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EVALUATION OF DIFFERENT EFFICIENCY CONCEPTS OF AN INTEGRATED ENERGY SYSTEM (IES)

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ABSTRACT

The Integrated Energy System (IES) market in the United States (US) and worldwide has been increasingly expanding over the last few years. But there is still a lot of disagreement in interpretation of one of the most important IES performance parameters – efficiency. Some organizations, for example, use higher heating value (HHV) of fuel in efficiency calculations while some use lower heating value (LHV). Some accounts for auxiliary and parasitic losses while others do not. Some adhere to the "first-law" of efficiency while some use other methods, i.e., calculations recommended by the Federal Energy Regulatory Commission or the US Combined Heat & Power Association.

Different efficiency concepts based on actual performance testing from the IES Laboratory at Oak Ridge National Laboratory (ORNL) are evaluated in this paper. The equipment studied included: a 30-kW microturbine, an air-to-water heat recovery unit (HRU), a 10-ton (35 kW) hot water-fired (indirect-fired) single-effect absorption chiller, and a direct-fired desiccant dehumidification unit. Efficiencies of different configurations of the above-mentioned equipment based on various approaches are compared. In addition, IES efficiency gains due to the replacement of a 1st generation HRU (effectiveness of approximately 75%) with a 2nd generation HRU (effectiveness of approximately 92%) for the same IES arrangement are discussed.

The results showed that the difference in HHV- and LHV-based efficiencies for different IES arrangements could reach 5-8%, and that the difference in efficiency values calculated with different methods for the same arrangement could reach 27%. Therefore, it is very important to develop standard guidelines for efficiency calculations that would be acceptable and used by the majority of IES manufacturers and end-users. At the very least, every manufacturer or user should clearly indicate the basis for their efficiency calculations.

INTRODUCTION

The increased transmission line flow problems caused by deregulation of the electric energy market in the US and other developed countries have created a key opportunity for the implementation and use of distributed energy resources (DER) with and without waste heat recovery. A 2001 report prepared by the National Energy Policy (NEP) Development Group identified cooling, heating, and power (CHP), or Integrated Energy Systems (IES), as a key strategy for addressing increased energy demands and peak power issues [1]. Also, it offers a means of increasing overall energy efficiency (by combining electrical and thermal loads) as well as avoiding transmission and distribution line losses.

Recent developments in DER technologies have created new opportunities for cost effective small-scale IES for use in commercial buildings. Prime movers, such as microturbines, reciprocating engines, and fuel cells, in combination with thermally activated technologies (TAT), which use waste heat from these prime movers either for heating or thermally-driven desiccant dehumidification (direct- or indirect-fired) and absorption cooling (direct- or indirect-fired), are a major driver for making IES viable and more cost effective.

Facilities for developing and testing IES under a variety of conditions have been developed at a number of organizations. These facilities allow the interaction of the IES components to be optimized, so that their efficiency and commercial viability can be maximized. Two such facilities with complimentary programs are: the IES Laboratory at ORNL and the Integration Test Center at the University Of Maryland (UMD).

The IES market in the US and other developed countries has been expanding over the last few years. But there is still a lot of disagreement in the interpretation of efficiency and rating conditions for IES products. Examples of standard rating conditions for various components of IES products include:

- Gas turbines and microturbines, ISO 3977-2 [2]: pressure of 101.3 kPa or 1 atm, temperature of 15°C or 59°F, relative humidity of 60%.
- Reciprocating engines, ISO 15550 [3]: pressure of 100 kPa or 0.987 atm, temperature of 25°C or 77°F, relative humidity of 30%.
- Chillers, ARI 560 [4], ARI 210/240 [5], ANSI/CGA Z21.40.4 [6]: temperature of 35°C or 95°F , relative humidity of 39%.

Standardizing these conditions for CHP is currently under development and is beyond the scope of this work.

