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Multi-objective design optimization of a cryo-polygeneration system in tropical climates - A techno-economic case study for a large-scale utility customer

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Abstract:

Small-medium scale decentralized polygeneration systems can provide multiple energy services for urban districts like universities and hospitals, with several energetic, economic and environmental benefits. Indeed, their impact on both energy efficiency, cost and emissions reduction might be disruptive especially in urban districts located in a tropical region, where the cooling demand is approximately stationary throughout the whole year. In this paper a multi-objective optimization model for distributed energy system in tropical climate is presented. The superstructure of the system comprehends a district cooling network that connects the users to medium-scale gas turbine system, solar PV plant, thermal and electrical chiller and a thermal storage. The optimization aims to determine the optimal design structure of the system, the size of each component inside the optimal solution and the optimal operation strategy. The multi-objective optimization is based on a three-level structure: 1) the simulation level developed in TRNSYS; 2) the optimization level based on a pareto-search algorithm developed in Matlab; 3) the Matlab-TRNSYS interface level. In this way the Pareto Front is identified and the possible improvements in both economic and environmental terms can be highlighted. The model has been applied to a specific real case study, namely a polygeneration system to be installed in the NTU campus located in Singapore, and it has been optimized for two different superstructure configurations. The results contribute significantly to developing an efficient and cost-effective energy storage polygeneration system and revealed that the optimized operation of the decentralized energy systems reduces energy costs and CO_2 emissions, as compared with a scenario without integration of renewables and electric energy storage system as well as conventional energy supply systems. Indeed, numerical results show that the Pareto frontier provides good balancing solutions for planners based on economic and sustainability priorities.

Keywords:

Distributed polygeneration system, Design optimization, Cold economy, LNG, Electrical energy storage, Thermal energy storage.

1. Introduction

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 [1][2]. The sustainability of heating and cooling is of high priority, and the strategy lists to achieve the sustainability goals are 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 [3,4]. Indeed, simultaneous production of heating, cooling and power in a combined cooling heating and power system results in higher overall efficiency in comparison with the separate heat and power production [3]. Furthermore, having the energy supply system close to end users offers several other advantages such as lower distribution and transmission cost, less power loss through the transmission and

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distribution line, alleviated environmental impacts, and enhanced resilience of the utility grid [5] . Mancarella [3] studied the status of existing models and evaluation methods for performance investigation of multi-energy systems (MES). A complete overview of MES considering various perspectives was provided. Jana et al. [6] presented the status of polygeneration technologies and their capacity to provide a sustainable energy solution. This study highlighted the necessity to conduct more research on multi-criteria optimization of polygeneration systems. Furthermore, the incorporation of innovative storage and generation units in complex polygeneration systems were suggested. A short review on optimization of polygeneration systems in urban applications was presented by Ghaem Sigarchian et al. [7]. The study emphasizes the necessity of further investigation on complex polygeneration systems to achieve results as close as possible to reality. Calise et al. [8] showed that for a combined production of electricity, cooling and heating to satisfy a defined end-user demand, distributed polygeneration systems (DPS) are the most efficient and sustainable way to simultaneously guarantee flexibility and reliability. Indeed, if a high penetration of unpredictable renewable energy sources is thought to be promoted, distributed polygeneration systems could allow to significantly increase the resiliency and flexibility of the power production and distribution networks [9]. Although almost no geographical region is at this stage yet, a potential promising outlook for energy infrastructures would then be a global spread of decentralized energy generation in which larger share of final energy consumption will be produced in a distributed way [10].

Directly responding to this ambitious target, a novel district scale demonstrator has been currently proposed and developed in Singapore [11], aiming to significantly contribute achieving the goal imposed by the country’s national agenda on sustainable development [12]. Based on the concept of distributed cryo-polygeneration system, namely an integrated rapidly deployable and highly energy-efficient solution that utilizes cold energy from Liquefied Natural Gas (LNG) and waste heat from power generation, the project might help in meeting the growing energy needs of urbanization and industrialization, especially in tropical and sub-tropical areas. In order to maximize the benefits from the cryo-polygeneration system while still providing the same quality of energy services produced by conventional energy system, the optimal design of the plant layout is necessary and it requires the techno-economic analysis of single components in order to maximize the efficiency of the available energy resources [13]. Indeed, in order to avoid incurring unnecessary costs while still providing the required resilience and reliability, decentralized polygeneration systems require accurate components design [14]. Nevertheless, profitability of the cryo-polygeneration system might not be the only driver for the design optimization of the system: indeed, considering as objective function the CO_2 emission, the optimization might lead to alternative system design. In such a context, a multiobjective approach helps identify balancing solutions to promote participation in the decision-making process and facilitate collective decisions. To this end, a multi-criteria optimization with respect to economic and ecological aspects and thus determination of Pareto optimal solutions has been methodologically developed. In literature the multi-objective optimization of distributed polygeneration systems has been the subject of many researchers within the recent years. Ahmadi et al. [15] presented the thermodynamic modelling and multi-objective optimization of an energy system for the simultaneous generation of electricity, heating, cooling and hot water. Gabrielli et al. [16] analyzed the design of a multi-energy system involving seasonal energy storage and based on a case study in a neighbourhood in Zurich, Switzerland, which is optimized in terms of total annual costs and carbon dioxide emissions. Ghaem Sigarchian et al. [17] applied a multi-objective optimization methodology to a small-scale decentralized polygeneration system: the distributed polygeneration systems reduces both CO_2 emissions and annualized total cost up to 29% and 19%, respectively.

