Translating cycle performance to system-level efficiency for sorption heat pumps

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Abstract

For sorption heat pumps, a gap often exists between metrics of efficiency provided in the literature (typically COP) and system-level performance expressed according to various national minimum energy performance standards and labeling schemes. Engineers and decision makers would benefit from a convenient, even if approximate, translation between the two. Focusing on fuel-fired heat pump systems, this work bridges the gap through a straightforward analytical model relating cycle COP to system performance, while incorporating practical system-level parameters. These parameters include burner efficiency, electrical power consumption, standby losses, cyclic losses, and flue gas heat exchanger effectiveness. Separate translations are provided for water heating and space heating for single and double effect water/LiBr and ammonia/water. The EES&L metric is generally 15-35% lower than the cycle COP. For metrics that are based on primary energy, the electrical consumption of the fuel-fired heat pump is of high importance. The burner efficiency is important in all cases.

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1. Introduction

Energy efficiency standards and labeling (EES&L) schemes define numerous widely varying metrics in various countries and for various product categories [1]. Despite the transnational nature of communication that occurs within research communities studying energy efficient technologies, the EES&L metrics used in researchers' local jurisdictions vary widely. Policy makers and the public tend to think in terms of local EES&L metrics, and may not understand the metrics used by research community, or the EES&L metrics in use in other jurisdictions. Meanwhile, researchers tend to understand the technology-specific metrics, such as the ubiquitous COP (coefficient of performance), and would benefit from a convenient translation to EES&L metrics. This work provides a template, with some examples, of translating technology-specific cycle efficiency into EES&L defined metrics of performance.

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Due to the complexity of many EES&L metric definitions, a simplified treatment is conducted in this work.

2. Efficiency metrics

EES&L metrics used in local jurisdictions vary widely. This work provides a template, with some examples, of translation of technology-specific cycle efficiency into EES&L defined metrics of performance.

Only a handful of examples are chosen in this paper, to illustrate the method of translation. Only an approximation is sought after, in order to give the proper magnitude of the metric. Determining a precise value of an EES&L metric would typically require physical testing of a fully packaged system, and will nevertheless vary with individual implementations of a particular technology. Thus the somewhat imprecise approach taken in this work is expected to be as accurate as possible, without having a particular physical implementation available for full testing.

2.1. Water heating

Water heating standards tend to be based on either a steady-state characterization (especially for on-demand systems) or a load profile-based characterization (especially for tank storage products). In this paper, the UEF for residential storage type water heaters is used.

2.2. Space heating

Space heating standards tend to be based on steady state evaluations, often at various temperature condition bins, which are then combined to a single metric using weighted average. In this paper, the AFUE (for natural gas furnaces), HSPF (for electric space heating heat pumps) and ηs (for electric space heating heat pumps) are used. These are not expected to be directly applicable to fuel-fired sorption equipment; however an approximate translation is provided.

3. Generic system definition

Figure 1 depicts a Sankey diagram for a generic thermally-driven heat pump. In this figure, η_{grid} is grid efficiency, η_b is burner efficiency, η_{ph} is the fraction of fuel energy captured by a secondary heat exchanger ("post heater") that is located in the flue gas stream after the main flue gas heat exchanger, COP is the thermal coefficient of performance of the heat pump, ECOP is the electrical coefficient of performance (useful heat produced per unit electricity consumed), and λ is a term to capture system-related losses involved with standby losses and cyclic operation.

