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Efficiency of poly-generating high temperature fuel cells

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A B S T R A C T

High temperature fuel cells can be designed and operated to poly-generate electricity, heat, and useful chemicals (e.g., hydrogen) in a variety of configurations. The highly integrated and synergistic nature of poly-generating high temperature fuel cell systems, however, precludes a simple definition of efficiency for analysis and comparison of performance to traditional methods. There is a need to develop and define a methodology to calculate each of the co-product efficiencies that is useful for comparative analyses. Methodologies for calculating poly-generation efficiencies are defined and discussed. The methodologies are applied to analysis of a Hydrogen Energy Station (H₂ES) showing that high conversion efficiency can be achieved for poly-generation of electricity and hydrogen.

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1. Introduction

Poly-generating systems include energy conversion devices that typically convert fuel chemical energy into multiple useful forms of energy or power. For instance, combined heat and power (CHP) systems generate electrical and thermal power from fuel in a single, integrated system. Poly-generating systems are typically comprised of a number of individual components, including for example a heat engine, generator, heat recovery equipment, and electrical interconnection hardware that are configured into an integrated whole system. The primary energy conversion device (i.e., the prime mover) is typically used to identify the type of poly-generating system. Prime movers include reciprocating engines, gas or steam turbines, and fuel cells that can produce electrical and thermal power from a variety of fuels, including natural gas, coal, and biofuels. Thermal energy from the system can be used in direct process applications or indirectly to produce steam, hot water, hot air for drying, or chilled water for process cooling [1].

High temperature fuel cells can be designed and operated to poly-generate electricity, heat, and useful chemicals in a variety of configurations [2]. The conversion of chemical energy to electrical energy that occurs at high temperatures allows for the production of electricity and high quality waste heat in cogeneration applications that can achieve ultra-low criteria pollutant emissions and high energy conversion efficiency. Since the electrochemical conversion process operates best using hydrogen-rich fuel, high temperature fuel cell systems typically contain integrated hydrogen

2. Efficiency calculation methodology

Fig. 1 presents the primary products as well as the total and allocated input energy streams, required to produce each product
Nomenclature

HTFC high-temperature fuel cell
H2ES hydrogen Energy Station
CHP combined heat and power
EPA Environmental Protection Agency
Q heat [kW]
LHV Lower heating value [kJ kg\(^{-1}\)]
\(kW\) kilowatts
\(\eta\) efficiency [%]
HSU hydrogen separation unit
PSA pressure swing adsorption
SMR steam methane reforming
SOFC solid oxide fuel cell
\(P\) electric power [kW]
T&D transmission and distribution
\(E\) energy flow [kW]
\(C\) chemical product
\(F\) fuel
\(H\) hydrogen product
\(U_F\) fuel utilization factor
U.S. United States
\(\dot{m}\) mass flow rate [kg s\(^{-1}\)]

Subscripts
PP power plant
CC combined cycle
CP chemical plant
ER external reformer
HC hydrocarbon
tot total
el electrical
H2 hydrogen
F fuel
FC fuel cell
SMR steam methane reforming
e\(^-\) electric generation

of a poly-generating HTFC. A methodology to accurately assess the performance of a poly-generating HTFC system that is also useful for comparative studies (i.e., studies that compare various methods for producing a certain product) is desired.

There are two major challenges associated with efficiency calculations for poly-generation HTFC systems. The first challenge is to assess a relative value for each of the co-products (perhaps based upon cost or price for each) so that one does not have to consider the energy content associated with electricity, thermal, and chemical products as of equal value. This issue is not addressed in the current paper so that overall efficiency is always calculated on the basis of a mixed sum of the poly-generated electricity, heat and chemical energy values.

The second major challenge associated with efficiency calculations for poly-generation HTFC is the allocation of appropriate fractions of the input energy flow to each of the co-products produced. This is the focus of the current paper. Table 1 shows four different efficiencies that must be defined for the poly-generating HTFC system.

Table 1

| Poly-generating efficiencies for the HTFC. |
|-------------------------------------------|
| Electrical efficiency (LHV) | Thermal efficiency (LHV) | Chemical product efficiency (LHV) | Total mixed efficiency (LHV) |
| \(\eta_{P}\) \(P_{net}/E_{P}\) | \(\eta_Q\) \(Q_{net}/E_Q\) | \(\eta_C\) \(C/E_C\) | \(\eta_{tot}\) \((P_{net} + Q_{net} + C)/E_{tot}\) |

Table 2

Conventional (state-of-the-art) plant efficiencies that can be used in the State-of-the-art method.