Nevertheless, there seems to be a lack in the literature of studies addressing the optimal operation and design of distributed polygeneration systems in cooling dominated geographical region, as for the urban district in a tropical area characterized by high and uniform temperature and humidity throughout the year. Indeed, although the investigation of energy systems in a cooling dominated context is gaining momentum in literature with few studies highlighting the benefit of district cooling [24] and energy storages in tropical areas [25,26], overall, a systematic and generalized research with an on-site real application on the decarbonization in tropical climate by means of decentralized polygeneration systems is still lacking [24]. In this framework, the present paper aims to go a step further by significantly improving the knowledge on this topic. Indeed, in this paper the multi-objective

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optimization model is applied to the cryo-polygeneration concept, and the Pareto frontiers associated to two different system configurations are evaluated. The results of the optimizations can be used to identify the best trade-off solutions. The main objective of the multi-objective optimization is to determine the optimal design (sizing) and the optimal operation strategy for any component within the optimal solution. Indeed, the analysis aims to evaluate the economic and environmental benefits of the integration between gas turbine, PV and energy storage solutions when the optimal synthesis and operation of the whole energy supply system are adopted.

2. Methodology

2.1. Cryo-polygeneration concept

The proposed cryo-polygeneration system concept (developed in TRNSYS) is shown in **Fig. 1**, consisting diverse technologies for electricity and cold energy generation and storage. The electric power is produced from the gas turbines (GT) and photovoltaics (PV) modules whereas the LNG regasification unit (RU), an absorption chiller (ABC) utilizing the waste exhaust heat from the gas turbine and vapour compression water-cooled chillers (WCC) are mainly to support the cooling loads. Cold thermal energy storage (CTES) and battery electrical energy storage (BESS) act as a buffer to complement the unpredictability of renewable energy sources and as a bulk storage to maximize the exploitation of excess thermal energy and electricity. More information regarding the simulation model can be found in Ref.[18].

Two design scenarios are considered to study the economical and environmental benefits of the critical distributed technologies (**Table 1**). The adopted search space values are set according to the demand and the available footprint area for each component. Scenario 1 consists of well-established technologies such as gas turbines, LNG regasification units, thermal (ABC) and electrical (WCC) chillers. In scenario 2, the photovoltaics (PV) system and thermal/electrical energy storage solutions (CTES and BESS) are included to understand the role and impact of renewable combined with energy storage. Conversely, the case where all the demands of the buildings are supplied by the electricity in a grid connected environment is taken as the baseline case scenario (**Fig. 2**). The performance results of this configuration will provide a reference for the two scenarios under investigation.

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

Components	Search Space				
	BC	1	2	Minimum	Maximum
GT	-	✓	✓	0	10000 kW$_e$
PV	-	-	✓	0	25000 kW$_p$
BESS	-	-	✓	0	80000 kWh$_e$
LNG RU	-	✓	✓	-	-
ABC	-	✓	✓	0	15000 kW$_c$
WCC	✓	✓	✓	0	15000 kW$_c$
CTES	-	-	✓	0	10000 m^3
Utility Grid (import)	✓	✓	✓	-	-

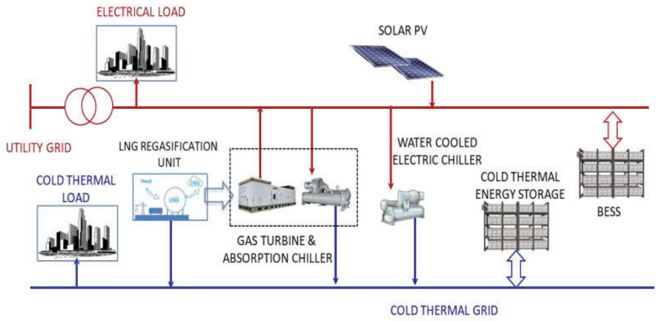


Fig. 1. Superstructure of the Cryo-polygeneration system.

