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Selection based on differences between cogeneration and trigeneration in various prime mover technologies

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ABSTRACT

Energy demands and fuel costs are continuously increasing which necessitates either finding new energy resources or improving current energy systems. Multi-generation systems as cogeneration (CHP) and trigeneration (CCHP) are interesting solutions that can enhance energy generation performance and fix some interrelated reliability, safety, and flexibility issues. In this regard, many prime mover technologies are available in which the choice between each is greatly dependent on end-user conditions and preferences. Yet, it is prior to choose whether cogeneration or trigeneration is more suitable. Thus, this paper reviews the main differences between CHP and CCHP systems in most available prime mover technologies, after which a selection table is proposed in order to make appropriate multi-generation system installation choices, depending on specific case study parameters. In general, CHP and CCHP systems yield positive technical and environmental performance impacts.

1. Introduction

Energy problems are increasing around the world due to population growth and rising living standards [1]. This has put the world to face daunting pressures on the energy market. For instance, the past decade witnessed a significant increase in electricity demand along with a considerable rise of its consumption as well as retail prices and fuel costs. Some countries suffer from these increasing demands with constant or even decreasing power supply, which leads to a progressive growth in the energy shortage gap [2,3]. Constraints on traditional electricity supply and delivery, global competition, climate change concerns, failing grid infrastructure, and security issues are another affecting forms that exert increasing pressure on the energy situation and thereby release additional environmental, human health, and financial consequences [4–17]. Thus, energy usage must be optimized through improving the efficiency of the applied energy systems, in addition to enhancing building designs and appliances, conserving energy, and promoting sustainable or renewable energy sources [18].

Buildings sector; residential, public, or commercial, represents 32% of total final energy consumption. In terms of primary energy consumption, they represent around 40% in most IEA countries [19]. This consumption is mainly split into electricity appliances consumption, space heating, space cooling and hot water usage. Conventionally, these loads are provided by electricity of the national power grid, and/or heat generated separately in boilers by burning natural gas or oil. But thermal power plants (internal combustion engines and steam/gas turbines) are characterized by a relative low total efficiency; where the average efficiency for electrical generation is less than 40% [20,21]. Even with fuel cells, total efficiency ranges from 30 to a best 60% value [22,23]. For heating loads as well, the conventional household boilers could be of only 70% efficiency [24]. Furthermore, the use of fossil fuels, upon which most conventional power generation systems are based, result in a huge amount of greenhouse gases (GHG) emissions. Meanwhile, the global oil supplies will reach a peak at some point after which they will start to decrease and never rise again. Hence, it is necessary to optimize the usage of the limited fuel resources in buildings sector. Therefore, separate production of electrical and thermal energy would be energetically and environmentally inefficient; it will be more reliable to produce both forms of energy in a single power production process. The utilization of the low-grade waste heat from the power generation process for heating and/or cooling/refrigeration will be one of the solutions to save the energy squandering, and thus is the employment of cogeneration or trigeneration technologies [25,26].

Installing energy efficient technologies like combined cooling, heating, and power (CCHP) in building sector is effective. At the present time, one of the most appealing and available energy efficiency measures is the CCHP technology. Overall energy demand drop, fuel

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Nomenclature

A	Surface Area
AFC	Alkaline Fuel Cell
BESP	Breakeven Electricity Selling Price
C	Cost
CC	Capital Cost
CCGT	Combined Cycle Gas Turbine
CCHP	Combined Cooling, Heating, and Power
CCP	Combined Cooling and Power
CCS	Carbon Capture and Storage
CHP	Combined Heating and Power
CI	Compression Ignition
Com	Commercial
COP	Coefficient of Performance
CPR	Compressor Pressure Ratio
CSR	Cost Saving Ratio
DHW	Domestic Hot Water
EEE	Equivalent Energy Efficiency
EUF	Energy Utilization Factor
FCS	Fuel Consumption/Cost Savings
FESR	Fuel Energy Saving Ratio
G	Gega
GHG	Greenhouse Gas
GT	Gas Turbine
HHV	Higher Heating Value
HRSG	Heat Recovery Steam Generator
HT	High Temperature
HX	Heat Exchanger
IC	Internal Combustion
ICE	Internal Combustion Engine
Ind	Industrial
IRR	Internal Return Rate
LHV	Lower Heating Value
LPG	Liquefied Petroleum Gas
LT	Low Temperature
$\dot{m}$	Flow Rate
M	Million/Mega
MCFC	Molten Carbonate Fuel Cell
MSCM	Metric Standard Cubic Meters
MT	Micro-Turbine
NG	Natural Gas
NPV	Net Present Value
OCS	Operating Cost Savings
ORC	Organic Rankine Cycle
P	Electric Power
PAFC	Phosphoric Acid Fuel Cell
PBP	Pay Back Period
PEC	Primary Energy Costs
PEMFC	Proton Exchange Membrane Fuel Cell
PER	Primary Energy Rate
PES	Primary Energy Savings
PFI	Performance Fraction Indicator
PHR	Power to Heat Ratio
ppb, ppm, ppmv	parts per billion, million, by volume
Q	Thermal Power
Res	Residential
RICE	Reciprocating Internal Combustion Engine
rpm	Rotations Per Minute
SE	Stirling Engine
SOFC	Solid Oxide Fuel Cell
ST	Steam Turbine
STIR	Steam Injection Rate
T	Temperature
U	Overall Heat Transfer Coefficient

Greek Letters

η	Energy Efficiency
ε	Exergy Efficiency
Δ	Difference

Subscripts

c	cooling
e	electrical
ER	Energy required
env	environment
f	fuel
h	heating
max	maximum
min	minimum
nom	nominal
op	operating
rec	recovery
req	required
t	total
th	thermal

independency, increased business competitiveness, GHG emissions cut, and electrical grid improvement are some of many benefits this technology can offer [11,22,27–34].

This paper mainly reviews the principles and benefits of CHP/CCHP systems, in addition to their different classifications, and basics differences in various prime movers technologies. At the end, a selection table is suggested in order to make a choice regarding the installation of multi-generation systems depending on specific measures and case study conditions.

2. Multi-generation technology principle

Cogeneration or combined heat and power (CHP) production is the use of a heat engine or power station to simultaneously generate electricity and useful heat. In this sequential energy production, both heat and power requirements are satisfied from a single fuel source. The heat, that would otherwise be wasted in the power production process (into natural environment through cooling towers, flue gas, or other means) is recuperated to provide process heat requirements, else being delivered with a separate fuel source, and thus providing significant fuel savings and pollution reductions [35,36]. So, cogeneration is a thermodynamically efficient use of fuel. Recovered heat can be used for heating processes, such as hot water for district heating and domestic use.

Trigeneration (or CCHP) is one step ahead of cogeneration [27,37], referring to the simultaneous generation of electricity, useful heating, and cooling from a single fuel source. Relative to CHP, the otherwise lost heat is captured and used to generate, in addition to power and heat, a cold effect. The latter can be produced either by thermally driven heat pumps or desiccant systems [27,35–41]. CCHP systems can attain higher overall efficiencies than traditional power plants or cogeneration [42–46]. Heating and cooling outputs may operate concurrently or alternately depending on needs and system construction.

The general concept of cogeneration and trigeneration systems is presented in Fig. 1. First, fuel and excess air are mixed and burned in order to drive a prime mover which in turn drives an electrical generator that produces electricity for final use. The energy of high-