| Comparable efficiency considered | Value (based upon LHV) | Comments |
|----------------------------------|------------------------|----------|
| Power plant efficiency \(\eta_{PP}\) | 0.47 | Distributed electricity generation using a stand-alone HTFC without poly-generation or co-generation [6] |
| | 0.92 | Average U.S. T&D system efficiency [7] |
| | 0.60 | Typical modern natural gas combined cycle plant [7] |
| Boiler efficiency \(\eta_{boiler}\) | 0.60 | Fueled boiler at less than full load [5] |
| | 0.85 | Natural gas boiler at full load [5] |
| Chemical plant efficiency \(\eta_{CP}\) | 0.79 | Centralized steam methane reformation (SMR) to produce pure hydrogen from natural gas [8] |
| | 0.65 | Centralized methanol production from natural gas [9] |
| | 0.65 | Distributed SMR to produce pure hydrogen [10] |
Table 3

| Methodology                  | Electrical efficiency $\eta_{el} = \frac{P_{net}}{E_{tot}}$ | Thermal efficiency $\eta_{th} = \frac{Q_{net}}{E_{tot}}$ | Chemical product efficiency $\eta_{c} = \frac{C}{E_{CP}}$ |
|-----------------------------|-------------------------------------------------------------|-------------------------------------------------------|--------------------------------------------------------|
| (1) State-of-the-art method  | $P_{net}/E_{tot} - (Q_{net}/\eta_{boiler}) - (C/\eta_{boiler})$ | $Q_{net}/E_{tot} - (P_{net}/\eta_{el}) - (C/\eta_{el})$ | $C/|E_{net} - (P_{net}/\eta_{el}) - (Q_{net}/\eta_{boiler})|$ | $C/|E_{net} - P_{el} - Q_{el}$ |
| (2) Ideal method            | $P_{net}/E_{tot} - Q_{net} = C$                             | $Q_{net}/E_{tot} - P_{net} = C$                        | $C/E_{CP}$                                             |
| (3) Supplemental inputs method | $P_{net}/E_{tot} - E_{Q} - E_{CP}$                          | $Q_{net}((Q_{net} = E_{burner} \cdot \eta_{burner} \cdot \eta_{boiler}) + E_{burner})$ | $C/E_{CP}$                                             |

Efficiencies for each of the co-products for comparative analyses.

ues are not useful for comparative studies. A similar challenge has been previously addressed by the Combined Heat and Power (CHP) community. The CHP Partnership of the Environmental Protection Agency (EPA) developed a methodology for allocating a certain fraction of the input energy to each of the co-products that is useful for comparative analyses [1]. The EPA defines the electrical and total mixed efficiencies for conventional CHP systems (i.e., generation of electricity and thermal power) as follows:

$$\eta_{CHP, tot} = \frac{P_{net} + Q_{net}}{E_{tot}}$$ (2)

$$\eta_{CHP, el} = \frac{P_{net}}{E_{tot} - (Q_{net}/\eta_{boiler})}$$ (3)

where $\eta_{CHP, tot}$ is the total mixed CHP efficiency, $\eta_{CHP, el}$ is the effective electrical efficiency (fuel utilization efficiency) and $\eta_{boiler}$ is the typical boiler efficiency. Boiler efficiencies depend upon the fuel type, combustion system limitations, and equipment design. State-of-the-art values range between 60% and 85% [5]. For this study, a value of 85% has been considered for a new state-of-the-art boiler.

Another method to allocate a portion of input energy flow to the production of each co-product, called Supplemental Inputs method, assumes that the portion of input energy flow used to generate each individual output ($P_{net}$, $Q_{net}$ or $C$) can be directly measured or accurately estimated. In other words, the supplemental energy input provided to the system for the express purpose of generating a co-product (compared to the same system that does not produce the co-product) is assumed to be the energy flow input of the co-product. This methodology is useful, although it is not always possible to independently determine the supplemental energy input values. It is important to note that with this approach, the portion of energy used to produce useful heat $E_{Q}$ is assumed to be comprised of the heat automatically produced during electricity generation $E_{Qe}$ plus the supplemental energy added to a burner.

**Fig. 2.** Schematics of H$_2$ES: (a) external reformation; (b) internal reformation.
that is part of the system, $E_{\text{burner}}$, for the purpose of producing heat (Eq. (4) and (5)):

$$E_Q = E_{Qe} + E_{\text{burner}}$$  \hspace{1cm} (4)

$$E_{Qe} = \frac{Q_e}{\eta_{Qe}}$$  \hspace{1cm} (5)

where $Q_e$ is the heat associated with the electricity production and $\eta_{Qe}$ corresponds to the thermal efficiency associated with the electricity production. Unfortunately, $\eta_{Qe}$ cannot be readily measured or estimated without major assumptions. In this work, it is assumed that $\eta_{Qe}$ corresponds to the normal boiler efficiency $\eta_{\text{boiler}}$. Similarly, $\eta_{\text{boiler}}$ is the efficiency of the burner inherent to the system to produce supplemental heat. Then, the total net heat produced $Q_{\text{net}}$ is

$$Q_{\text{net}} = Q_e + E_{\text{burner}}/\eta_{\text{boiler}}$$  \hspace{1cm} (6)

By rearranging Eqs. (4)–(6), the portion of input energy allocated to produce heat is

$$E_Q = Q_{\text{net}} - E_{\text{burner}}/\eta_{\text{boiler}} + E_{\text{burner}}$$  \hspace{1cm} (7)

Table 3 summarizes the three methodologies developed to calculate the efficiencies of generic poly-generating HTFC systems that produce electricity, heat and chemical products.