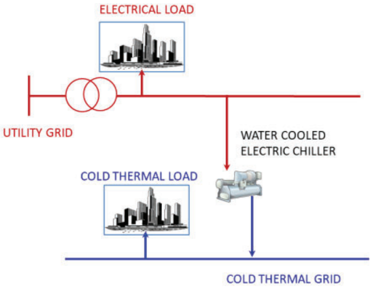


Fig. 2. Superstructure of the baseline case scenario.

2.2. System model

The layouts described in Section 2.1 were dynamically modeled and simulated in TRNSYS environment. TRNSYS is an object-oriented based software that enables to simulate the transient behavior of systems predominantly focused on assessing the performance of thermal and electrical energy systems. The software is made up of two main parts: a simulation engine to solve the dynamic mathematical problem and a large library of built-in components or types (e.g., pumps, mixers, diverters, heat exchangers, etc.), often validated by experimental data. **Fig. 3** shows the cryo-polygeneration system layout implemented in TRNSYS environment: red lines refer to the electricity stream; brown line represents the waste heat flow from the gas turbine to the absorption chiller; green line refers to the LNG stream and blue lines represent chilled water stream.

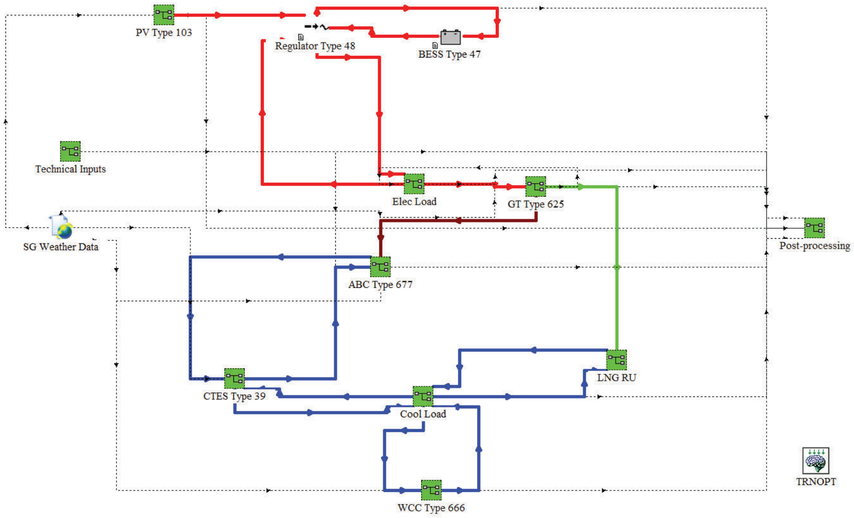


Fig. 3. General layout of the TRNSYS-Cryo-polygeneration system.

2.2. Mathematical problem

Electricity demand and electricity required by vapour compression chiller can be satisfied by grid power, by the electricity provided by the gas turbines, PV, and by the electricity discharged from the BESS. It is assumed that all the electricity provided by GT and PV is self-consumed, while no extra electricity is sold back to the power grid. Space cooling demand can be satisfied by thermal energy provided by the GT through the absorption chiller, vapour compression chillers, and by thermal energy discharged from the CTES.

2.2.1 Decision variables

In the optimization problem, the decision variables include: the existence and sizes of energy devices; operation status (on/off) and energy rates provided by energy devices; capacities of electrical and thermal storage devices; electricity and heat rate input and output to/from electrical and thermal storage devices.

2.2.2 Economic objective function

The total annualized cost (TAC) is the first objective function of the optimization process, a premier economic index taking into account all the expenses during the yearly operational of the project, defined as:

$$TAC = CAPEX_{ann} + OPEX_{UG} + OPEX_{fuel} + OPEX_{O\&M} + OPEX_{CO2} \tag{1}$$

The key parameters for the economic analysis are defined for the different scenarios as follows.

