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Design Optimization of a novel Cryo-Polygeneration demonstrator – Techno-economic feasibility study for a tropical climate in Singapore

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ABSTRACT

Decentralized polygeneration systems can provide multiple energy services for urban districts like universities and hospitals, with several energetic, economic and environmental benefits. However, deciding the right design or optimal capacities for such integrated multi-energy sources would require sophisticated modelling and optimization techniques. Furthermore, several design parameters and time-varying loads and weather conditions influence the performance of polygeneration systems. This study investigated the effects of renewables, storage units and time-varying loads (electricity, heat and cold) on the performance of a cryo-polygeneration system expected to be installed in 2022 at the NTU campus located in Singapore. Diverse design scenarios were analyzed to study the effect of critical components such as absorption chiller, cold storage and solar PV units with energy storage. The optimal design capacities derived confirms higher efficiency and economic performance than the reference system, i.e., generating the power and heat and power separately. The results are of great interest to academia and industry and contribute significantly to developing an efficient and cost-effective energy storage polygeneration system.

Keywords: Polygeneration system, LNG, Optimization problem, Energy Storage.

NONMENCLATURE

Abbreviations	
ABC	Absorption Chiller
BESS	Battery energy storage system
CTES	Cold Thermal Energy Storage
DER	Distributed Energy Resource
GT	Gas Turbine
PV	Photovoltaic system
RU	Regasification Unit
UG	Utility Grid
WCC	Water cooled electrical chiller

1. INTRODUCTION

As set forth by the European Commission's Strategy on Heating and Cooling [1] and IEA [2], the energy demand for space heating and cooling is growing faster in buildings and already causing enormous strain on electricity systems in many countries, as well as driving up emissions. Indeed, improving the sustainability of heating and cooling is a priority, and the strategy lists the goals of decreasing demand, increasing efficiency, and switching to renewable primary energy sources. To this end, the concept of decentralized polygeneration system and microgrid should be recognized as an enabling technology system with great potential. Polygeneration energy systems using multiple energy sources (e.g., wind, biomass, solar) and delivering multiple energy services (i.e., heating, cooling, and electricity) have potential economic and environmental benefits over traditional energy generation systems [3–5]. In particular, the concept of cryo-polygeneration system, an integrated rapidly deployable and highly energy-efficient solution that utilizes cold energy from Liquefied Natural Gas (LNG) and waste heat from power generation, might help in meeting the growing energy needs of urbanization and industrialization, especially in sub-tropical areas. Indeed, the premium-quality physical exergy in LNG at cryogenic temperature, usually wasted during regasification, might be recovered through direct utilization (i.e. food

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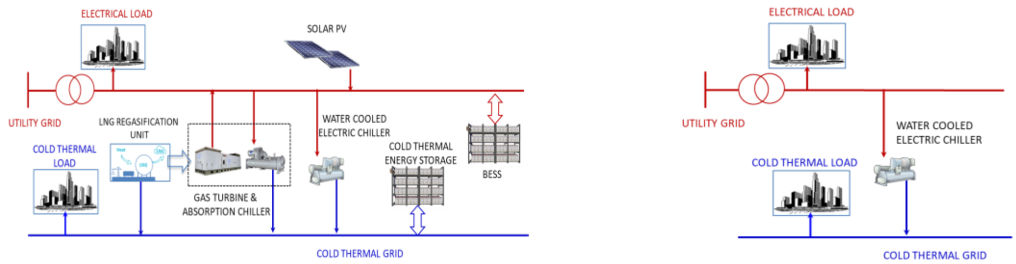


(a) (b)

Fig. 1. Schematic of (a) Cryo-polygeneration system and (b) base-case.

industry/warehouses [6]) or by storing it in dedicated thermal energy storage [7]. To this end, a district scale demonstration will be developed in Nanyang Technological University (NTU) in Singapore [8], becoming the first showcase of systems integration that can be exported overseas as an urban solution. In particular, the Cryo-Polygeneration is a novel one-stop solution that encompasses all technologies, concepts by which power generation, cold energy harnessing, cold export, cryogenic power generation, city gas generation can be jointly generated from one solution based on the needs of the customer. High levels of energy efficiency can be achieved by utilizing cold from LNG and waste heat from power generation.

