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Economic value of flexible hydrogen-based polygeneration energy systems

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HIGHLIGHTS

- Assess the economic value of fossil-fuel polygeneration energy systems (PES).
- Analyze the cost competitiveness of static and flexible PES.
- Derive and quantify PES levelized cost of hydrogen and unit profit-margin.
- Derive and quantify PES real-option values of diversification and flexibility.
- Assess the economic competitiveness of Hydrogen Energy California (HECA).

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ABSTRACT

Polygeneration energy systems (PES) have the potential to provide a flexible, high-efficiency, and low-emissions alternative for power generation and chemical synthesis from fossil fuels. This study aims to assess the economic value of fossil-fuel PES which rely on hydrogen as an intermediate product. Our analysis focuses on a representative PES configuration that uses coal as the primary energy input and produces electricity and fertilizer as end-products. We derive a series of propositions that assess the cost competitiveness of the modeled PES under both static and flexible operation modes. The result is a set of metrics that quantify the levelized cost of hydrogen, the unit profit-margin of PES, and the real-option values of 'diversification' and 'flexibility' embedded in PES. These metrics are subsequently applied to assess the economics of Hydrogen Energy California (HECA), a PES currently under development in California. Under our technical and economic assumptions, HECA's levelized cost of hydrogen is estimated at 1.373 $\$/kg_h$. The profitability of HECA as a static PES increases in the share of hydrogen converted to fertilizer rather than electricity. However, when configured as a flexible PES, HECA almost breaks even on a pre-tax basis. Diversification and flexibility are valuable for HECA when polygeneration is compared to static monogeneration of electricity, but these two real options have no value when comparing polygeneration to static monogeneration of fertilizers.

1. Introduction

Fossil fuels meet 87% of today's global energy demand [1] and are used to generate 68% of the global electricity supply [2]. Concerns over climate change, growing energy consumption, and energy security compel fossil-fuel plants to meet increasing regulatory and market challenges: lower emissions, higher efficiency, and more flexible operations to complement intermittent renewables and hedge against fluctuations in energy prices. Polygeneration energy systems (PES) have the potential to meet all these challenges.

While polygeneration generally describes a wide range of multi-input multi-output industrial processes [3], this study focuses on polygeneration energy systems that use fossil fuels as inputs and produce hydrogen as an intermediate product [4]. PES offers multiple advantages over conventional single-output or 'monogeneration' systems. Technically, polygeneration allows better process- and heat-integration among various production and ancillary units, which reduces energy losses and thus results in higher energy-conversion efficiency. This higher efficiency, combined with the utilization of carbon in chemical synthesis,

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Nomenclature

Acronyms

AGRU	acid-gas removal unit
ASU	air separation unit
CCS	carbon capture and storage
CO_2	carbon dioxide
COE	cost of energy
HECA	Hydrogen Energy California
HSU	hydrogen separation unit
MRU	mercury remova unit
NPV	net present value
PES	polygeneration energy system
PRU	particulate removal unit
SRU	shift-reaction unit
c_l	cost of capacity per one unit of output l (\$/kWh or \$/kg$_l$)
CF	capacity factor
CM_{lk}	contribution margin from converting one kilogram of hydrogen to output l in year k (\$/kg$_h$)
$ICMF_{lk}$	incremental contribution margin from flexible switching of hydrogen conversion to output l in year k (\$/kg$_h$)
j_l	time-averaged fixed operating cost per one unit of output l (\$/kWh or \$/kg$_l$)
$LCOE$	levelized cost of electricity (\$/kWh)
$LCOH$	levelized cost of hydrogen (\$/kg$_h$)
$LCOP$	levelized cost of polygeneration (\$/kg$_h$)
LIC_l	levelized incremental cost of the subsystem producing output l (\$/kWh or \$/kg$_l$)
m	total number of hours in one year (h)
m_l	number of yearly hours during which production rate of output l should be maximized (h)
$\widetilde{m}_l$	set of yearly hours during which production rate of output l should be maximized
N_h	production capacity of the hydrogen subsystem (kg$_h$/h)
P_l	price of output l (\$/kWh or \$/kg$_l$)
PM	unit profit-margin per one kilogram of produced hydrogen (\$/kg$_h$)
S_a	storage capacity of ammonia (kg$_a$)
SJ_{lk}	fixed operating cost per unit-capacity of output l in year k ((\$/yr)/kW or (\$/yr)/(kg$_l$/h))
SP_l	system price; cost per unit-capacity of output l (in \$/kW or \$/(kg$_l$/h))
T	useful lifetime of the facility (yr)
U_c	net CO_2 production rate per one kilogram of produced hydrogen (kWh/kg$_h$)
VOD	value of diversification (\$/kg$_h$)
VOF	value of flexibility (\$/kg$_h$)
VOP	value of polygeneration (\$/kg$_h$)
w_l	time-averaged variable cost per one unit of output l (\$/kWh or \$/kg$_l$)
x_k	degradation factor; the percentage of initial capacity that is still functional at year k
X_l	conversion rate of one kilogram of hydrogen to output l (kWh/kg$_h$ or kg$_l$/kg$_h$)
y_l	fraction of hydrogen allocated to the production of fertilizer l