CAPEX_{ann} is the annualized sum of the capital costs, the balance of plants and installation costs of the kth component of the system computed as:

$$CAPEX_{ann} = \sum_{k} CAPEX_k \cdot CRF_k = \sum_{k} SC_k \cdot C_k \cdot CRF_k \tag{2}$$

Where SC_k and C_k are the specific capital cost and the capacity of k^{th} component, respectively; CRF is the capital recovery factor of the k^{th} component which takes into account the effect of annual interest rate “i” and the component lifetime “N_k” expressed as:

$$CRF = \frac{i \cdot (1+i)^{N_k}}{(1+i)^{N_k} + 1} \tag{3}$$

$OPEX_{UG}$ accounts for the annual operational cost due to the utilization of the utility grid. It comprises three main factors, namely a) the contracted capacity charge, b) the electricity purchased at a certain electricity tariff *ET,* daily subject to peak and off-peak time periods and c) the use of systems or transmissions costs:

$$OPEX_{UG} = P_{UG,max} \cdot C_{cap,ch} + \int_{0}^{365} P_{UG} \cdot [ET(t) + UOS(t)] \cdot dt \tag{4}$$

$OPEX_{fuel}$ accounts for the annual operational cost related to the total amount of LNG purchased (m_{LNG}) at a defined price (p_{LNG}):

$$OPEX_{fuel} = \int_{0}^{365} m_{LNG} \cdot p_{LNG}(t) \cdot dt \tag{5}$$

$OPEX_{O\&M}$ are the annual operational and maintenance costs of the k^{th} component expressed as a fraction ($\phi_{O\&M,k}$) of the total $CAPEX_k$:

$$OPEX_{O\&M} = \sum_{k} CAPEX_k \cdot \phi_{O\&M,k} \tag{6}$$

As of now, conforming to the Paris Agreement, an increasing number of countries promote energy efficiency measures and the adoption of renewables by including a carbon tax [47,48]. To this end, an operational annual cost related to this tax (taxCO2 expressed in $/tonCO2) is included in the economic analysis as OPEXCO2 computed as:

$$OPEX_{CO2} = \int_{0}^{365} m_{CO2}(t) \cdot tax_{CO2} \cdot dt \tag{7}$$

The key input data for the techno-economic analysis used in this work are depicted in **Table 2**.

Table 2. DES Economic parameters [17,19–23].

Parameter	GT	PV	BESS	LNG RU	ABC	WCC	CTES
SC	$1200\ \$/\mathrm{kW_e}$	$883\ \$/\mathrm{kW_e}$	$380\ \$/\mathrm{kWh_e}$	43.5 \$/kgh	$230\ \$/\mathrm{kW_c}$	$150\ \$/\mathrm{kW_c}$	$31.8\ \$/\mathrm{kWh_c}$
ϕ [%]	3	0.5	1	0.5	2	2	1
Lifetime [years]	30	30	20	30	30	30	30

2.2.3 Emissions objective function

The environmental objective is to minimize the environmental impacts in terms of CO_2 emission from the electricity grid and the consumed fuels. The CO_2 emission due to the use of electricity from the electricity grid is evaluated by multiplying the grid emission factor of the electricity grid (GEF [kg_{CO2}/kWh_e]), and the total amount of electricity purchased from the grid. The carbon intensity of the electricity grid that the cryo-polygenerator is connected to is the amount of CO_2 emission per unit of electricity generated which depends on the fuel mix of Singapore [24]. The CO_2 emission due to the natural gas consumption is evaluated by multiplying the carbon intensity of the fuel, (CI_{NG} [kg_{CO2}/kg_{NG}]), and the total amount of fuel consumption of the cryo-polygenerator system:

$$m_{CO_2} = \int_{0}^{365} P_{UG} \cdot [GEF] \cdot dt + m_{fuel} \cdot CI_{NG} \tag{8}$$

2.2.4 Constraints

The objective function is constrained to the energy balance equation following the rules and limitations of the operating strategies. 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 gas turbine is prevented below recommended minimum partial load ratio (PLR) to increase its lifetime and decrease the emissions [25]. This constraint is implemented in TRNSYS by a differential controller component limiting the gas turbine operation as follows:

$$0.2 \leq PLR\ (t) \leq 1 \tag{9}$$

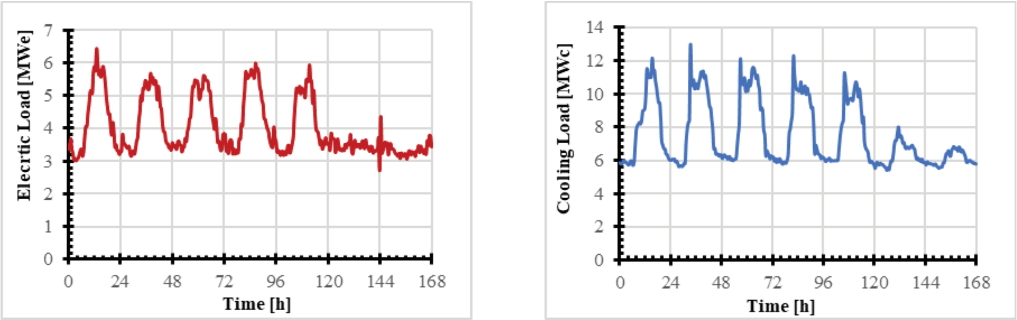
- The capacity of the DPS components is limited to the identified optimization search space. The adopted search space values are set according to the demand and the available footprint area for each component.
- The operations of the electrical and thermal energy storage (BESS and CTES) are limited to their maximum and minimum state of charge.
- Revenues from the PV electricity feed-in are not accounted in the TAC equation as it is not within the scope of this work to merely maximize this profit by operating a small power plant. Nevertheless, this component can be further analyzed in future works.