Differently from the state of art literature in the microgrid sector mostly focusing on the electrical system performance and reliability, this paper deals with the optimal design of the above mentioned cryo-polygeneration system to meet the electrical and cooling load of a building located in the NTU campus. In order to explore the effect of the thermal energy storage system (TES), photovoltaic system (PV) and battery energy storage system (BESS), three design scenarios have been evaluated and compared with a baseline case scenario representing the business-as-usual case study.

2. METHODOLOGY AND MODEL DESCRIPTION

2.1 The cryo-polygeneration system: Reference system and different case scenarios

The cryo-polygeneration system developed in TRNSYS consists of electricity and cooling generation units and cold and electric energy storage devices. Fig. 1a shows the schematic of the proposed cryo-polygeneration system developed in TRNSYS consists of electricity and cooling generation units and cold and electric energy storage devices.

The electric power system comprises a gas turbine (GT) and PV modules. An LNG regasification unit (RU), an absorption chiller (ABC), recovering the waste heat of the GT exhaust gases, and a vapour compression water-cooled chiller (WCC) are to support cooling demands. Cold thermal energy storage (CTES) and BESS helps to suppress or absorb the unpredictable renewable energy sources and maximize the exploitation of excess heat and electricity. Three design scenarios are considered to study the effects of the critical components such as renewable energy sources and electrical and thermal storage (Table 1). Scenario 1 consists of a GT system, an LNG regasification unit, an absorption chiller and a vapour compression chiller. In scenario 2, a CTES system is added to the first scenario. In scenario 3, PV modules and BESS are added to the second scenario. It is worth underlining that the cryo-polygeneration system is connected to a utility grid in all the case scenarios under analysis. The majority of the buildings taps power from the utility grid to support their electrical and cooling loads using electric chillers. This case where all the demands are supplied by the electricity in a grid connected environment is taken as the baseline case scenario (Fig. 1b)

2.2 Operating strategies

The GT initially supplies the electricity demand. The power deficit will be provided primarily by renewable energy sources (PV modules) and the BESS. In case of a further power deficit, the electricity will be imported from the utility grid at the Singaporean electricity tariff [9], while no electricity export to the utility grid (UG) will be considered. The cooling demand is firstly covered by

Table 1 Cryo-polygeneration design case scenarios, optimization search space and capital costs.

Components	Case Scenarios				CAPEX	OPEX	Search Space	
	BC	1	2	3			Minimum	Maximum
GT	-	✓	✓	✓	1200 $/kW_e$	0.005 $/kWh_e$	0	10000 kW_e
PV	-	-	-	✓	1006 $/kW_p$	4 $/kW_p$/year	0	8000 kW_p
BESS	-	-	-	✓	380 $/kWh_e$	0.002 $/kWh_e$/year	0	10000 kWh_e
LNG RU	-	✓	✓	✓	133$/tpa_{LNG}$	2.5 % CAPEX/year	-	-
ABC	-	✓	✓	✓	230 $/kW_c$	0.001 $/kW_c$/year	0	15000 kW_c
WCC	✓	✓	✓	✓	150 $/kW_c$	0.001 $/kW_c$/year	0	15000 kW_c
CTES	-	-	✓	✓	100 $/m^3$	0.002 $/kWh_c$	0	6000 m^3
Utility Grid (import)	✓	✓	✓	✓	-	-	-	-

the LNG RU and subsequently by the ABC operation integrated with the cold thermal energy storage. The WCC will be used as a backup to cover the remaining cooling load not covered by LNG RU and ABC.

2.3 Optimization problem

In this section, the general structure of the optimization tool and the optimization technique has been explained. The optimal design and sizing of the cryo-polygeneration components are based on a three-level configuration. The simulation level (TRNSYS [10]), the particle swarm optimization (PSO) level (GenOpt [11]) and the interface for the communication between those two levels (TRNOPT). In particular, TRNSYS is dynamic simulation software whose solver calls the subroutines present in the input file and tries to solve the equations for each simulation time step. GenOpt is a software package used for optimization that minimizes an objective function by evaluating an external simulation program. The TRNOpt library in TRNSYS acts as an interface between TRNSYS simulator and the GENOPT Optimizer and streamlines the optimization process.