This study will focus on IES efficiency only. Usually, efficiency is used to compare how effectively units utilize energy to provide similar output. One common characteristic of efficiency definitions is that they provide a ratio of energy output per unit of energy input, so that IES units of different capacities can be readily compared. The problem is that there are many ways to define efficiency, especially when both electric and thermal energy are involved. In this study, various efficiency definitions will be discussed and compared using performance data gathered at the ORNL and UMD facilities.

The position of this paper isn't to develop new calculation methods or indices for rating IES performance metrics nor to reinvent or redefine thermodynamic processes. This is outside the scope of this study. The purpose of this paper is to show how different efficiency values related to an integrated electrical and thermal system can be produced from the same test data depending upon which calculation method is used. Although, we focus only on MTG prime movers for the IES system, the efficiency calculation can get even more complicated when different prime movers are compared. This is due to the different standard operating conditions specified for these different prime movers. By far the worst culprit to differences in efficiency values is whether LHV or HHV for the natural gas is used.

NOMENCLATURE

Acronyms:

AC = absorption chiller
DFDD = direct-fired desiccant dehumidifier
DG = distributed generation or generator
DOE = U.S. Department of Energy
HHV = higher heating value (i.e, of natural gas)
HPR = heat-to-power ratio
HRU = heat recovery unit
IES = Integrated Energy System
LHV = lower heating value (i.e, of natural gas)
MBtu = million Btu
MTG = microturbine, or microturbo generator
rb = rouble
RTU = roof top unit
TAT = thermally-activated technology

Variables:

k = normalizing factor
Q = fuel or energy input, TAT useful output
W = electric power output, parasitics
η = efficiency

Subscripts

c = AC cooling
econ = economical
el = electrical power output
fuel-sav = fuel savings
fuel-ut = fuel utilization
in = input
L = latent cooling
norm = normalized
par = electrical parasitics
th = thermal, heating
typ = typical

EXPERIMENTAL SETUP

Two IES setups are discussed in this paper. The first one, IES Laboratory, is based on a 30-kW microturbine generator (MTG). The thermally-activated technologies (TAT) consist of a 2nd generation heat recovery unit (HRU), an indirect-fired (hot water-fired) 10-ton (35 kW) single-effect absorption chiller (AC), and a direct-fired desiccant dehumidification unit (DFDD) (Figure 1) [7]. A 1st generation HRU was previously tested and upgraded based partly on the results from testing at the IES Laboratory. The efficiency improvement achieved by the 2nd generation HRU will be discussed later in this paper. There is an air duct network from the MTG exhaust to the HRU and/or to the direct-fired desiccant dehumidifier. Also, there is a water loop network from the HRU to the indirect-fired desiccant dehumidifier and absorption chiller. Finally, there is an air mixing chamber leading to the air duct network (for mixing outside air with exhaust air to lower its temperature and/or supplement its volume). The HRU, which is designed to capture the waste heat from the MTG exhaust gas, is used to produce hot water for the absorption chiller. The insulated duct system along with outside air mixing is used to provide hot air for the direct-fired dehumidification unit.

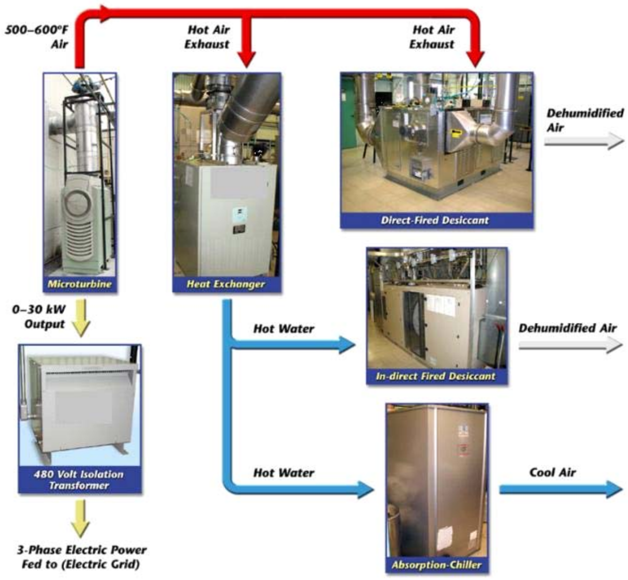

Figure 1. IES Laboratory.

