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Economic dispatch of a single micro-gas turbine under CHP operation

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HIGHLIGHTS

- Economic dispatch of a micro gas turbine is considered for smart grid integration.
- A detailed thermodynamic cycle analysis is conducted for variable load CHP operation.
- Benefits are shown for case studies with real demand profiles and energy tariffs.
- Optimal unit schedule can be electricity, heat, revenue or maintenance-cost driven.

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ABSTRACT

This work considers the economic dispatch of a single micro-gas turbine under combined heat and power (CHP) operation. A detailed thermodynamic cycle analysis is conducted on a representative micro-gas turbine unit with non-constant component efficiencies and recuperator bypass. Based on partial and full load configurations, an accurate optimization model is developed for solving the economic dispatch problem of integrating the turbine into the grid. The financial benefit and viability of this approach is then examined on four detailed scenarios using real data on energy demand profiles and electricity tariffs. The analysis considers the optimal operation in a large hotel, a full-service restaurant, a small hotel, and a residential neighborhood during various seasons. The optimal schedule follows four fundamental economic drivers which are electricity, heat, revenue, and maintenance-cost driven.

1. Introduction

Presently, all business models (POLES, IEA, World Bank) forecast a drastic increase in the global demand for energy supply, where predictions reflect double the primary energy consumption from 2000 to 2020 [1]. More recent studies commissioned by the European Union, the U.S. Energy Information Administration (EIA), and the World Bank, all present similar projections of electricity demand increase by roughly 100% from 2000 to 2050 [2–4].

In order to satisfy this ever-growing electricity demand, the choice of fuel is among the challenges of economic policy. This choice is significantly dependent on national resources and long-term political interests. Although there exist variations in fuel type distribution between different countries [2], in an aggregate sense, it is expected that the relative shares of coal and nuclear are to decrease [4]. Charting the predictions of net electricity generation (in TWh) over the course of 50 years (until 2050), Fig. 1 presents the evolution of the dependency to various fuel sources. According to this EU energy market simulation, the future demand for power generation will be exceedingly accommodated by the renewable energy sources, as well as natural gas.

The issue of renewable energy, in particular solar and wind power, presents a specific challenge to the grid infrastructure. As their capacity is not always available, electricity generation becomes highly dependent on the time of day, the seasons, and the weather. The fluctuations in generation require more re-dispatches by grid operators, and therefore, the renewables alone cannot dominate the future generation infrastructure. Along these lines, the European Union's electricity generation from natural gas has tripled from the 1990s to early 2000s [5]. This trend of continued introduction of natural gas is foreseen in most industrialized countries.

The largest increase in the use of natural gas for power generation will primarily be accommodated by the introduction of

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Nomenclature

Abbreviations

CCHP	Combined Cooling, Heating and Power
CHP	Combined Heating and Power
COP	Coefficient of Performance
DAG	Directed Acyclic Graph
FAR	Fuel to Air Ratio
FC	Fixed Cost
FPE	Fixed Price of Energy
GT	Gas Turbine
HRU	Heat Recovery Unit
MGT	Micro Gas Turbine
PDC	Peak Demand Charging
ToU	Time-of-Use Energy Rate
UT	Utility
WP	Working Parameter

Economic dispatch nomenclature

ΔT	step size
$C_{GT}()$	fuel cost function
$C^P_{UT}(), C^H_{UT}()$	utility power and heat cost functions
$f_{GT}()$	turbine dynamics
$P(t), H(t)$	nominal power and heat demand
p_i, h_j	turbine speed and bypass valve position
$u_{GT}(t)$	turbine control variable at time t
$x_{GT}(t)$	turbine state at time t
$x^P_{UT}(t), x^H_{UT}(t)$	power and heat purchased from utility

