Techno-economic analysis of innovative solutions for island grids with high renewable solar share

Abhishek Dubey[1*], *Alessandro* Sorce[1], *Massimo* Rivarolo[1], *Alberto* Traverso[1] and *Silvio* Sala[2]
[1]Thermochemical Power Group, DIME, University of Genova, Italy
[2]WinGD - Winterthur Gas & Diesel, Switzerland

Abstract. This paper presents a techno-economic analysis of a hybrid dispatch strategy on an island through conventional internal combustion engine (ICE) and innovative gas turbine (GT) with pressure gain combustion (PGC) in the presence of renewable solar-PV. Plant configurations with conventional technologies were defined based on established industrial data, and specifications of novel PGC-GT technology were estimated using the industrial data of conventional GT and on-design results available in the literature. Optimization of the operational strategy was conducted in W-ECoMP, a modular and flexible software tool developed by Thermochemical Power Group (TPG) at the University of Genova. The performance of different hybrid plants was analyzed in terms of annual production, fuel consumption, curtailment, CO_2 emissions, cost, and sensitivity to fuel price. This is complemented by a parallel paper investigating the mechanical rotating inertia features of such prime movers, further supporting their suitability in enabling the integration of non-dispatchable renewables. Results showed that the 2-stroke ICE technology provided the best performance in terms of emissions and cost. Moreover, for all dispatchable prime movers, minimum LCOE occurred at an optimum value of PV capacity that facilitated annual CO_2 reduction by 58.6 kton and LCOE reduction by 8.9 €/MWh. Finally, the optimum PV capacity was found to increase with fuel price, signifying the environmental benefits of high fuel prices.

1. Introduction

Renewable energy has witnessed remarkable growth in recent years due to increased global attention towards net-zero emissions. In 2019, for the first time, electricity production from renewables grew at a higher rate than that from natural gas and coal [1]. In 2021, around 38% of the annual global electricity was produced from clean sources, with the contribution from wind and solar together being 10.3% [2]. In particular, the solar-PV exceeded 1000 TWh in 2021 [3]. Due to these advancements and regulatory incentives, the cost of utility-scale PV technology has declined by 82% since 2010, making it a key technology for large-scale clean power generation [4].

Despite the accelerated decarbonization, more than 60% of the world's electricity is still produced from fossil fuels and electricity generation is responsible for 40% of energy-related CO_2 emissions [5]. This high share of conventional powerplant technologies is due to their superior reliability, flexibility and stability. On the other hand, renewable production from wind and solar is not programmable and weather dependent, which causes control and transmission issues [6]. Moreover, a lack of adequate storage and transmission infrastructure often leads to the curtailment of excess production [6]. Because of these challenges, an optimized hybrid solution comprising renewables and the conventional plant provides a reliable and flexible strategy for large-scale power dispatch and, hence, has gathered significant research interest [7–10]. A study by Ding et al. showed that a hybrid wind-solar plant coupled with a solar thermal storage system could reduce annual CO_2 emission by

*Corresponding author: abhishek.dubey@edu.unige.it

15,470 tonnes compared to conventional coal plants [7]. Similarly, Rashid et al. reported up to 23.78% reduction in greenhouse emissions in a natural gas thermal plant hybridized with a parabolic trough solar collector [8].

A significant fraction of the population lives in geographically decentralized and remote areas with inadequate connection to the national grid. This results in higher transportation costs of fuel, machinery and labor, making conventional generation uneconomical and renewable a more attractive approach [9]. Additionally, because of challenges related to infrastructure, transmission and congestion in the centralized national grids, deployment of renewables on islands or disconnected grids potentially allows higher growth and cost reduction of the renewable technology. A study performed by Arefin et al. on an 8.7kW hybrid wind-diesel energy system on an Indonesian island showed an annual reduction in total cost by 32.45% and CO_2 emission by 29 ton [9]. Rashid et al. investigated dispatch through a PV-wind-diesel hybrid system on an island in Bangladesh and showed a significant CO_2 reduction of 67% through 67.3% renewable generation with a cost of 0.393 USD /kWh [10].