The other IES setup, which is the Integration Test Center, consists of a 60-kW MTG, an exhaust-fired AC and a solid DFDD [8]. The exhaust gas from the MTG is supplied in series first to the AC and then to the DFDD. Chilled water produced in the AC and dry air from the DFDD enters the roof top unit (RTU), and the supply air is used for the building conditioning purposes (Figure 2).

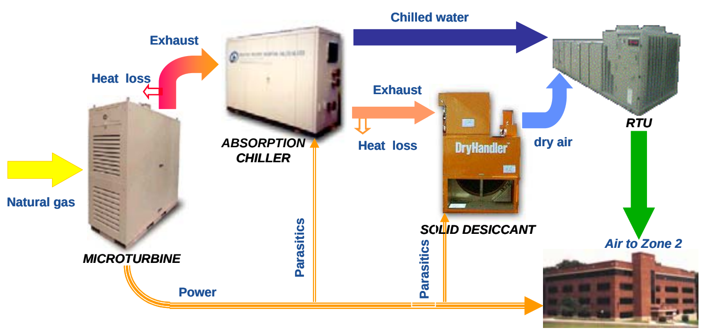

Figure 2. IES Facility at the Integration Test Center

EFFICIENCY DEFINITIONS

The various efficiency definitions considered in this study are discussed below.

Separate component efficiency is the ratio of useful energy output to fuel or thermal input of each specific IES unit. Examples for the current IES arrangements are:

MTG electrical efficiency:

$$\eta_{el} = \frac{W_{el}}{Q_{in}} \cdot 100 \qquad 1);$$

HRU thermal efficiency:

$$\eta_{th} = \frac{Q_{th}}{Q_{in-HRU}} \cdot 100 \qquad (2a),$$

or including electrical parasitics of the HRU by adding them to the heat input (gross energy input):

$$\eta_{th} = \frac{Q_{th}}{Q_{in-HRU} + W_{par}} \cdot 100 \qquad (2b),$$

or subtracting them from the useful thermal output (net energy output):

$$\eta_{th} = \frac{Q_{th} - W_{par}}{Q_{in-HRU}} \cdot 100 \qquad (2c).$$

AC cooling efficiency:

$$\eta_{c} = \frac{Q_{c}}{Q_{in-AC}} \cdot 100 \qquad (3a),$$

or including electrical parasitics of the AC by adding them to the heat input:

$$\eta_{c} = \frac{Q_{c}}{Q_{in-AC} + W_{par}} \cdot 100 \qquad (3b),$$

or subtracting them from the useful thermal output:

$$\eta_{c} = \frac{Q_{c} - W_{par}}{Q_{in-AC}} \cdot 100 \qquad (3c).$$

DFDD latent efficiency:

$$\eta_{L} = \frac{Q_{L}}{Q_{in-DFDD}} \cdot 100 \qquad (4a),$$

or including electrical parasitics of the DFDD by adding them to the heat input:

$$\eta_{L} = \frac{Q_{L}}{Q_{in-DFDD} + W_{par}} \cdot 100 \qquad (4b),$$

or subtracting them from the useful thermal output:

$$\eta_L = \frac{Q_L - W_{par}}{Q_{in-DFDD}} \cdot 100 \quad (4c).$$

These methods of efficiency interpretation don't cover the IES as a whole, although it is useful for performance evaluation of individual units.

Heat-to-power ratio is the ratio of the useful thermal output to the net electrical power output (Btu/kWh or kJ/kWh) [9, 10]:

$$\eta_{HPR} = \frac{Q_{th}}{W_{el}} \quad (5).$$

This method can be useful in evaluation of different IES operating regimes.