2.2.5 Optimization method

In this section, the general structure of the optimization tool and the optimization technique has been explained. The optimal design (sizing) and operational strategy of the cryo-polygeneration components are based on a three-level configuration. The simulation level (TRNSYS [26]), the "multi-objective genetic algorithm" (gamultiobj) level [27]) and the interface for the communication between those two levels (Matlab [28]). 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. Gamultiobj is a multi-objective optimization algorithm that minimizes multiple objective functions subject to a set of constraints. The Matlab code developed by the authors acts as an interface between TRNSYS simulator and the "gamultiobj" algorithm and streamlines the optimization process. The multi- objective genetic algorithm in-built in MATLAB, i.e. the gamultiobj function [64], is based on the very popular Non-dominated Sorting Genetic Algorithm – II [27], and is frequently utilized in literature [29] for the accuracy of the Pareto front.

3. Results

This section discusses the optimal DERs capacities obtained for the cryo-polygenerator system and compares the economics and environmental benefits of polygeneration configurations with reference to the base case. The objective functions are 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, future projections are assumed for all scenarios. The economic analysis was carried out based on 30 years project lifetime. Given those input data, by solving the multi-objective optimization problem, the Pareto front, consisting of the best possible trade-offs between the two objectives, can be obtained. Each point of the Pareto front corresponds to a different operation strategy of the DES. The operators of DESs can choose the operation strategy from the Pareto front based on the economic and environmental priorities.



(a) (b)

Fig. 4. Weekly electricity (a) and cooling (b) demands for the building located in NTU campus.

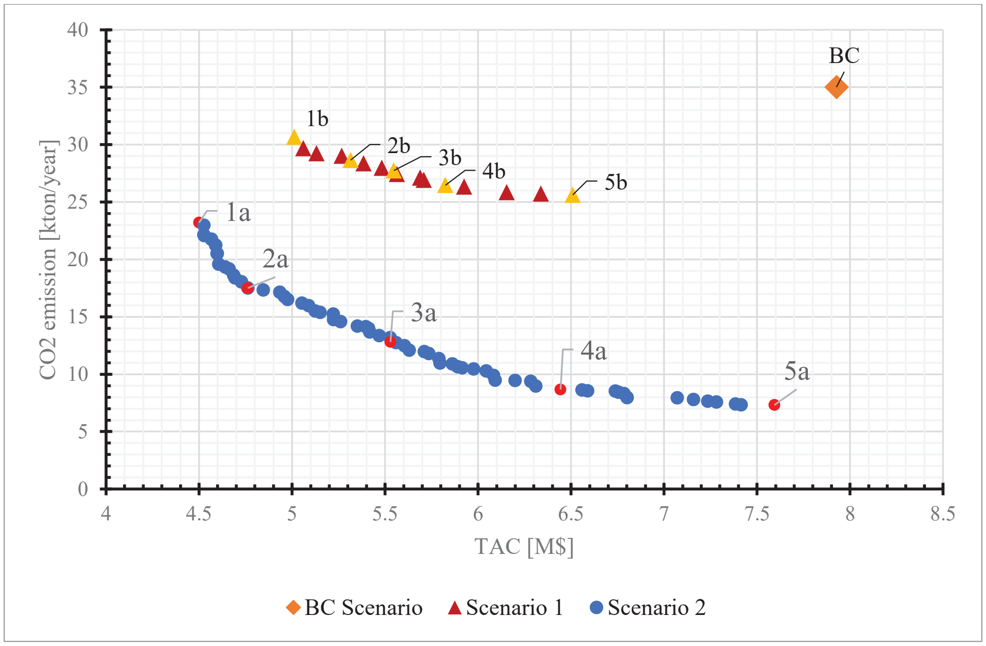


Fig. 5. Pareto front for Scenario 1 and Scenario 2.

