisation factor (TR)	12.8	21.0	28.7
Minimum TES capacity (TR)	14.71	112.16	158.78
Operating range of chiller (TR)	37~87	50~78	50~100

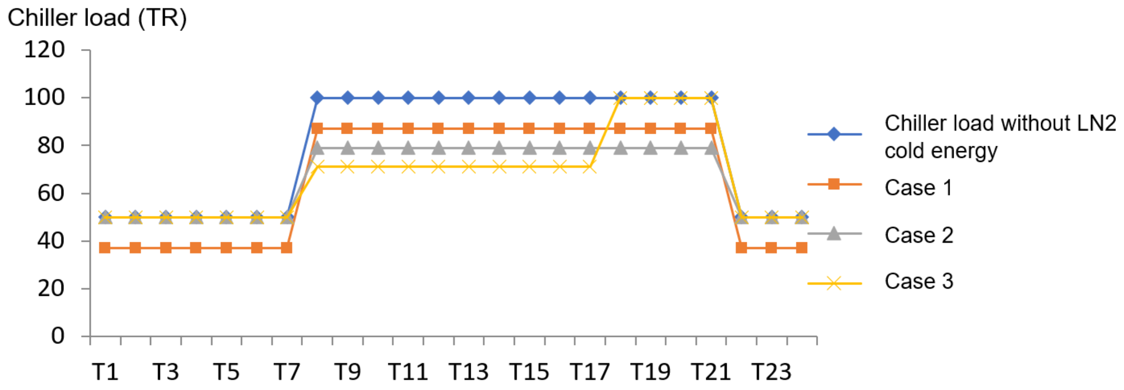


Figure 5: Load profile of chiller before and after considering the LN2 cold energy recovery (Case 1, 2 and 3)

5. Conclusion

A time-based cascade analysis, i.e., CESCA, is developed to determine the maximum peak shave load with the minimum capacity of the TES for the LN2 cold energy recovery system. It can also be concluded that with shorter peak shaving duration, the magnitude of peak shaving and TES storage size could be increased. Further economic analysis could be carried out to examine the financial impact of integrating the LN2 cold energy recovery system into the cold utility system of the industry.

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