Some particular poly-generating applications may not value or capture one of the co-products. For these special cases, the methodologies presented in Table 3 remain valid even though one co-product is not considered a useful product, in which case, the amount produced is considered zero.

### 3. Hydrogen Energy Station (H2ES) application

The Hydrogen Energy Station (H2ES) is a particular case of a poly-generating HTFC that produces electricity, heat and hydrogen [4]. HTFCs generate electricity and heat through exothermic electrochemical reactions. Generated heat is utilized by the endothermic internal reformation reactions, which usually require less heat than that which is available [11]. Surplus heat is used to preheat the fuel and oxidant streams before they enter the fuel cell and to produce the steam required for system operations. Steam is typically required for reformation (e.g., steam methane reforming) and/or to prevent carbonization (or coking) in the fuel streams of the system [12]. In a conventional CHP-HTFC system, remaining thermal energy contained in the exhaust gases is used downstream of the fuel cell for cogeneration applications [11]. The H2ES partially extracts hydrogen from the system, which inevitably leaves less thermal energy in the exhaust.

There are two main HTFC configurations that can be used to produce hydrogen: (1) using the fuel cell exhaust heat to drive the reformation reactions in an external reformer, or (2) relying upon the internal reforming capabilities of HTFCs [2]. In the external reformation case, a dedicated stream of supplemental hydrocarbon fuel is fed into the external reformer and heat is transferred from the fuel cell exhaust to the external reformer. In the internal reformation case, the amount of high quality heat produced by the exothermic electrochemical reactions within the stack is typically greater than the heat required for fuel processing. Therefore, more hydrocarbon fuel than that required for the electricity generation can be processed in within the HTFC anode compartment. As a result, the anode-off gas contains a hydrogen-rich stream that can be subsequently purified [3]. Fig. 2 shows the schematics of the H2ES using external and internal reformation.

As shown in Fig. 2, H2ES systems incorporate a hydrogen separation unit (HSU), which is based upon use of a pressure swing absorption (PSA) strategy for hydrogen purification [13]. PSA processes require compression work, which is taken from the electricity produced by the fuel cell. $P_{\text{net}}$ is the difference between the gross power produced by the HTFC and the power required for the PSA process. Therefore, there is a reduction of the net power produced by the HTFC due to hydrogen production and purification, which accounts for the efficiency of the HSU block [14].

For the particular case of the H2ES, the generic terms and equations for determining allocation of input energy flows to each of the co-products become the equations summarized in Table 4.

#### Table 4

| Parameter | Generic | H2ES | Description |
|-----------|---------|------|-------------|
| Chemical output | $C$ | $H$ | $n_{\text{H}_2} \times LHV_{\text{H}_2}$ | Hydrogen output [15] |
| Supplemental energy to produce thermal output | $E_{\text{burner}}$ | $-$ | $-$ | No need to add energy |
| Supplemental energy to produce hydrogen | $E_{CP}$ | $E_{H_2}$ | $P_{\text{PSA}}$ | $F_{\text{PSA}}$ = Additional fuel feedstock [kW] $P_{\text{PSA}}$ = Compression work for PSA process [kW] |

Fig. 3. Example results for the developed methodologies applied to the specific case of an H2ES producing only electricity and hydrogen (heat not valued).
The parameters defined in Table 4 may be used in both external and internal reforming cases. However, the additional fuel feedstock used to produce hydrogen, \(F_H\), must be defined for each configuration. The definition of \(F_H\) for internal and external reforming configurations, respectively, is

\[
(U_t - UF) \cdot \dot{E}_{tot}
\]

\[
\dot{m}_{HC,in,ER} \times LHV_{HC}
\]

where \(U_t\) is the normal fuel utilization factor of a typical co-generating HTFC and \(UF\) is the fuel utilization factor when hydrogen is produced (ie., \(H_2\)ES). Utilization factor is defined as the fraction of the total fuel that is used in the fuel cell to generate electricity, which must be lower than 100% to sustain an operating voltage [11]. \(E_{tot}\) is the total energy flow input defined as

\[
E_{tot} = \dot{m}_{HC,in} \times LHV_{HC}
\]

\(\dot{m}_{HC,in}\) is the total mass flow rate of hydrocarbon fuel fed into the system whereas \(\dot{m}_{HC,in,ER}\) is the mass flow rate of the fuel fed into the external reformer. The difference between the two fuel utilization factors represents the percentage of additional fuel feedstock added for the express purpose of producing the hydrogen. Obviously, \(U_t > UF\).

