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Short communication

Efficiency of poly-generating high temperature fuel cells

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ABSTRACT

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 cells, 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 hydro-

carbon reforming processes that use fuel cell heat and catalysts to produce a hydrogen rich mixture. The high temperatures and heat are required to overcome the endothermicity of reformation reactions and lead to high quality heat that can be used as a co-product. Since a fuel cell cannot consume all of the fuel in the anode compartment, a certain fraction of the hydrogen containing stream is always available for other purposes (e.g., producing heat for use in other parts of the system via a catalytic oxidizer, or producing useful chemical co-products such as hydrogen [2]).

Three synergistic performance benefits can be achieved with poly-generating high temperature fuel cells (HTFC): (1) additional endothermic reformation cools the fuel cell, thereby reducing auxiliary power associated with forced air cooling, (2) lower fuel utilization associated with excess fuel throughput raises the fuel cell operating voltage, and (3) waste heat is directly used to produce a valuable chemical co-product (e.g., hydrogen) [3].

These synergistic features of integrated poly-generating HTFC systems lead to overall low emissions and high efficiency [3,4], but, because the systems simultaneously produce electricity, thermal and chemical energy, efficiencies can be measured and expressed in a number of different ways. As a result, there is a need to define and adopt methodologies to calculate each of the co-product efficiencies in a manner that allows effective and accurate comparisons of poly-generating systems to conventional generation systems. In this work, different methodologies for calculating poly-generation efficiencies are defined and discussed.

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

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Nomenclature

HTFC	high-temperature fuel cell
H ₂ ES	hydrogen Energy Station
CHP	combined heat and power
EPA	Environmental Protection Agency
Q	heat [kW]
LHV	Lower heating value [kJ kg ⁻¹]
kW	kilowatts
η	efficiency [%]
HSU	hydrogen separation unit
PSA	pressure swing adsorption
SMR	steam methane reformation
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
H ₂	hydrogen
F	fuel
FC	fuel cell
SMR	steam methane reformation
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

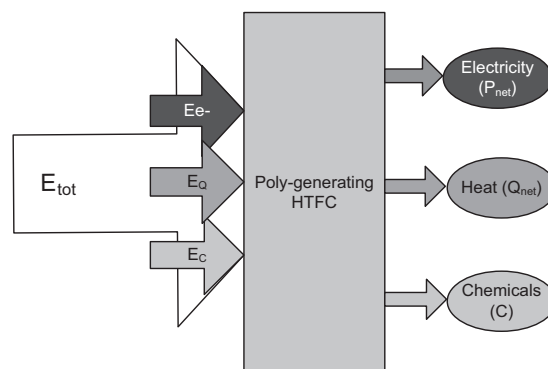


Fig. 1. Energy flow input and main products of a generic poly-generating HTFC.

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.

P_{net} is the net electric power produced [kW], Q_{net} is the net thermal energy flow produced [kW], C is the chemical energy flow of the chemical co-product [kW] and E_{e^-} , E_Q , and E_C are the input energy flows assessed to generate electricity, heat and chemicals, respectively. E_{tot} is the total energy flow input defined as follows:

$$E_{tot} = E_{e^-} + E_Q + E_C \quad (1)$$

The calculation of total mixed efficiency η_{tot} is straightforward since all the inputs and all of the outputs are measurable. However, the determination of the portion of the input energy flow used to generate each individual output stream E_{e^-} , E_Q , and E_C is not trivial. In this work, different methods to appropriately allocate fractions of the input energy flow to each of the co-products produced are developed and discussed.

While one could calculate individual co-product efficiency values as fractional contributions to system total mixed efficiency (i.e., divide each co-product power by E_{tot}), these efficiency val-

Table 1
Poly-generating efficiencies for the HTFC.