Overall efficiency is the most commonly used efficiency definition to date. It is the ratio of the sum of net electrical power output and total useful heating/cooling/latent output from TAT devices to the fuel input [9, 10]:

$$\eta_{overall} = \frac{W_{el} + \sum Q}{Q_{in}} \cdot 100 \quad (6a),$$

or including electrical parasitics of all TAT devices of the current IES arrangement by adding them to the heat input:

$$\eta_{overall} = \frac{W_{el} + \sum Q}{Q_{in} + \sum W_{par}} \cdot 100 \quad (6b),$$

or subtracting them from the net electrical output:

$$\eta_{overall} = \frac{(W_{el} - \sum W_{par}) + \sum Q}{Q_{in}} \cdot 100 \quad (6c).$$

It should be noted that Q_{in} could be based on HHV or LHV of fuel input such as natural gas. Therefore, care should be taken in comparing efficiency numbers from various sources because the difference could be as much as 10%. A better comparison is to be consistent in the use of LHV or HHV.

Normalized overall efficiency accounts for the relative difficulty of producing electric energy as compared to the total useful heating/cooling/latent output [11, 12]:

$$\eta_{norm} = \frac{W_{el} + \sum (Q \cdot k)}{Q_{in}} \cdot 100 \quad (7a),$$

or including electrical parasitics of all TAT devices of the current IES arrangement by adding them to the heat input:

$$\eta_{norm} = \frac{W_{el} + \sum (Q \cdot k)}{Q_{in} + \sum W_{par}} \cdot 100 \quad (7b),$$

or subtracting them from the net electrical output:

$$\eta_{norm} = \frac{(W_{el} - \sum W_{par}) + \sum (Q \cdot k)}{Q_{in}} \cdot 100 \quad (7c).$$

The heat input used in calculation of the η_{norm} could be based on the LHV or HHV of the fuel. The normalizing factor k is used to show the relative value of thermal to electrical products. FERC suggests using a normalizing factor k of 0.5 and the LHV of the fuel [12]. It should be noted that if electrical parasitics are accounted for in the calculation of the η_{norm}, the TAT unit efficiency should also account for these parasitics.

Fuel utilization efficiency is the ratio of the net electrical power output to the net fuel input [9]. The net fuel input is obtained by subtracting the fuel input that is used to produce useful heating/cooling/latent output(s), at a given TAT device efficiency(ies), from the total fuel input:

$$\eta_{fuel-ut} = \frac{W_{el}}{Q_{in} - \sum (\frac{Q}{\eta})} \cdot 100 \quad (8a),$$

or including electrical parasitics of all TAT devices of the current IES arrangement by adding them to the heat input:

$$\eta_{fuel-ut} = \frac{W_{el}}{Q_{in} + \sum W_{par} - \sum (\frac{Q}{\eta})} \cdot 100 \quad (8b),$$

or subtracting them from the net electrical output:

$$\eta_{fuel-ut} = \frac{(W_{el} - \sum W_{par})}{Q_{in} - \sum (\frac{Q}{\eta})} \cdot 100 \quad (8c).$$

Fuel energy savings efficiency reflects fuel savings associated with IES power generation as compared to the use of separate heating/cooling/latent and electric power sources [4], where η_{typ-el} is the typical average electric grid efficiency (i.e., 33% for the HHV of natural gas), and η_{typ-th} is the typical average TAT device efficiency (i.e., 80%) [12, 13]:

$$\eta_{fuel-sav} = (1 - \frac{Q_{in}}{\frac{W_{el}}{\eta_{typ-el}} + \sum(\frac{Q}{\eta_{typ-th}})}) \cdot 100 \quad (9a),$$

or including electrical parasitics of all TAT devices of the current IES arrangement by adding them to the heat input:

$$\eta_{fuel-sav} = (1 - \frac{Q_{in} + \sum W_{par}}{\frac{W_{el}}{\eta_{typ-el}} + \sum(\frac{Q}{\eta_{typ-th}})}) \cdot 100 \quad (9b),$$

or subtracting them from the net electrical output:

$$\eta_{fuel-sav} = (1 - \frac{Q_{in}}{\frac{(W_{el} - \sum W_{par})}{\eta_{typ-el}} + \sum(\frac{Q}{\eta_{typ-th}})}) \cdot 100 \quad (9c).$$