Table 5 shows the final efficiency equations that result for the specific application of poly-generating hydrogen with a HTFC for the three different methodologies defined herein.

Fig. 3 presents efficiency results (on a LHV basis) that are useful in comparative analyses for each of the methodologies for the specific case of an \(H_2\)ES that co-produces only electricity and hydrogen (heat is not valued). The \(H_2\)ES considered for this analysis is capable of producing 1 MW of gross electric power and 564 kg day\(^{-1}\) of hydrogen fuel via internal reformation (Fig. 2b). The input fuel is pure methane and the hydrogen co-producing HTFC is a solid oxide fuel cell (SOFC) that operates at 60% fuel utilization factor. Parasitic loads are mostly associated with pressure swing adsorption (PSA) and represent approximately 30% of the total gross electric power produced. The comparison case for the example considered here is conventional production of electricity from a state-of-the-art combined cycle plant and centralized production of hydrogen using steam-methane reformation (SMR).

In the State-of-the-art method, each product efficiency is calculated assuming that the other co-products are produced via conventional technologies, which might be relatively inefficient. As a result, this methodology produces relatively high co-product efficiency values. The Ideal poly-generation method results in the lowest co-product efficiencies since it is assumed that the other co-products are produced at 100% efficiency. The Supplemental Inputs method determines co-product efficiency on the basis of supplemental energy inputs, leading to relatively higher co-product efficiencies as shown in Fig. 3. In all cases the overall mixed (electricity and hydrogen) efficiency is 69.5%.

While each of the methodologies produces co-product efficiency values that are reasonable for comparing to other means of producing each co-product, the Ideal poly-generation method, certainly underestimates other co-product input energy flow. The State-of-the-art method assesses input energy flow on the basis of state-of-the-art production alternatives (natural gas combined cycle plant and centralized SMR in this case), and the Supplemental Inputs method assesses such on the basis of known (or measured) supplemental energy flow input. For this \(H_2\)ES case, State-of-the-art and Supplemental Inputs methods reasonably assess input fuel quantities to each co-product and demonstrate the synergistic co-production of heat and power from an HTFC, which is effectively comparable to or slightly better than much larger state-of-the-art production methods.

| Method | Total mixed efficiency | Hydrogen efficiency | Thermal efficiency | Electrical efficiency |
|--------|------------------------|---------------------|--------------------|----------------------|
| 1 State-of-the-art method | (\(P_{net} + Q_{es} + H_{es}\))/\(Q_{net}\)) | \(H_{es}/(Q_{net})\) | \(P_{net}/(Q_{net})\) | \((P_{net} - Q_{es} - H_{es})/Q_{net}\) |
| 2 State-of-the-art method | (\(P_{net} + Q_{es} + H_{es}\))/\(Q_{net}\)) | \(H_{es}/(Q_{net})\) | \(P_{net}/(Q_{net})\) | \((P_{net} - Q_{es} - H_{es})/Q_{net}\) |
| 3 State-of-the-art method | (\(P_{net} + Q_{es} + H_{es}\))/\(Q_{net}\)) | \(H_{es}/(Q_{net})\) | \(P_{net}/(Q_{net})\) | \((P_{net} - Q_{es} - H_{es})/Q_{net}\) |
4. Summary and conclusions

The highly integrated and synergistic nature of poly-generating high temperature fuel cells precludes a simple definition of efficiency for analysis and comparison of poly-generation performance to traditional methods. The current work has developed three methodologies for calculating co-product efficiencies that are useful for comparative studies.

There are multiple ways of defining the co-product efficiencies in a poly-generating system. All of the current methodologies are based upon different and reasonable assumptions for the portion of input energy flow that is allocated to each of the co-products. It should be clear that there is not a unique solution and that each of the methodologies proposed can be used in comparative analyses if based upon truthful assumptions. All the methodologies presented and developed herein except the third one (i.e., Supplemental Inputs Method) are based upon previously presented methods applied to similar poly-generating systems. The Supplemental Inputs Method has been developed specifically for this work and is recommended to calculate poly-generating system co-product efficiencies for comparative analyses. All parameters used in this methodology are measurable, and this method allows direct comparison of each co-product efficiency to the efficiency of other methods for producing such a product alone.

The methodologies have been applied to a Hydrogen Energy Station (H2ES) showing that high conversion efficiency can be achieved for poly-generation of each of the co-products (electricity and hydrogen).

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