Greek symbols

τ	discount rate
γ^k	discount factor in year k
λ	fraction of hydrogen production capacity allocated to electricity generation
$1-\lambda$	fraction of hydrogen production capacity allocated to fertilizer generation
K	constant-equivalent fraction of hydrogen production capacity allocated for fertilizer generation
Φ_l	correction factor to account for time-dependent variable costs during $\widetilde{m}_l$

Subscripts

a	ammonia without storage
as	ammonia with storage
c	carbon dioxide
e	electricity
f	fertilizer
h	hydrogen
max	maximum
min	minimum
UAN	urea and ammonium nitrate solution
urea	urea

results in lower carbon dioxide (CO_2) emissions [5,6]. In addition, the production rates of PES can be either fixed or adjusted over time. We refer to a system with fixed production rates as 'static' or 'steady-state' polygeneration and a system with variable production rates as 'flexible' or 'dispatchable' polygeneration [7]. Flexible polygeneration can exploit frequent variations in commodity prices; while fuel switching and mixing capabilities help attenuate the risks of fuel-price shocks, production diversification and dispatchability help capture the benefits of product-price peaks [7,8]. Furthermore, hydrogen markets are currently underdeveloped [9–11], which renders merchant hydrogen prices an imperfect indicator of cost and value. By converting hydrogen to valuable commodities, polygeneration offers an incentive to expand investments in hydrogen infrastructure.

The advantages of polygeneration systems merit a rigorous analysis of their economic competitiveness within the broader energy landscape. In this study, we develop a set of generalizable metrics that can be used to valuate fossil-fuel polygeneration energy systems. These economic metrics achieve three goals. First, they calculate the levelized cost and profitability of both static and flexible polygeneration, irrespective of the type of used fossil fuels or generated end-products. Second, they facilitate a consistent comparison of the economics of polygeneration relative to that of monogeneration, with special emphasis on electricity monogeneration alternatives (e.g. natural gas or wind). Finally, they quantify the value of two real options enabled by polygeneration: the value of diversifying end-products and the value of flexibly varying the production rates of end-products over time.

The main motivation for our analysis stems from the fact that different methodologies have been used to evaluate polygeneration economics, including net present value [7,8,12,13], profit index [12], payout time [14], cost of energy [15,16], and others [17–19]. While each methodology has its own merits, the lack of methodological consistency prevents accurate comparison of polygeneration economics under different technical assumptions and operational settings. The economic metrics we propose offer one way to overcome this problem. Specifically, we express all metrics in monetary value per unit of hydrogen produced, for hydrogen is a common intermediate product across polygeneration energy systems of various process configurations and end-product portfolios.

While some previous studies have used the cost of energy (*COE*) (\$/kWh) to compare polygeneration to monogeneration, such an