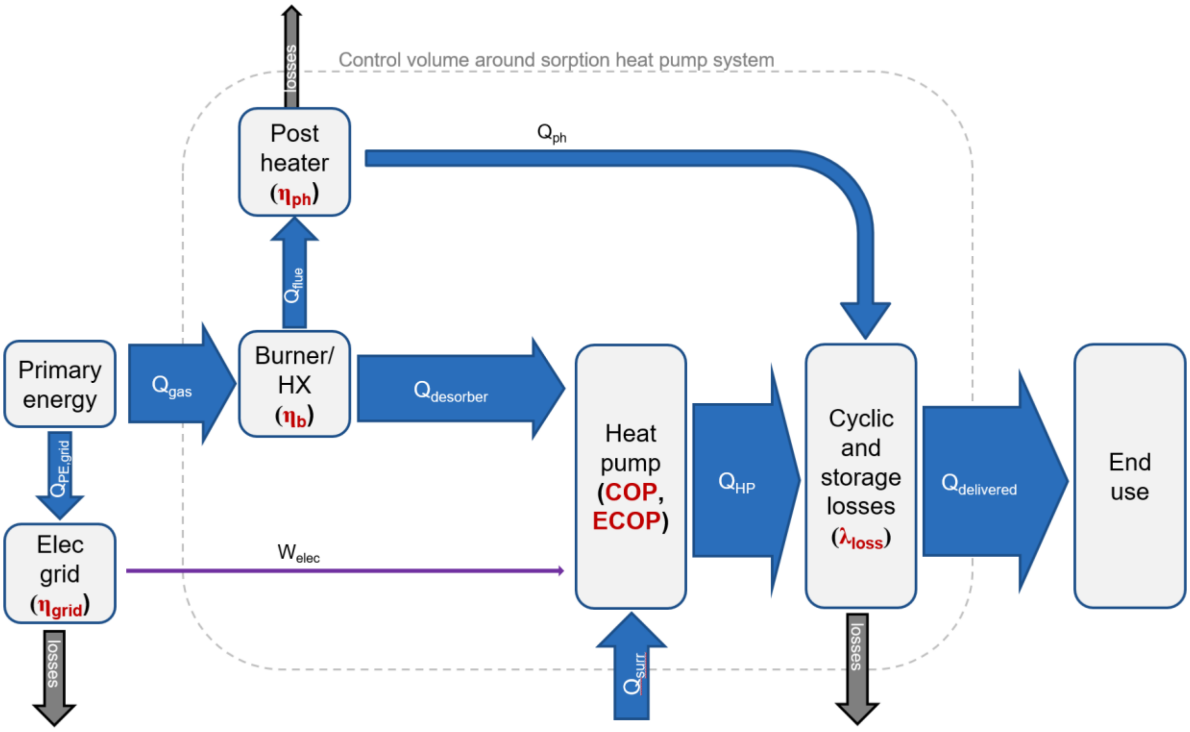

Fig. 1. Sankey diagram for a generic gas-driven heat pump serving a heating load. Components are labeled in black text, component performance parameters in red text, and energy flows in white text.

An expression for the efficiency of a generic sorption heat pump can be derived based on the Sankey diagram shown in Figure 1. As described in [2], this yields Equation (1) when η_{prim} is defined in terms of primary energy consumed per unit energy delivered; Equation (2) when η_{site} is defined as the site (or final) energy consumed per unit energy delivered, and Equation (3) when η_{fuel} is defined as the fuel energy consumed per unit energy delivered.

$$\frac{1}{\eta_{prim}} = \frac{1}{\lambda}\left(\frac{1}{\eta_b COP + \eta_{ph}} + \frac{1}{\eta_{grid} ECOP}\right) \tag{1}$$

$$\frac{1}{\eta_{site}} = \frac{1}{\lambda}\left(\frac{1}{\eta_b COP + \eta_{ph}} + \frac{1}{ECOP}\right) \tag{2}$$

$$\frac{1}{\eta_{fuel}} = \frac{1}{\lambda}\left(\frac{1}{\eta_b COP + \eta_{ph}}\right) \tag{3}$$

These three Equations (1)-(3) provide the building blocks to translate cycle efficiency (COP) into the various EES&L metrics used to describe system performance.

4. Formulation of EES&L metrics in terms of COP

In order to formulate an expression for an EES&L metric in terms of COP, one must begin with the definition of the EES&L metric. As shown in Table 1, these can be categorized based on whether they are single- or multi-point evaluations (with weighting factors provided in Table 2), and whether steady-state or transient in nature. They can also be categorized by treatment of gas energy (calorific value) and electrical energy, whether on primary basis, site basis, or neglected.

In cases where standby and cyclic losses are accounted for in the EES&L metric, those effects are realized in the term λ.