Alongside widespread renewable penetration, efforts are underway to develop more efficient variants of conventional fossil-fuel systems to reduce emissions during the transition to net-zero. In this regard, Pressure Gain Combustion (PGC), an innovative GT cycle characterized by pressure rise during the heat addition, has captured serious attention as a major upgrade over existing GTs operating with isobaric combustion [11–13]. It can provide substantial cycle-level improvements in terms of efficiency and fuel consumption over conventional GTs [13–15].

The present study aims at the techno-economic analysis of an island dispatch through novel PGC-based GT and conventional two-stroke (2S) and four-stroke (4S) ICE engines in the presence of large-scale solar-PV. Electricity generation through different plant configurations was optimized to supply maximum power through solar-PV while minimizing cost to reduce fuel consumption and CO_2 emission. Although numerous past studies have investigated the cycle-level thermodynamics of PGC [11–15], a plant-level techno-economic analysis of a PGC-based energy system is not available in the open literature to the best of the author's knowledge.

2. Methodology

2.1 PGC model

A fundamental characteristic of all PGC approaches is their inherently unsteady and periodic nature which presents a challenge in their theoretical modeling for steady-state thermodynamic analysis. For the current study, a constant volume combustion model developed by Nalim [16] has been used here to represent PGC. The thermodynamic states of the model are elucidated in Fig. 1(a). Pressure gain combustion (2-3b) is modeled as an isochoric combustion (2-3a) process followed by an internal isentropic expansion (3a-3b) inside the combustor that does not produce work and generates a representative steady state at combustor outlet (3b). Downstream of the combustor, the working fluid is expanded (3b-4) to atmospheric pressure (4) in a turbine to produce cycle work. Figure 1(b) shows the theoretical efficiency benefits of the PGC cycle over the conventional Brayton cycle obtained through on-design parametric analysis. Data presented in Fig. 1(b) have been generated considering a combustor inlet pressure loss of 5% and constant pressure combustion loss of 20% to simulate realistic conditions [13].

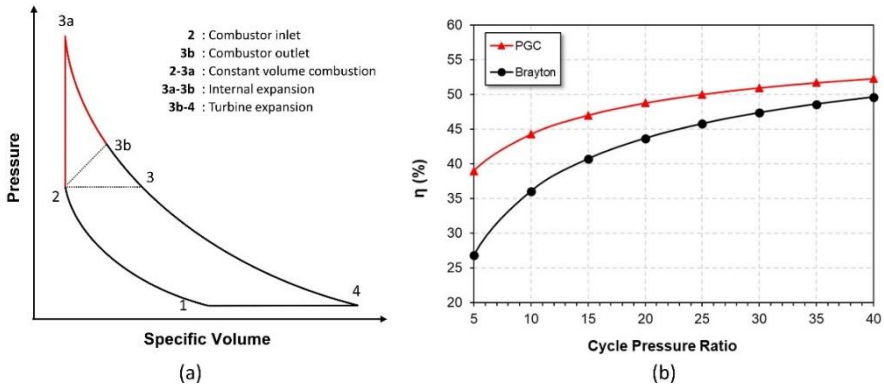


Fig. 1. Thermodynamic model of the PGC (a) and comparison of on-design PGC cycle efficiency with Brayton cycle (b).

2.2 Layouts and simulation

The techno-economic performance was investigated considering three different hybrid plant layouts comprising conventional 4S and 2S ICEs and novel PGC-based GT. Installed solar-PV capacity was varied from 10-130 MW_e for all prime movers. The number of units for each generator was selected to meet the peak demand of 100 MW_e. Specifications of the employed technologies and economic parameters are listed in Table 1. Cost parameters for gas turbine and solar PV were obtained from the technology data provided by Danish Energy Agency [17], and those for ICE engines were based on private communication with industry partners.