Economic efficiency is the modified version of the overall efficiency to account for economic values of fuel input ($\$_{in}$), net electrical power output ($\$_{el}$), and useful heating/cooling/latent output ($\$_{th}$) [9]:

$$\eta_{econ} = \frac{W_{el} \cdot \$_{el} + \sum(Q \cdot \$)}{Q_{in} \cdot \$_{in}} \cdot 100 \quad (10a),$$

or including electrical parasitics of all TAT devices of the current IES arrangement by adding them to the heat input:

$$\eta_{econ} = \frac{W_{el} \cdot \$_{el} + \sum(Q \cdot \$)}{Q_{in} \cdot \$_{in} + \sum(W_{par} \cdot \$_{el})} \cdot 100 \quad (10b)$$

or subtracting them from the net electrical output:

$$\eta_{econ} = \frac{[(W_{el} - \sum W_{par}) \cdot \$_{el}] + \sum(Q \cdot \$)}{Q_{in} \cdot \$_{in}} \cdot 100 \quad (10c).$$

Each value coefficient is based on the cost to generate each energy stream (i.e., total cost of electric ($) and total electric consumption (kW) to generate $/kW).

CASE STUDIES

There are three case studies considered in this section. The first case presents the comparison of various efficiency calculation methods for the IES consisting of a 30-kW MTG and HRU only. The comparisons are for the 1st and the 2nd generation HRUs, use of LHV or HHV of fuel, and inclusion or exclusion of electrical parasitics associated with the HRU operation. The second case is the system efficiency calculation for the overall IES (30-kW MTG, 2nd generation HRU, AC, and DFDD) and different combinations of these units. The third case deals with the combined performance of a building IES at full load, which integrates a 60-kW MTG, an exhaust-fired AC, and a DFDD. The detailed description of the test procedures and instrumentation involved is given in other publications [7, 8].

The basic test and price parameters used in calculation of the efficiencies for the first case are shown in Tables 1 and 2. The tests were performed at similar ambient temperature, MTG power output, HRU flowrate and thermal load. The resulting efficiency calculations are given in Table 3.

These data clearly indicate that the HRU replacement lead to an increase in overall IES efficiencies. These data also show the large difference in efficiency values that were calculated with different methods. If fuel savings and economic efficiencies are excluded from consideration, this difference could reach 26.6%. Use of the LHV of natural gas instead of HHV in calculations increases the efficiency in most cases by 6.1-7.4%. This depends on the method of calculation used. Regarding the electrical parasitics, the use of normalized, fuel utilization and fuel savings efficiencies mitigates or offsets the effect of these parasitics, if they are added to the heat input. Exclusion of the electrical parasitics from consideration in other methods of efficiency calculation (except for the economic efficiency) increases the efficiency by 0.8-1.2%. But subtraction of electrical parasitics from the net electrical power output almost always decreases the efficiencies. In some cases this may result in negative efficiency values: for example, calculation of fuel savings efficiency with electrical parasitics added to the heat input may show some benefits (2.3%), but when these parasitics are subtracted from the net electrical power output, the efficiency becomes negative (-1.2%, Table 3). Therefore, both manufacturers and end-users of the IES equipment should indicate clearly what efficiency definition they using to calculate their system performance to ensure proper interpretation of technical data and comparison of data with others.

Analysis of the economic efficiency produced some interesting results. The comparison was made for three different locations: Tennessee (USA), New York State (USA), and Moscow Region (Russia). The 2003 commercial gas and electric prices for the US locations are taken from [15], and the similar 2004 data plus price for the thermal energy in Moscow Region - from [16] (Table 2).