2.4 Key performance indicators, objective function and constraints

Compared to the baseline case scenario, the fuel consumption and electricity savings of the cryo-polygeneration is calculated by considering the primary energy saving (PES) metric, obtained specifying the efficiency reference values for separate production of heat and electricity [12–14], respectively. Minimizing the total annualized cost is the objective function of the optimization process, a premier economic index taking into account all the expenses during the lifetime of the project, defined as:

$$TAC = \sum_{s} CAPEX \cdot CRF + \sum_{y} C_{UG,y} + \sum_{y} C_{fuel,y} + \sum_{y} C_{OM,y} + \sum_{y} C_{carbtax,y} \quad (1)$$

Where CAPEX is the sum of the capital costs, the balance of plants and installation costs of the cryo-polygeneration systems; C_{UG} is the annual operation cost related to the electricity purchase from the utility grid; C_{fuel} is the annual fuel costs; $C_{O\&M}$ are the annual operation and maintenance costs; $C_{carbtax}$ is the annual cost due to a carbon tax introduced to promote the producers to improve the energy conversion efficiencies and the adoption of renewable energy technologies [15]; CRF is the capital recovery factor which takes into account the effect of annual interest rate "*i*" and the project lifetime "*N*". The objective function is constrained to the energy balance equation following the rules and limitations of the operating strategies. The goal of optimization is to determine the optimal capacities of various technologies i.e., the decision variables are the nominal capacities of GT, PV, BESS, ABC, CTES and WCC, etc. Some of the critical constraints accounted in the design optimization problem are:

- The electricity and cooling demands are fulfilled at all periods. Otherwise, a high dynamic penalty is imposed on the objective function based on the deviation from the desired value (complete load satisfaction).
- The operation of the GT is prevented below recommended minimum partial load ratio (PLR) to increase its lifetime and decrease the emissions [16]. This constraint is implemented in TRNSYS by a

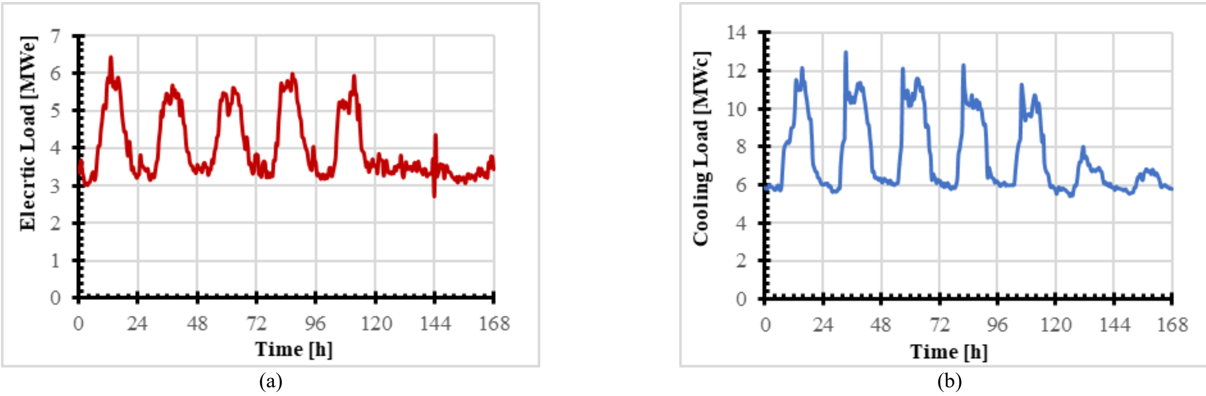


Fig. 2. Weekly electricity (a) and cooling (b) demands for the building located in NTU campus.

differential controller component limiting the GT operation as follows:

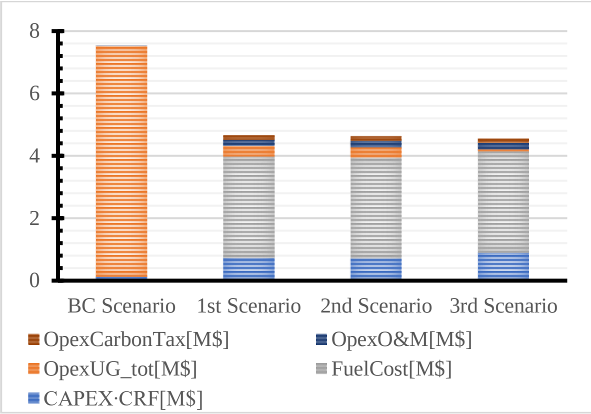
$$0.4 \leq PLR\ (t) \leq 1 \tag{2}$$

- The capacity of the distributed energy resources (DERs) is limited to the identified optimization search space. The adopted search space values are set according to the demand and the available footprint area for each DERs.
- The operations of the energy storage devices (BESS and CTES) are limited to their maximum and minimum state of charge.