In order to understand how the operation strategies of the DES affect the TAC and the CO2 emission, the results at various trade-off points are shown in **Fig. 5** illustrating the Pareto Fronts obtained for both scenarios. For the sake of comparison, the optimal point of operation for the baseline case scenario previously computed in Ref.[18] has been added in **Fig. 5**. Indeed, the baseline scenario represents the business-as-usual configuration where the utility grid provides the electricity to cover the electric and cooling demand and therefore the electricity cost is predominant (≈95 %) compared to all the other TAC cost components. From **Fig. 5**, it can be noticed that for all scenarios the TAC and the carbon emissions are conflicting objectives, i.e. the higher the TAC is the lower the carbon emissions are.

For both scenarios, all the optimal solutions outperform the baseline scenario both in terms of TAC and CO_2 emissions. Furthermore, the optimized solutions of Scenario 1 experience a lower variance of the objective functions compared to scenario 2 with average values of 5.6 MUSD and 27.67 ktonCO$_2$/year for the TAC and CO2 emissions, respectively. The reason for this is the smaller number of available technologies, hence there are less degrees of freedom. Despite a quite evident environmental benefits due to the introduction of renewables and electric energy storage with an average decrease of the CO_2 emissions (13.88 ktonCO$_2$/year), Scenario 2 provides a more diversity pool of optimal solutions with similar average of the TAC compared to Scenario 1. In order to provide a more accurate analysis of the results, for each scenario, component sizes for five different solutions (highlighted in **Fig. 5**) are evaluated. For each solution the component sizes are numerically reported in **Table 3** while the different TAC cost breakdown are plotted in **Fig. 6**-**Fig. 7**. As previously mentioned, Fig. 4 can be utilized by the operators of the cryo-polygeneration system to economically and environmentally assess different design point of the plant, helping thus identifying balancing solution to simultaneously promote cost savings and sustainability. Indeed, by looking at the five different solutions in the two Pareto fronts in **Fig. 5**, it can be noticed that for the same TAC user can choose solution 4a instead of solution 5b to gain ≈66% environmental benefits in terms of carbon emissions. Another potential greener choice would be selecting solution 2a in place of solution 1a to reduce 25% carbon emissions at the expense of only ≈6% increase in TAC.

In Scenario 2, it is evident that, as solutions move towards the carbon emissions objective the capacity of less carbon intensive technologies, such as PV and BESS, is increased, simultaneously reducing the GT capacity. The absorption chiller capacities follow the same trend of the gas turbines with a general decrease due to the reduction of the available waste heat at the GT outlet. As a result, the size of the WCC increases to balance the reduction of the cooling fulfilled by the ABC. Nevertheless, as shown in **Fig. 8a**, reporting the ratio of the current ABC capacity to the potential

ABC capacity exploiting 100 % of the waste heat available (f_{ABC}), it can be seen that it is not anymore economically convenient to enhance the ABC capacity. Indeed, when the PV capacity started to be predominant over the gas turbine, part of the green electricity produced by the PV is conveyed to cover the electricity consumption of the WCC, whose technology is significantly cheaper than absorption chiller. As a result, the maximum available potential capacity of ABC is not fully exploited and the ratio f_{ABC} decreases along the Pareto front. Conversely in Scenario 1 (**Fig. 8b**), since PV is not considered in the optimization search space, the ratio f_{ABC} increases as the GT capacity decreases in order to maximize the exploitation of the available waste heat.

Table 3. Optimal Technologies capacities from Multi-objective optimization for 5 different solutions.

Solutions	P_{GT} [kW_e]	Q_{ABC}[kW_c]	Q_{WCC} [kW_c]	P_{PV} [MW_p]	V_{CTES} [m^3]	C_{EES} [MWh_e]	TAC [M$]	CO2 em [kton/year]
Scenario 2								
1a	4532	8373	6285	6700	4783	2.69	4.50	23.20
2a	3346	6074	10107	14629	3109	3.58	4.76	17.51
3a	2488	3463	10405	20494	3494	21.42	5.53	12.82
4a	2260	2569	10669	22793	3483	50.98	6.44	8.67
5a	2254	2453	11029	22841	3955	73.95	7.59	7.31
Scenario 1								
1b	5389	7862	4742	-	3098	-	5.01	30.68
2b	3895	7238	4763	-	3235	-	5.31	28.65
3b	3375	7217	5298	-	3423	-	5.55	27.75
4b	2682	6084	5379	-	3554	-	5.82	26.47
5b	1754	4085	7646	-	3675	-	6.51	25.63