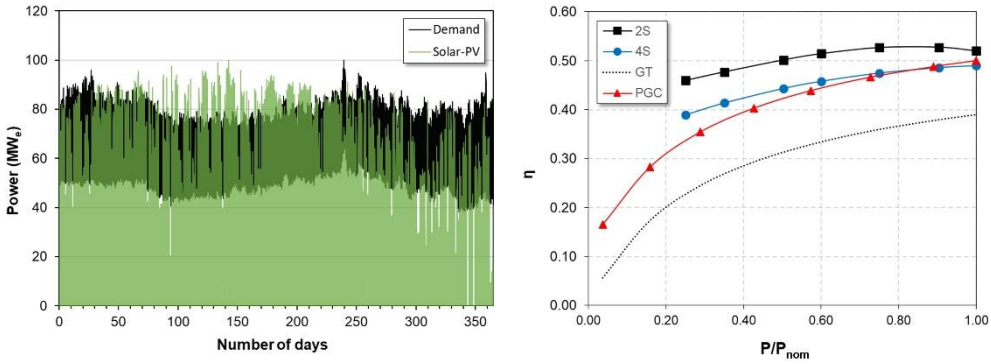
Optimization of the operational strategy for all cases was performed in W-ECoMP (Web-based Economic Cogeneration Modular Program), a software tool developed by Thermochemical Power Group (TPG) at the University of Genova in the last twenty years [18–20], capable of performing thermo-economic time-dependent analysis of conventional and innovative energy systems. It employs a genetic algorithm for selecting the best strategy to minimize the total annual cost of electricity generation. The component sizes and capital costs were fixed for a given plant configuration and only the variable costs were minimized. Also, since electricity trade to the National grid is not allowed in the island scenario, the excess power generation was limited to 1 MW_e to avoid penalty. Furthermore, excess PV generation was curtailed, minimum off-design power was set to $0.25P_{nom}$ and at least one generator unit was always kept operational at $0.25P_{nom}$ to satisfy the auxiliary power requirements in all hybrid plant configurations. For all the cases, natural gas was considered as the reference fuel and simulations were carried out for a total of 8,784 hours to simulate the complete year.

Technology	P_{nom} (MW_e)	η_{nom} (%)	No. of Units	Min. off Design P (%)	CAPEX (€/MW_e)	$OPEX_{fix}$ (€/MW_e/Year)	$OPEX_{var}$ (€/MWh)	Fuel Price (€/kg)
4S-ICE	20.095	48.7	5	25	1,000,000	9,750	5.4	0.45
2S-ICE	25.000	52.0	4	25	1,100,000	9,750	2.0	0.45
PGC-GT	50.000	50.0	2	25	876,000	19,500	5.4	0.45
Solar-PV	10-130	-	-	-	1,460,000	12,800	-	-

Table 1. Technical and economic parameters of the hybrid plant layouts.

The island scenario was represented by the real-time load profile and solar-PV generation data from a Canary Island. Figure 2(a) shows the annual demand profile with renewable production from 100 MW_e PV capacity. The off-design performance curves of generators are shown in Fig.2(b). Since the off-design curve for novel PGC technology is unavailable, for the present work, it was estimated through the data of the GE-LM6000 engine, upscaled to

the on-design PGC efficiency results (Fig 1(b)). As it can be seen, the off-design efficiency variation for ICEs is relatively flat compared to that of PGC-GT. To consider the technology development costs, CAPEX for PGC-GT was kept 20% higher than that of existing GT of a similar class.



(a) (b)

Fig. 2. Annual demand and 100 MW_e PV profiles (a) and off-design performance curves of the different prime-movers (b).

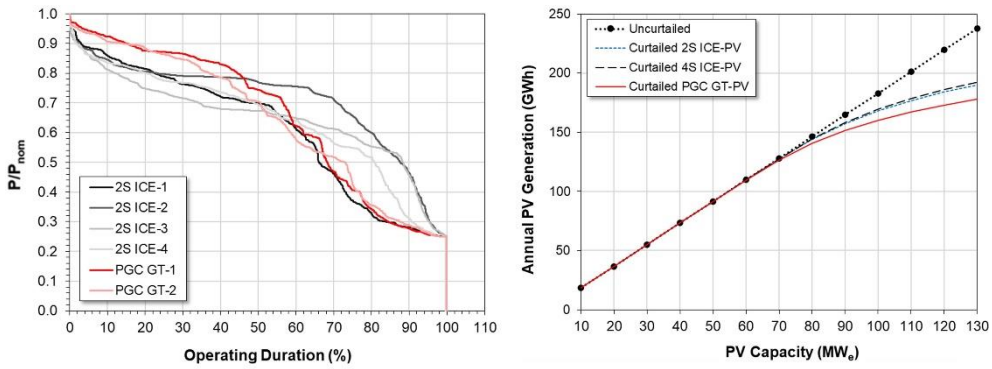
Finally, the LCOE of the annual electricity generation was calculated from Eq. (1) using the economic parameters listed in Table 1.