Table 1. Basic Test Parameters Used in Calculation of Efficiencies – Test Case No. 1

Parameters	Unit	IES with 1st generation HRU	IES with 2nd generation HRU
Ambient temperature	°F (°C)	90.8 (32.7)	89.9 (32.2)
Heat input with natural gas – HHV	Btu/h (kW)	385633.0 (113.2)	399257.1 (116.9)
Heat input with natural gas – LHV	Btu/h (kW)	347069.7 (101.6)	359331.9 (105.2)
MTG electric power output	kW (Btu/h)	21.3 (72727.1)	21.8 (74434.4)
Heat supplied to HRU	Btu/h (kW)	160408.5 (47.0)	177916.0 (52.1)
Heat recovered by HRU	Btu/h (kW)	144694.9 (42.4)	164520.5 (48.2)

Table 2. Gas, Electric, and Thermal Prices for Different Locations

Parameters	Tennessee, USA 2003	New York, USA 2003	Moscow, Russia 2004
Gas price [10, 11]	8.63 $/1000 ft^3	8.78 $/1000 ft^3	912 rb/1000 m^3
Gas price, $/MBtu*	8.11 (HHV) 9.01 (LHV)	8.25 (HHV) 9.17 (LHV)	0.85 (HHV) 0.94 (LHV)
Electric price [10, 11]	6.55 c/kWh	13.13 c/kWh	1.34 rb/kWh
Electric price, $/MBtu**	19.18	38.40	13.77
Thermal price [11]	-	-	380 rb/Gcal
Thermal price, $/MBtu	-	-	0.0034

Notes: *the HHV of natural gas is 1064.4 Btu/ft^3,
the LHV of natural gas is 958.0 Btu/ft^3.
**exchange rate 1 $ = 28.5 rb:

From the data it is evident that the economic efficiency strongly depends on the price ratio between final products and raw materials. For example, in Moscow Region, Russia, this ratio is 6.8 times higher than in Tennessee, USA. Therefore, assuming all other conditions being the same, and if the HHV of natural gas is used in calculations, the economic efficiency (electrical) of this IES in Moscow Region would be 6.8 times higher than in Tennessee. It should be noted that the economic efficiency is site specific and depends on the energy prices at the site. This is confirmed by the drastic reduction in overall economic efficiency with addition of the useful thermal output with a relatively low market price in Moscow Region. This difference in prices also contributes to increased efficiency when electrical parasitics are subtracted from the net electrical power output as compared to the case when they are added to the heat input. This is different from all other efficiency methods. Also, since natural gas price is given on volumetric basis, there is no difference in economic efficiency calculated with HHV or LHV of natural gas.

The second case includes more IES units but excludes analysis of some efficiency definitions, for example, overall economic efficiency, due to unavailability of prices for cooling or latent cooling output. Table 4 presents the test parameters used in calculation of the efficiencies; the efficiencies of individual components of the IES, as well as Heat to Power Ratio (HPR), are given in Table 5. Table 6 shows the efficiencies of different IES arrangements.

The data produced suggests that it might be beneficial to perform analysis of IES operation based on different efficiency definitions. For example, addition of a hot water-fired AC reduces $\eta_{fuel\text{-}ut}$ by 3.2% (with the inclusion of all the electrical parasitics added to the heat input), decreases the overall efficiency by 13.8%, and changes the fuel savings efficiency from positive 2.9% to negative 18.1%. But addition of DFDD using the MTG exhaust gas after HRU as the energy input significantly increases the IES efficiency. Thus as expected, it confirms that more extensive use of exhaust heat results in more efficient IES. If IES units are arranged in series (with intermediate heat recovery), then the resulting efficiency should account for all electrical parasitics, including those of intermediate units that provide energy inputs to the IES units downstream.

The results also show that the number of units included in IES and the associated value of electrical parasitics can result in significant difference between the efficiencies calculated with the two methods of either adding the electrical parasitics to the heat input or subtracting these parasitics from the net electrical output. The difference in the overall efficiency calculation increases from 0.7% for the IES consisting of MTG and HRU only to 5.2% for the IES consisting of four units: MTG, HRU, AC, and DFDD. In the case of fuel savings efficiency it is much more drastic; increasing from 3.3% (MTG + HRU) to 34.5% (total IES – MTG + HRU + AC + DFDD).