Gas turbine nomenclature

$(\cdot)_{0i}$	stagnation conditions at station i
$(\cdot)_2$	compressor inlet station
$(\cdot)_{31}$	combustor inlet station
$(\cdot)_3$	recuperator cold inlet station
$(\cdot)_4$	turbine inlet station
$(\cdot)_{51}$	recuperator hot outlet station
$(\cdot)_5$	recuperator hot inlet station
$(\cdot)_6$	heat recovery unit inlet station
$(\cdot)_7$	heat recovery unit outlet station
$(\cdot)_{air}$	air parameter
$(\cdot)_b$	combustor parameter
$(\cdot)_{corr}$	corrected parameter
$(\cdot)_c$	compressor parameter
$(\cdot)_{dp}$	design point parameter
$(\cdot)_{el}$	electrical parameter
$(\cdot)_f$	fuel parameter
$(\cdot)_{HRU}$	HRU parameter
$(\cdot)_{max}$	maximal possible parameter
$(\cdot)_m$	mechanical parameter
$(\cdot)_{rec}$	recuperator parameter
$(\cdot)_{ref}$	reference conditions
$(\cdot)_s$	isentropic ideal process
$(\cdot)_t$	turbine parameter
β	HRU bypass valve position
$\dot{m}$	mass flow
$\dot{Q}_r$	specific fuel energy
η	efficiency
γ_c	heat capacity ratio - cold flow
γ_h	heat capacity ratio - hot flow
Ω	combustor loading parameter
ζ	bypass ratio
C	heat capacity
C_p	heat capacity at constant pressure
h	enthalpy
N	rotational speed
P	pressure
P_l	part load factor
$P_{compressor}$	compressor power
P_{gen}	generator power
P_{heat}	heating power
q	heat transfer rate
T	temperature

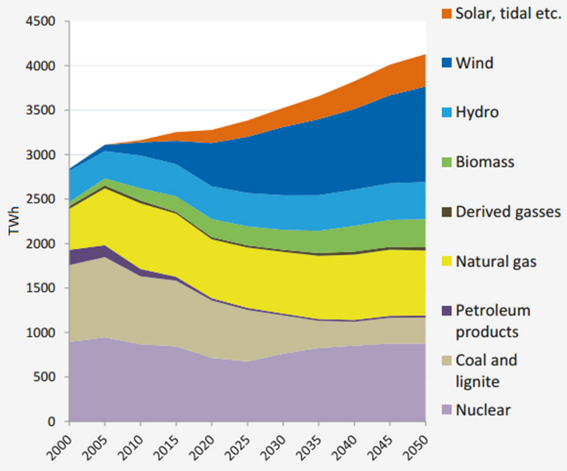

Fig. 1. Trends in electricity generation for the European Union (reproduced from [4]).

combined cycle systems, where the local consumers become the provider for their electricity, hot water, heat, and chill production [5–7]. The technological attractiveness of combined cooling, heat, and power (CCHP) units was the focus of several recent scientific studies [8–10]. Among the available options for CCHP production (such as internal-combustion, piston-steam, and stirling engines, as well as hydrogen fuel cells, combined solar plants, and steam-turbines), micro-gas turbines offer many advantages for small-scale generation. These include high power-to-weight ratio, relative size (low terrain footprint), reliability (smaller number of moving parts), lower noise and vibrations, multi-fuel capability, and lower greenhouse gas emissions [11–13]. Due to their relative low thermal and mechanical inertia, micro gas turbine units are agile and flexible, capable of short start-up times [14], along with rapid operational transitions between partial and full-load [11–13]. Furthermore, polygeneration systems that incorporate MGTs can theoretically achieve thermal efficiencies of above 85% [7].

This has motivated scientific efforts invested in determining the economically favorable conditions towards the smart grid integration of MGT powered CCHP units [15–20]. In these studies, the MGT model is often generic with fixed component and cycle efficiencies [15–18]. Furthermore, even when more refined models are considered [19,20], the thermo-economic analysis is either absent [20] or lacks realistic heat/power demand profiles and the associated variable pricing of electricity [15–19]. This level of abstraction is only sufficient to provide a first-pass estimate on whether a MGT may be suitable as a base load CCHP unit.