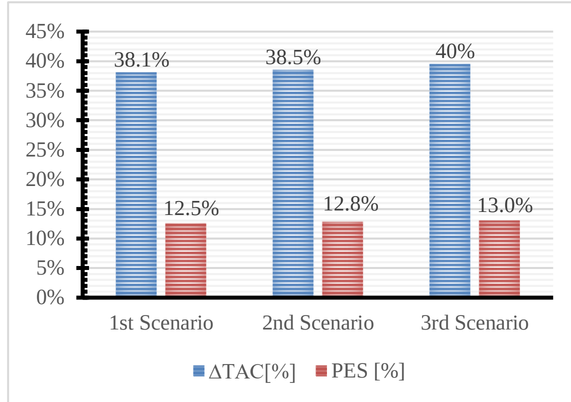
3. RESULTS AND DISCUSSION

This section discusses the optimal DERs capacities obtained for different polygeneration configurations and compares the economics and energy benefits of polygeneration configurations with reference to the base case. The objective function is estimated by performing TRNSYS simulation for one year with a half an hour time resolution. The electricity and cooling demands are defined on half an hourly basis and are available thanks to smart meters connected directly with the building. Fig. 2 shows representative weekly electrical and cooling demand, a segment of yearly demands considered in this study. Other crucial input data such as fuel price, Singapore weather data, carbon tax, and future projections are assumed for all scenarios. The economic analysis was carried out based on 30 years project lifetime. For each scenario, the cost benefits and energy savings derived with reference to minimum total annualized cost (i.e. the cost function of the optimization) are shown in Fig. 3. Table 2 shows the optimal solutions derived for all scenarios of the Cryo-Polygeneration system using TRNOPT and TRNSYS.

- The baseline scenario represents the business-as-usual configuration where the utility grid provides the electricity to cover the electric and cooling demand. As shown in Fig. 3a, the electricity cost is predominant with around 98 % compared to the other TAC cost components.
- Scenario 1 is the most straightforward architecture of the cryo-polygeneration system without the support of any thermal/electrical storage and renewable energy sources. The optimal capacities of a GT, an LNG RU and an ABC lead to a significant reduction in the TAC as high as 38.1 % with a PES of 12.5 %, indicating a substantial decrease in fuel consumption compared to the baseline case due to the simultaneous production of electricity and cooling energy. It is worth noting that the regasification unit can cover only a small amount of cooling load (≈300 kW_c) compared to the absorption chiller capacity.
- Scenario 2 integrates the cold thermal energy storage (chilled water tank) into the absorption chiller loop, efficiently managing the waste heat from the gas turbine to support future cooling demands. Indeed, the size of the WCC electric chiller is smaller than the previous scenarios since part of the cooling demand is provided by thermal energy storage. The same downscale concept applies to the size of the ABC since the thermal energy storage allows to cover the peak cooling demand, limiting the ABC operation to cover the baseload of the cooling demand essentially. The thermal energy storage implementation allows a further decrease in the TAC and the primary energy consumption compared to the baseline scenario. The thermal efficiency (defined as the ratio of the thermal energy utilized by the ABC to the total thermal energy available) is 2 % higher than scenario 2, indicating a



(a)



(b)

Fig. 3. Costs components of the TAC (a) and TAC savings and PES (b) for the optimized case scenarios compared to the baseline scenario.

Table 2. Optimal Technologies capacity from Design Optimization.

Components	Case Scenarios			
	BC	1	2	3
GT [kWe]	-	6820	6731	6942
PV [kWp]	-	-	-	1072
BESS [kWhe]	-	-	-	2160
LNG RU [kWc]	-	300	300	300
ABC [kWc]	-	10272	9005	11293
WCC [kWc]	13070	2163	400	550
CTES [m^3]	-	-	4127	4389
Max import UG [kWe]	9950	2500	2580	50

more efficient utilization of the waste heat converted into cooling energy.