The third case that involves 60-MW MTG considers the same efficiency definitions as the previous one. The test parameters are listed in Table 7, and the efficiencies of individual IES components and different IES arrangements – in Tables 8 and 9. It should be noted that MTG+AC+DFDD arrangement in this case is similar to MTG+HRU+DFDD arrangement from the second case, using exhaust-fired AC instead of HRU (intermediate heat recovery). The basic trends in the behavior of different efficiencies are the same as in the case with 30-kW MTG, but due to higher individual efficiencies of IES units, the absolute efficiency values are higher.

Table 3. Calculated Efficiencies – Test Case No. 1.

Efficiency	IES with 1st generation HRU				IES with 2nd generation HRU			
	HHV		LHV		HHV		LHV	
	No W_{par}	W_{par}	No W_{par}	W_{par}	No W_{par}	W_{par}	No W_{par}	W_{par}
η_{el}	18.9		21.0		18.6		20.7	
η_{th}	90.2	86.5	90.2	86.5	92.5	89.2	92.5	89.2
η_{HPR}, Btu/kWh (kJ/kWh)	6777.3 (7143.3)				7547.9 (7955.5)			
$\eta_{overall}$	56.4	55.4 54.6	62.7	61.5 60.7	59.8	58.9 58.2	66.5	65.3 64.6
η_{norm} (FERC)*			41.8	41.0 39.9			43.6	42.8 41.7
$\eta_{fuel-ut}$	32.3	32.3 30.2	39.0	39.0 36.7	33.6	33.6 31.6	41.0	41.0 38.8
$\eta_{fuel-sav}$	4.0	2.3 -1.2	4.0	2.2 -1.1	7.4	5.8 2.9	7.4	5.8 2.9
$\eta_{econ-el}$ (TN 2000)	44.7				44.1			
$\eta_{econ-el}$ (NY 2000)	87.9				86.7			
$\eta_{econ-el}$ (Mos 2004)	306.0				301.8			
η_{econ} (Mos 2004)	306.2	238.1 277.6	306.2	238.1 277.6	301.9	238.0 275.1	301.9	238.0 275.1

Note: efficiency marked with "*" is based on the LHV of natural gas; the remaining ones – on the HHV of natural gas. The upper values in the columns account for electrical parasitics by their addition to the heat input and the bottom values account for electrical parasitics by their subtraction from the net electrical output.

Table 4. Basic Test Parameters Used in Calculation of Efficiencies – Test Case No. 2

Parameters	Unit	IES with 2nd generation HRU
Ambient temperature	^oF (^oC)	76.9 (24.9)
Heat input with natural gas – HHV	Btu/h (kW)	412383.9 (113.2)
MTG electric power output	kW (Btu/h)	22.8 (72727.1)
Heat supplied to HRU	Btu/h (kW)	168478.4 (49.4)
Thermal output of HRU	Btu/h (kW)	156574.8 (45.9)
Electrical parasitics of HRU	kW (Btu/h)	2.0 (6828.8)
Heat supplied to AC	Btu/h (kW)	147517.5 (43.2)
Cooling output of AC	Btu/h (kW)	103663.8 (30.4)
Electrical parasitics of AC	kW (Btu/h)	3.6 (12291.9)
Heat supplied to DFDD	Btu/h (kW)	43851.0 (12.8)
Latent output of DFDD	Btu/h (kW)	28248.8 (8.3)
Electrical parasitics of DFDD	kW (Btu/h)	6.0 (20486.5)

Table 5. Calculated Efficiencies of Individual IES Components and HPR – Test Case No. 2.

Efficiency	MTG	HRU		AC		DFDD	
		No W_{par}	W_{par}	No W_{par}	W_{par}	No W_{par}	W_{par}
η_{el}	18.9						
η_{th}		92.9	89.3 88.8				
η_c				70.3	64.8 61.9		
η_l						64.4	43.8 17.4
η_{HPR}, Btu/kWh (kJ/kWh)	6857.6 (7227.9)						

Table 6. Calculated IES Efficiencies – Test Case No. 2.