Electrical efficiency (LHV)	Thermal efficiency (LHV)	Chemical product efficiency (LHV)	Total mixed efficiency (LHV)
η_{e^-}	η_Q	η_C	η_{tot}
P_{net}/E_{e^-}	Q_{net}/E_Q	C/E_C	$(P_{net} + Q_{net} + C)/E_{tot}$

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	0.47	Distributed electricity generation using a stand-alone HTFC without poly-generation or co-generation [6]
η_{PP}	0.92	Average U.S. T&D system efficiency [7]
	0.60	Typical modern natural gas combined cycle plant [7]
Boiler efficiency η_{boiler}	0.60	Fueled boiler at less than full load [5]
	0.85	Natural gas boiler at full load [5]
Chemical plant efficiency η_{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
Efficiencies for each of the co-products for comparative analyses.

Methodology	Electrical efficiency $\eta_{el} = P_{net}/E_{e^-}$	Thermal efficiency $\eta_{th} = Q_{net}/E_Q$	Chemical product efficiency $\eta_c = C/E_C$
(1) State-of-the-art method	$P_{net}/(E_{tot} - (Q_{net}/\eta_{boiler}) - (C/\eta_{CP}))$	$Q_{net}/(E_{tot} - (P_{net}/\eta_{PP}) - (C/\eta_{CP}))$	$C/(E_{tot} - (P_{net}/\eta_{PP}) - (Q_{net}/\eta_{boiler}))$
(2) Ideal method	$P_{net}/E_{tot} - Q_{net} - C$	$Q_{net}/E_{tot} - P_{net} - C$	$C/E_{tot} - P_{net} - Q_{net}$
(3) Supplemental inputs method	$P_{net}/E_{tot} - E_Q - E_{CP}$	$Q_{net}/((Q_{net} - E_{burner}\eta_{burner}/\eta_{boiler}) + E_{burner})$	C/E_{CP}

ues are not useful for comparatives 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:

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

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

where $\eta_{CHP,tot}$ is the total mixed CHP efficiency, η_{CHP,e^-} is the effective electrical efficiency (or fuel utilization efficiency) and η_{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.

η_{CHP,e^-} is the ratio of the net electric power output to the net energy flow consumption associated with electricity as a single product. The net energy flow consumption for producing electricity excludes the portion of input energy used for producing useful heat output by assuming that it would otherwise have had to be produced by a typical boiler with characteristic boiler efficiency (η_{boiler}). A similar approach is suggested herein for allocating the appropriate fraction of the input energy flow to each of the co-products in a poly-generation HTFC. This approach, labeled *State-of-the-art method*, assumes that the net energy consumption for producing each one of the co-products (P_{net} , Q_{net} or C)

excludes the portion of input energy flow for producing the other useful outputs by assuming that they would otherwise have had to be produced via state-of-the-art conventional methods. The corresponding efficiencies associated with the state-of-the-art conventional methods and some typical values that can be used in this methodology are presented in Table 2.

The second approach, labeled *Ideal poly-generation method*, is identical to the *State-of-the-art method* except that it is assumed that all of the co-products are generated with an efficiency of 100%. While this methodology may be useful to evaluate the overall performance of a poly-generating HTFC, the efficiency calculated for each of the co-products unduly attributes too much input energy flow to each co-product, which must be understood and accounted for in comparatives studies. This method is based upon the efficiency calculations presented by FuelCell Energy and Air Products on their latest publication [13].

Another method to allocate a portion of input energy flow to the production of each co-product, called *Supplemental Inputs method* herein, 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