$$LCOE = \frac{(CAPEX + OPEX_{fix} + OPEX_{var} + Fuel\ Cost)}{Total\ Electricity\ Production} \quad (1)$$

3. Results and discussion

3.1 Production and curtailment

The results from the time-dependent optimization process showed that all hybrid plant configurations were able to meet the demand while maximizing the renewable dispatch and minimizing cost. Due to the relatively flat off-design curves of ICEs (Fig. 2(b)), 2S and 4S generators operated at near-nominal efficiency for most of the operating duration compared to PGC-GT, resulting in lower fuel consumption. Figure 3(a) shows the percentage of operating duration for different off-design power levels for 2S and PGC technology. It is seen that load distribution in PGC-GT is more homogenous than in the ICE engine, which might affect its maintenance requirements and cost.



(a) (b)

Fig. 3. Engine off-design power as a function of operating duration (a) and degree of curtailment in different plant layouts (b).

The amount of annual PV curtailment for all three hybrid layouts is shown in Figure 3(b). The curtailment starts at around 50 MW_e PV capacity and is highest for PGC-GT due to its highest $P_{min} = 0.25P_{nom}$ (Table 1), which implies that the hybrid PGC-GT plant consumes more fuel to dispatch the same load, compared to ICE counterparts. For the PGC-GT plant with 130 MW_e PV capacity, nearly 60 GWh or 25% of usable solar generation is curtailed, underscoring the significance of adequate large-scale storage and power-to-gas systems.

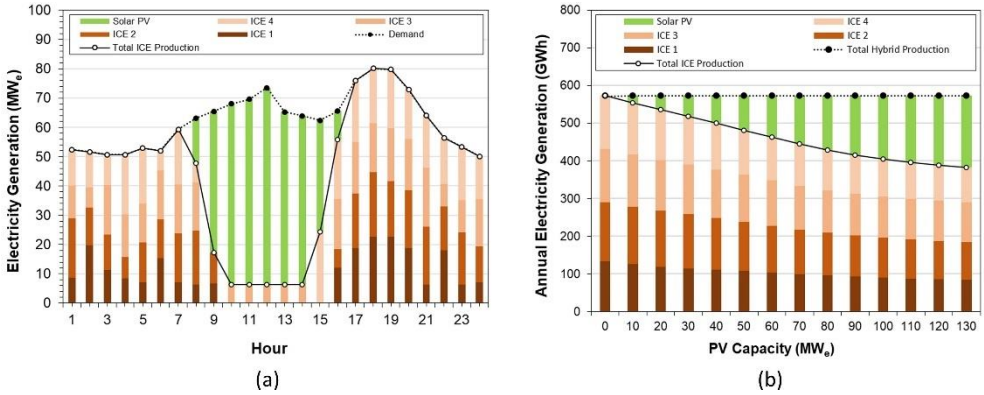


Fig. 4. Representative production profile (a) and penetration of PV with increased capacity (b) for the hybrid 2S ICE-PV with 100 MW_e PV capacity

A representative 24-hour production profile for a typical weekday is presented in Fig. 4(a) for the hybrid 2S ICE-PV layout. It shows that, within the optimization constraints mentioned previously, the W-ECoMP is able to maximize the dispatch through renewable PV. Additionally, Fig. 4(b) shows the increasing dispatch share of renewable in the annual production. However, the rate of increase of PV share reduces at higher PV capacities due to the effect of curtailment.

3.2 Emissions and economics

A carbon dioxide emission coefficient of 55.82 kg/GJ was used to estimate the total emitted CO_2 with known fuel consumption. Figure 5(a) shows the reduction of emissions with PV for all hybrid cases. As can be seen, the PGC-GT configuration produced the highest emissions compared to hybrid ICEs. This is because of the higher fuel consumption of PGC-GT resulting from poor off-design efficiency and reduced solar production due to higher curtailment.