Efficiency	MTG+HRU		MTG+HRU+AC		MTG+HRU+DFDD		Total IES	
	No W_{par}	W_{par}	No W_{par}	W_{par}	No W_{par}	W_{par}	No W_{par}	W_{par}
$\eta_{overall}$	56.9	55.9 55.2	44.0	42.1 39.3	63.7	59.7 57.0	50.9	46.4 41.2
η_{norm} (FERC)*	42.1	41.3 40.2	35.0	33.2 29.7	45.9	42.7 38.5	38.8	35.0 32.4
$\eta_{fuel-ut}$	31.9	31.9 30.1	29.4	28.7 23.9	38.9	38.9 29.3	35.2	34.2 25.3
$\eta_{fuel-sav}$	4.5	2.9 -0.4	-12.8	-18.1 -34.3	11.7	5.8 -7.5	-2.8	-12.8 -47.3

Note: efficiency marked with "*" is based on the LHV of natural gas; the remaining ones – on the HHV of natural gas. The upper values in the columns account for electrical parasitics by their addition to the heat input and the bottom values account for electrical parasitics by their subtraction from the net electrical output.

Table 7. Basic Test Parameters Used in Calculation of Efficiencies – Test Case No. 3

Parameters	Unit	IES with 60kW microturbine
Ambient temperature	^oF (^oC)	73.0 (22.8)
Heat input with natural gas – HHV	Btu/h (kW)	718938 (210.7)
MTG electric power output	kW (Btu/h)	52.1 (177772)
Exhaust heat consumed by AC	Btu/h (kW)	271606 (79.6)
Cooling output of AC	Btu/h (kW)	206434 (60.5)
Electrical parasitics of AC	kW (Btu/h)	6.4 (21838)
Exhaust heat supplied to DFDD	Btu/h (kW)	124202 (36.4)
Latent output of DFDD	Btu/h (kW)	88819 (26.0)
Electrical parasitics of DFDD	kW (Btu/h)	8.1 (27638)

Table 8. Calculated Efficiencies of Individual IES Components – Test Case No. 3.

Efficiency	MTG	AC		DFDD	
		No W_{par}	W_{par}	No W_{par}	W_{par}
η_{el}	24.79				
η_c		76.0	70.4 67.9		
η_l				71.5	58.5 49.3

Table 9. Calculated Efficiencies of Individual IES Components – Test Case No. 3.

Efficiency	MTG+AC		Total IES (MTG+AC+DFDD)	
	No W_{par}	W_{par}	No W_{par}	W_{par}
$\eta_{overall}$	53.4	51.9 50.4	65.8	61.6 58.9
η_{norm} (FERC)*	43.4	42.0 40.1	50.3	46.7 42.6
$\eta_{fuel-ut}$	39.7	39.7 37.6	55.0	55.0 46.9
$\eta_{fuel-sav}$	9.8	7.0 1.6	20.8	15.3 3.7

Note: efficiency marked with "*" is based on the LHV of natural gas; the remaining ones – on the HHV of natural gas. The upper values in the columns account for electrical parasitics by their addition to the heat input and the bottom values account for electrical parasitics by their subtraction from the net electrical output.

CONCLUSIONS

This study shows that the definition of efficiency can make quite a difference in its value. The results showed that the difference in HHV- and LHV-based efficiencies for different IES arrangement could reach 6.1-7.4%, and that the difference in efficiency values calculated with different methods for the same arrangement could reach 26.6%. The use of lower heating value provides an optimistic view of performance. HHV should be adopted in these calculations as the price of the natural gas is based on HHV.

For the short-term, both IES equipment manufacturers and end-users should be clearly aware of the efficiency definition used. In the long-term, it is very important to develop standard guidelines for efficiency calculations that would be acceptable and used by the majority of IES manufacturers and end-users. These guidelines are currently under development and are based on HHV of fuel.

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