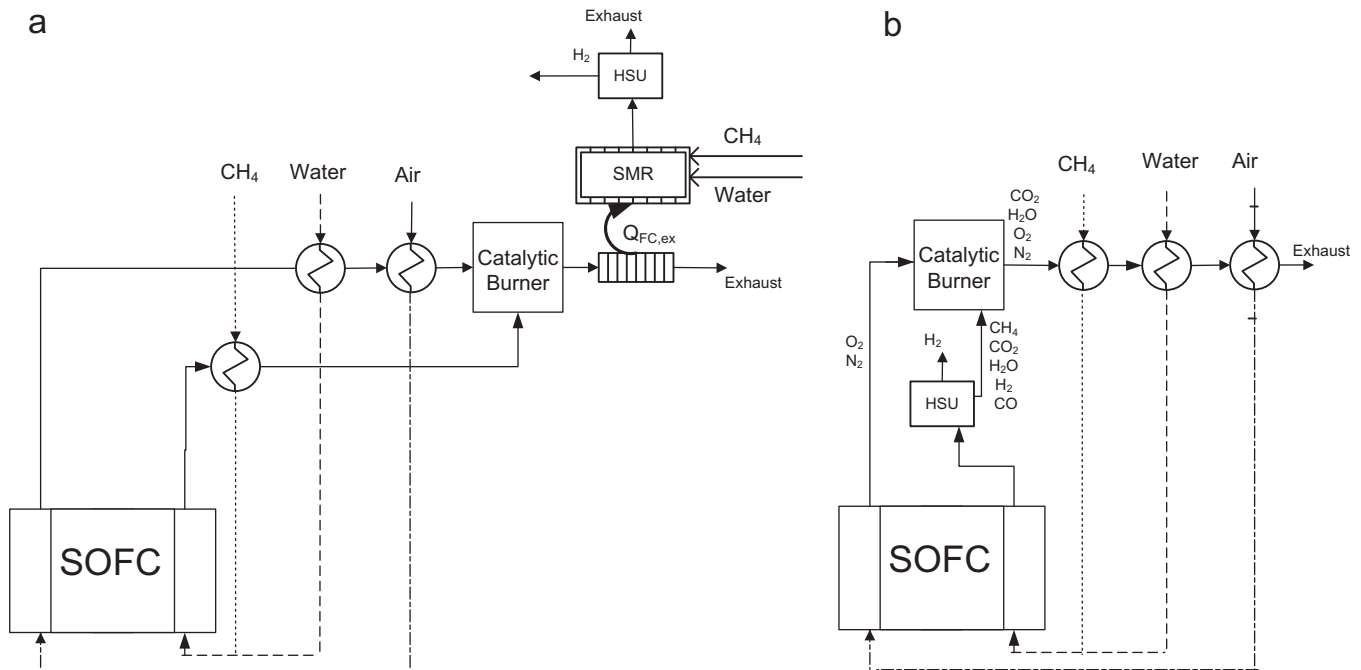


Fig. 2. Schematics of H2ES: (a) external reformation; (b) internal reformation.

Table 4
Particular allocations of input energy flows to each of the co-products for the H₂ES application.

Parameter	Generic	H ₂ ES	Description	
Chemical output	C	H	$=\dot{m}_{H_2} \times LHV_{H_2}$	Hydrogen output [15]
Supplemental energy to produce thermal output	E_{burner}	–	–	No need to add energy
Supplemental energy to produce hydrogen	E_{CP}	E_{H_2}	$= F_{H_2} + \frac{P_{PSA}}{\eta_{CC}}$	F_{H_2} = Additional fuel feedstock [kW] P_{PSA} = Compression work for PSA process [kW]

that is part of the system, E_{burner} , for the purpose of producing heat (Eq. (4) and (5)):

$$E_Q = E_{Qe^-} + E_{burner} \quad (4)$$

$$E_{Qe^-} = \frac{Q_{e^-}}{\eta_{Qe^-}} \quad (5)$$

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

$$Q_{net} = Q_{e^-} + E_{burner}\eta_{burner} \quad (6)$$

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

$$E_Q = \frac{Q_{net} - E_{burner}\eta_{burner}}{\eta_{boiler}} + E_{burner} \quad (7)$$

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_{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.