- Scenario 4 considers renewables and electric energy storage by introducing the PV and BESS systems. The implementation of PV and BESS provides substantial benefits by substantially lowering and almost nullify the dependance on the utility grid. It reduces the primary energy of the cryo-polygeneration system (PES = 13 %) and, above all, significantly increases the cost savings as high as 40 %, the best result among the case scenarios considered.

4. CONCLUSIONS

This paper discussed a design optimization framework of novel cryo-polygeneration systems consisting of different distributed energy resources. The results confirm the workability of the framework that effectively determines the optimal design of the system. The developed model has been applied to a real case study, a cryo-polygeneration system, expected to be operative during 2022 Q3, capable to cover the electric and cooling demand of a building located in a Singaporean university campus (NTU). The application of the model indicates that the implementation of the cryo-polygeneration system has significant energetic and economic benefits. Indeed, the results promote integrating cold thermal energy storage and renewable energy system (PV) into the cryo-polygeneration system since their integration has significantly decreased primary energy consumption and the total annualized cost up to 13 % and 40 %, respectively, compared to the baseline case scenario. In future investigations, the model will investigate the effects of different operating strategies and load characteristics on the performance of cryo-polygeneration systems.

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REFERENCE

[1] European Commission. An EU strategy on heating and

cooling 2016. vol. 53. 2016.
[2] International Energy Agency (IEA). The Future of Cooling - Opportunities for energy- efficient air conditioning. 2018.
[3] Mancarella P. MES (multi-energy systems): An overview of concepts and evaluation models. Energy 2014;65:1–17. https://doi.org/10.1016/j.energy.2013.10.041.
[4] Calise F, de Notaristefani di Vastogirardi G, Dentice d'Accadia M, Vicidomini M. Simulation of polygeneration systems. Energy 2018;163:290–337. https://doi.org/10.1016/j.energy.2018.08.052.
[5] Mazzoni S, Ooi S, Tafone A, Borri E, Comodi G, Romagnoli A. Liquid Air Energy Storage as a polygeneration system to solve the unit commitment and economic dispatch problems in micro-grids applications. Energy Procedia 2019;158:5026–33. https://doi.org/10.1016/j.egypro.2019.01.660.
[6] La Rocca V. Cold recovery during regasification of LNG part two: Applications in an Agro Food Industry and a Hypermarket. Energy 2011;36:4897–908. https://doi.org/10.1016/J.ENERGY.2011.05.034.
[7] Tafone A, Borri E, Cabeza LF, Romagnoli A. Innovative cryogenic Phase Change Material (PCM) based cold thermal energy storage for Liquid Air Energy Storage (LAES) – Numerical dynamic modelling and experimental study of a packed bed unit. Appl Energy 2021;301:117417. https://doi.org/10.1016/J.APENERGY.2021.117417.
[8] Cryo-Polygeneration | Surbana Jurong-NTU Corporate Laboratory | NTU Singapore n.d. https://www.ntu.edu.sg/sj-ntu/research-focus/research-projects/cryo-polygeneration (accessed August 9, 2021).
[9] EMA | Electricity Tariffs n.d. https://www.ema.gov.sg/Residential_Electricity_Tariffs.aspx (accessed August 28, 2021).
[10] Welcome | TRNSYS : Transient System Simulation Tool n.d. http://www.trnsys.com/index.html (accessed August 10, 2021).
[11] GenOpt n.d. https://simulationresearch.lbl.gov/GO/ (accessed August 10, 2021).
[12] European Parliament. Directive 2012/27/EU of the European Parliament and of the Council 2012.
[13] Tian L, Allan S. SINGAPORE COUNTRY REPORT 2017.
[14] Buchet P. Strategic Energy Management For Resilience Energy Efficiency for industrial boiler houses-State of art and latest innovations 2015.
[15] NEA | Carbon Tax n.d. https://www.nea.gov.sg/our-services/climate-change-energy-efficiency/climate-change/carbon-tax (accessed August 17, 2021).
[16] Boyce MP. Gas Turbine Engineering Handbook. Gas Turbine Eng Handb 2012. https://doi.org/10.1016/C2009-0-64242-2.