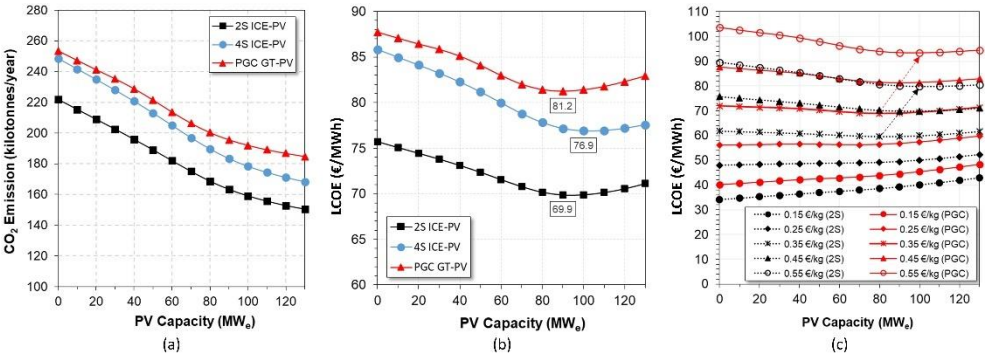


Fig. 5. Annual emission of carbon dioxide (a), LCOE (b) and LCOE sensitivity with fuel price (c) for different plant layouts. Arrows indicate the shift of minimum LCOE with fuel price.

The LCOE of plant operation estimated from Eq. (1) is shown in Fig. 5(b). It is found that the LCOE values exhibit minima with the PV capacity, highlighting an optimum PV capacity for each hybrid plant. The presence of LCOE minima is due to the favorable effect of reduced fuel cost and the unfavorable effect of curtailment with increasing PV capacity. Interestingly, the LCOE of the PGC-GT hybrid is higher than the ICE hybrid due to its poor off-design efficiency and higher P_{min}. Moreover, although the CAPEX of 2S-ICE is slightly higher than 4S-ICE, its LCOE is much lower because of higher efficiency and lower $OPEX_{var}$. Finally, it is worth noting that the optimum PV enables annual CO_2 reductions of 58.6, 70.2 and 57.7 kton with respect to operation without PV for 2S-ICE, 4S-ICE and PGC-GT layouts, respectively.

The sensitivity of LCOE and optimum PV capacity with fuel price, presented in Fig. 5 (c), shows that the minimum LCOE increases with fuel price as would be expected, but the optimum PV capacity also increases. From the environmental perspective, this increase of optimum PV capacity with fuel price is an important trend as higher PV installation will lead to reduced fuel burn and CO_2 emissions, as is evident from the monotonic reduction of CO_2 emission with PV shown in Fig. 5 (a). It signifies the driving potential towards more renewable penetration with increasing fuel prices. On the contrary, low fuel prices are economically unfavorable for high PV capacity and therefore are environmentally disadvantageous. For all the studied cases, the 2S ICE-PV configuration performed best in terms of cost and emissions, and the novel PGC-GT technology still exhibited subordinate performance compared to ICEs, largely due to its poor off-design efficiency and higher P_{min}. Therefore, to gain better insights into the viability of PGC, it is worthwhile to investigate PGC-GT in the combined cycle configuration at a wider range of classes.

4. Conclusion

The study investigated the optimized energy dispatch on an island through proven ICE and innovative PGC technologies augmented by high renewable solar-PV. Hybrid plant operation with solar-PV showed an annual CO_2 reduction by 58,600 tons and an LCOE reduction by 8.9 €/MWh with increased PV capacity. Due to the curtailment effect, an optimum PV capacity exists, allowing for the minimum cost of island energy, depending on the specific dispatchable assets. Moreover, a sensitivity analysis showed the environmental advantages of increasing fuel prices. With the layouts and specifications investigated, the PGC-GT exhibited suboptimal performance compared to ICEs, mainly due to its poor off-design characteristics and higher P_{min}. To further evaluate the techno-economic viability of PGC systems, analysis with combined cycles, energy storage, power-to-gas and carbon pricing is recommended at a wider range of operating conditions and component sizes.

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6. Nomenclature

Abbreviations

P	Power [W]
CAPEX	Capital Cost (€)
OPEX	Operational Cost (€)

LCOE Levelized cost of energy (€/MWh)

Subscripts

e electrical
fix Fixed cost
var Variable cost
nom Nominal power
min Minimum off-design power

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