By evaluating the TAC breakdown of the different optimal points for both Scenarios (**Fig. 6**-**Fig. 7**), different optimal strategies can be identified. Indeed, the analysis of the inhomogeneous distribution of the main cost components' shares within the TAC provides further insights to explain the economic and environmental performance of the cryo-polygeneration system at the different optimal points. Since Scenario 1 relies only on the electricity provided by the GT and the electric grid, the operational costs due to fossil fuels consumption (Fuel_cost) and the ones due to the electric grid (OpexUG and Opex_capacity) are inversely proportional shifting to greener configurations. In addition, due to the decrease of the GT and ABC capacity, the CAPEX share in the TAC tends to decrease as well. Conversely, in Scenario 2, moving from solution 1 to solution 5 characterized by lower CO_2 emissions, the CAPEX becomes predominant with the highest TAC share (≈71 %) followed by operational cost due to the electricity grid (≈15 %). Indeed, in order to guarantee lower CO_2 emissions, the optimization algorithm prefers to enhance the capacity installation of the most expensive technologies such as PV and BESS, at the cost of sacrificing the TAC of the plant exponentially increased with the CAPEX. Simultaneously, despite the highest PV (23 MW_p) and BESS (73 MWh_e) capacities adopted for solution 5, the cryo-polygeneration system does not manage to satisfy the electricity peaks further increasing the necessity to tap into the electricity grid.

This is particularly verified for intermediate solutions (2-3) while the operational cost due to the electricity grid starts to decrease for solution 4-5 with the heavily installation of the BESS capacity capable to partially satisfy the peak of the electric demand.

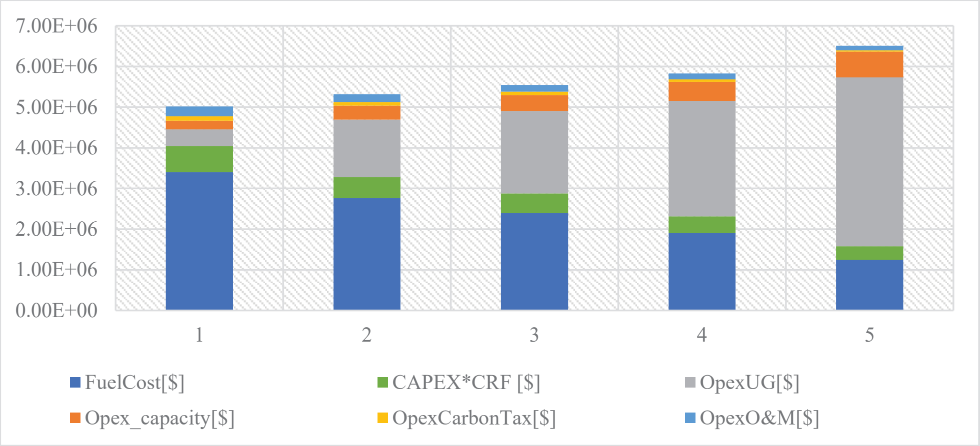


Fig. 6. Costs components of the TAC for Scenario 1.