Table 1. Treatment of energy by selected metrics

Product category	Metric	Units	Conditions	Gas heating value	Electrical energy (η_{grid})	Sink fluid in	Sink fluid out	Source dry bulb temperature
Water heater	UEF [4]	Energy/ energy	Transient load profile	Gross	Site basis	14.4°C (water)	51.7°C	19.7°C
Space heating furnace	AFUE [5]	Energy/ energy	Steady state	Gross	Ignored*	18.3°C+ (air)	Typically† 37.8 to 54.4°C	Not specified**
Space heating heat pump	HSPF [6]	Energy [Btu]/ energy [Wh]	Steady state, bin-method	N/A‡	Site basis	21.1°C (air)	Typically† 32.2 to 40.6°C	+8.3, +1.7, and -8.3°C
Space heating heat pump	η_s [7]	Energy/ energy	Steady state, bin-method	Gross	Primary (0.4)	47°C (water)	55°C	+14, +7, +2°C
Space heating heat pump	η_s [7]	Energy/ energy	Steady state, bin-method	Gross	Primary (0.4)	30°C (water)	35°C	+14, +7, +2°C

*a fan efficiency rating (FER) is reported separately

†air supply temperature is based on manufacturer specifications for each individual product

‡not specified in [6], which is intended for electrical products. For this paper, gross heating value is used.

**+10°C is used as a placeholder value to allow calculation in this paper

Table 2. Weighting factors for selected bin-based metrics

Product category	Standard	
Space heating heat pump	AHRI 210/240	(See [8], Table 19, Region IV column)
Space heating heat pump	EU 811/2013	+14°C: 0.228 +7°C: 0.3°2 +2°C: 0.420

Many metrics, such as the UEF as defined in the US for gas-fired storage type water heaters, can be readily accommodated since they correspond directly to one of the Equations (1)-(3). The UEF is simply the energy efficiency on a site energy-basis, as shown in Equation (2), or in other words, UEF=η_{site}. This is expressed in more detail in Equation (4), in which the COP has been written as $COP|_{T_{UEF}}$, since it must be evaluated under the temperature conditions specified in the UEF test procedure. In addition, the evaluation of this energy efficiency proceeds according to a prescribed load profile and test conditions. Thus it requires some engineering knowledge of the test procedure to make a reasonable estimate of terms such as λ in this case.

Table 2 summarizes the temperatures for each EES&L metric.

$$\frac{1}{UEF} = \frac{1}{\eta_{site}} = \frac{1}{\lambda}\left(\frac{1}{\eta_b COP|_{T_{UEF}} + \eta_{ph}} + \frac{1}{ECOP}\right) \tag{4}$$

The AFUE, since it was designed for a device that does not directly interact with the outdoor ambient, is not able to be evaluated for a heat pump product. If one postulates an outdoor temperature, then a number can be calculated. Here we postulate 10°C to allow an approximate evaluation of an AFUE-equivalent for gas heat pumps, according to Equation (5).

$$\frac{1}{AFUE} = \frac{1}{\eta_{fuel}} = \frac{1}{\lambda}\left(\frac{1}{\eta_b COP|_{T_{AFUE}} + \eta_{ph}}\right) \tag{5}$$

Although the HSPF was intended for electrically driven heat pumps, its temperature levels and bin-method can be used to propose an HSPF equivalent for gas heat pumps. Since a bin-method is used in calculating HSPF, it is expressed as a summation of terms that are multiplied by a weighting factor, W_i, as in Equation (6). Note that the HSPF definition actually includes degradation coefficients, defrost effects, auxiliary backup energy consumption, and other considerations not included in Equation (6). Nevertheless, Equation (6) is meant as an approximation of HSPF. To have suitable accuracy as written, the COP term would need to account for defrost and any auxiliary heater usage, and the λ term would need to account for the remaining effects.

$$\frac{1}{HSPF} = \sum_i \frac{1}{\eta_{site,i}} W_i = \sum_i \frac{1}{\lambda}\left(\frac{1}{\eta_b COP|_{T_i} + \eta_{ph}} + \frac{1}{ECOP}\right) W_i \quad (6)$$

Next, the seasonal space heating energy efficiency η_s can be approximated by Equation (7).