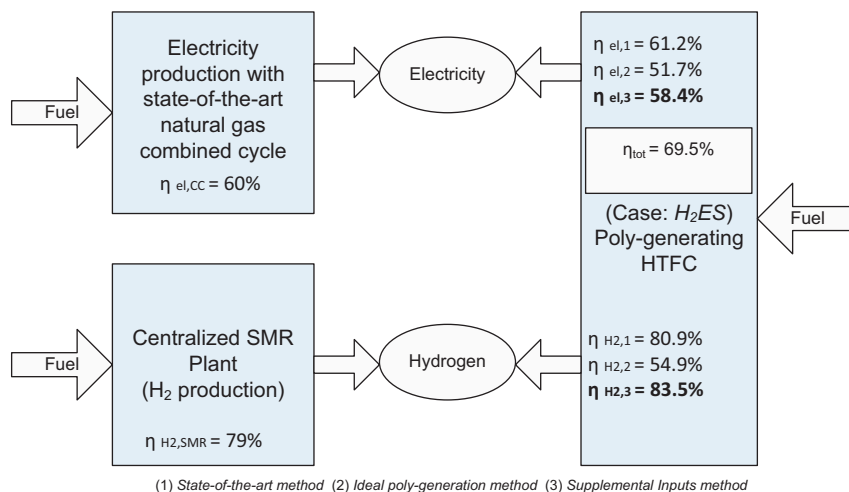


Fig. 3. Example results for the developed methodologies applied to the specific case of an H₂ES producing only electricity and hydrogen (heat not valued).

The parameters defined in Table 4 may be used in both external and internal reformation cases. However, the additional fuel feedstock used to produce hydrogen, F_{H_2} , must be defined for each configuration. The definition of F_{H_2} for internal and external reforming configurations, respectively, is

$$(U_F - U_{F,H_2ES}) \cdot E_{tot} \tag{8}$$

$$\dot{m}_{HC,in,ER} \times LHV_{HC} \tag{9}$$

where U_F is the normal fuel utilization factor of a typical co-generating HTFC and U_{F,H_2ES} is the fuel utilization factor when hydrogen is produced (i.e., H_2ES). 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

$$E_{tot} = \dot{m}_{HC,in} \times LHV_{HC} \tag{10}$$

$\dot{m}_{HC,in}$ 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, $U_F > U_{F,H_2ES}$.

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_2ES that co-produces only electricity and hydrogen (heat is not valued). The H_2ES 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_2ES 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.

Table 5 Efficiencies for each of the co-products for comparative analyses (Methods: (1) *State-of-the-art method*; (2) *Ideal method*; (3) *Supplemental Inputs Method*).

Method	Electrical efficiency	Thermal efficiency	Hydrogen efficiency	Total mixed efficiency
1	$P_{net}/(E_{tot} - (Q_{net}/\eta_{boiler}) - (H/\eta_{SMR}))$	$Q_{net}/(E_{tot} - (P_{net}/\eta_{cc}) - (H/\eta_{SMR}))$	$H/(E_{tot} - (P_{net}/\eta_{cc}) - (Q_{net}/\eta_{boiler}))$	$(P_{net} + Q_{net} + H)/E_{tot}$
2	$P_{net}/(E_{tot} - Q_{net} - H)$	$Q_{net}/(E_{tot} - P_{net} - H)$	$H/(E_{tot} - P_{net} - Q_{net})$	$(P_{net} + Q_{net} + H)/E_{tot}$
3	External Internal	$P_{net}/(E_{tot} - (Q_{e-}/\eta_{boiler}) - (F_{H_2} + (P_{PSA}/\eta_{cc})))$ $P_{net}/(E_{tot} - (Q_{e-}/\eta_{boiler}) - ((U_F - U_{F,H_2ES})E_{tot} + (P_{PSA}/\eta_{cc})))$	$Q_{net}/(Q_{net}/\eta_{boiler}) = \eta_{boiler}$	$H/((F_{H_2} + (P_{PSA}/\eta_{cc}))/((U_F - U_{F,H_2ES})E_{tot} + (P_{PSA}/\eta_{cc})))$ $(P_{net} + Q_{net} + H)/E_{tot}$

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* (H_2ES) showing that high conversion efficiency can be achieved for poly-generation of each of the co-products (electricity and hydrogen).

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