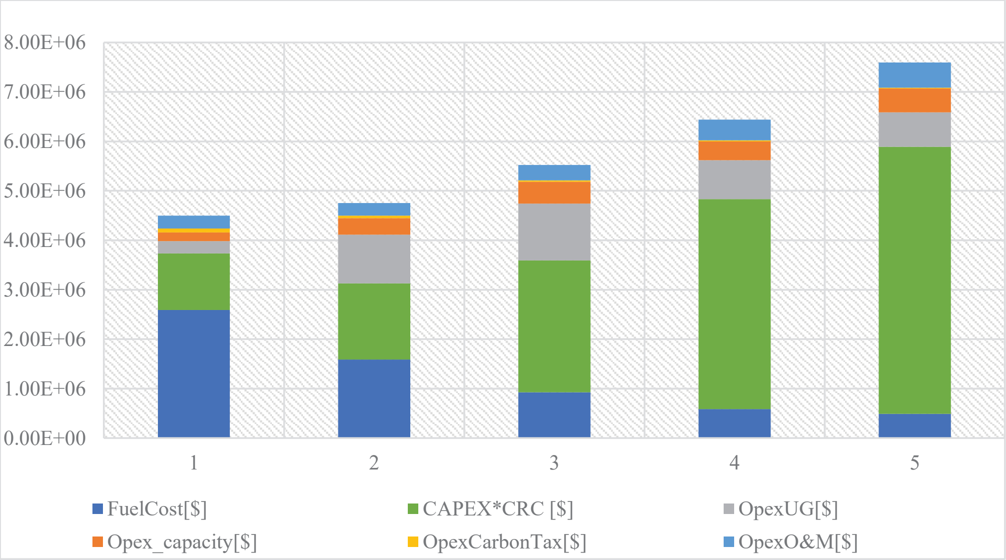
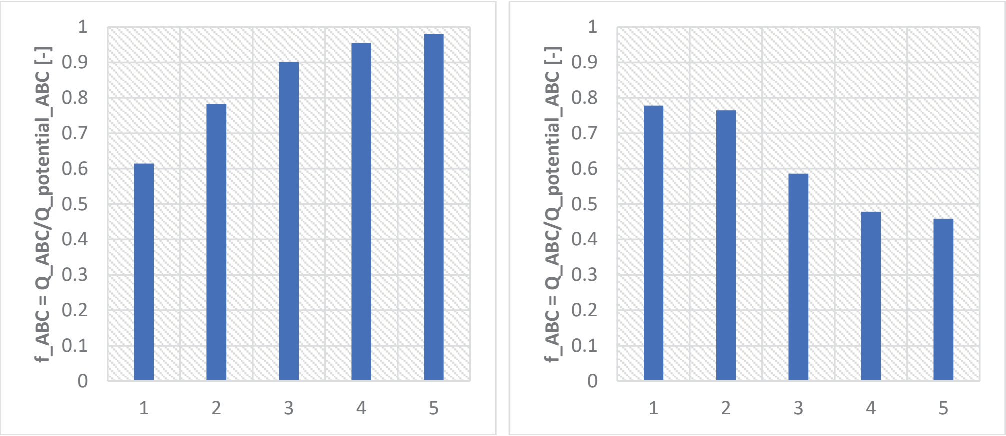


Fig. 7. Costs components of the TAC for Scenario 2.



(a)

(b)

Fig. 8. ABC capacity ratio (f_{ABC}) for Scenario 1 (a) and Scenario 2 (b).

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4. Conclusions

This paper discussed a design multi-objective optimization framework of novel cryo-polygeneration systems consisting of different distributed energy resources. The developed model has been applied to a real case study, a cryo-polygeneration system, expected to be operative during 2024 Q1, capable to cover the electric and cooling demand of a building located in a Singaporean university campus (NTU). The results confirm the workability of the framework that effectively determines the best possible trade-offs (Pareto fronts) between the total annualized cost and CO_2 emission. Thus, the operators of DESs can choose the operation strategy from the Pareto front based on their cost and environmental priorities. The results also indicates that the implementation of renewables and electric energy storage in the cryo-polygeneration system (2nd scenario) has significant economic and environmental benefits over the 1st scenario, reducing the total annualized cost and the carbon emissions up to 30 % and 10 %, respectively. Furthermore, in this scenario, by further increasing the PV and BESS capacities, different greener solutions can be achieved, although to the detriment of the total annualized cost due to the current high capital cost of the BESS. In future investigations, the model will analyze the effects of: 1) the island mode scenario; 2) PV electricity exported to the grid; 3) different operating strategies and load characteristics on the performance of cryo-polygeneration systems as well as the design of DES under uncertainty to provide more robust results; 4) the potential carbon emissions related to the construction of the decentralized energy systems.

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Nomenclature

Acronyms		UG	Utility Grid
ABC	Absorption Chiller	UOS	Use of system
AC	Air conditioning	WCC	Water cooled electrical chiller
BC	Baseline Case	*Symbols*	
BESS	Battery energy storage system	η	Efficiency [%]
CAPEX	Capital Cost [$]	i	Discount rate [%]
CRF	Capital Recovery Factor	N	Lifetime project [years]
COP	Coefficient of Performance	φ	CAPEX Fraction [%]
CTES	Cold Thermal Energy Storage	*Subscripts*	
DPS	Distributed Polygeneration System	ann	annualized
EL	Electrical load [kW_e]	base	baseline
ET	Electricity tariff [$\$/kWh_e$]	c	cooling
G	Solar irradiance [W/m_2]	ch	charge
GEF	Grid Emission Factor	cap	capacity
GT	Gas Turbine	db	deadband
HE	Heat Exchanger	e	electric
LNG	Liquefied Natural Gas	FL	Full-load
NPV	Net Present Value [$]	imp	imported
OPEX	Operational cost [$]	max	maximum
PES	Primary energy savings	min	minimum
PLR	Partial Load Ratio	NC	Nominal capacity
PV	Photovoltaic system	nom	nominal
RU	Regasification Unit	ref	reference
SC	Specific CAPEX	s	system

STC	Standard test conditions	th	thermal
TAC	Total annualized cost	y	years

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