$$\frac{1}{\eta_s} = \sum_i \frac{1}{\eta_{prim,i}} W_i = \sum_i \frac{1}{\lambda}\left(\frac{1}{\eta_b COP|_{T_i} + \eta_{ph}} + \frac{1}{\eta_{grid} ECOP}\right) W_i \quad (7)$$

5. COP curves for selected technologies

In order to evaluate an expression, it is necessary to know the COP at the temperature(s) specifies in the test procedure relevant to a particular metric, in addition to values of system-level parameters such as burner efficiency and ECOP. Since COP varies strongly with temperature, and can be known with a fairly high degree of certainty knowing only the working fluid, it is addressed in this section. The treatment of system-level parameters is handles in the next section.

Based on simulations in SorpSim [3] and Engineering Equation Solver (EES), curves were generated for selected technologies at the temperatures of interest shown in Table 1.

Models of a single-effect and a double-effect absorption heat pump using LiBr/water working pair were built in SorpSim based on templates of typical system design of these two cycle configurations. Fluid temperatures were set according to Table 1 for state points of interest including the heated water outlets after the absorber and condenser, as well as the air inlet at the evaporator. The heat input temperatures were also set at the desorber to be sufficient to drive the cycle. The COP for each system was calculated as the ratio of heat rejection in the absorber and condenser against the heat input at the desorber.

Models of a single-effect ammonia/water absorption heat pump, as well as a Generator-Absorber-eXchanger (GAX) cycle were built in EES based on example cases introduced in [9]. Temperature approaches were assumed to model the heat transfer between external flows and the working fluid flow in the loop. For heated water streams in the condenser, absorber, and rectifier, the working fluid stream leaving the component was set at 2°C higher than the heated water outlet temperature. For source air streams in the evaporator and those heating components in space heating applications, the working fluid stream leaving the component was set at 7°C below the air temperature. The COP for each system was calculated as the ratio of heat rejection in absorber, condenser, and rectifier(s) against the heat input at the desorber.

Note that below 5°C, the water-based system must rely entirely on auxiliary backup heat.

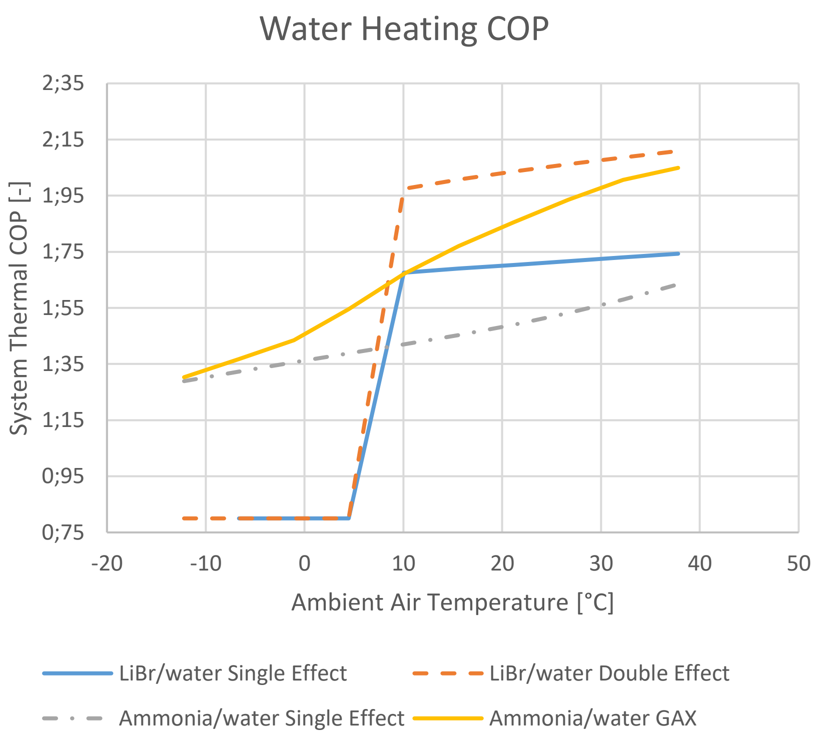

Fig. 2. COP curves of LiBr/water and ammonia/water absorption heat pumps at operation condition of water heating

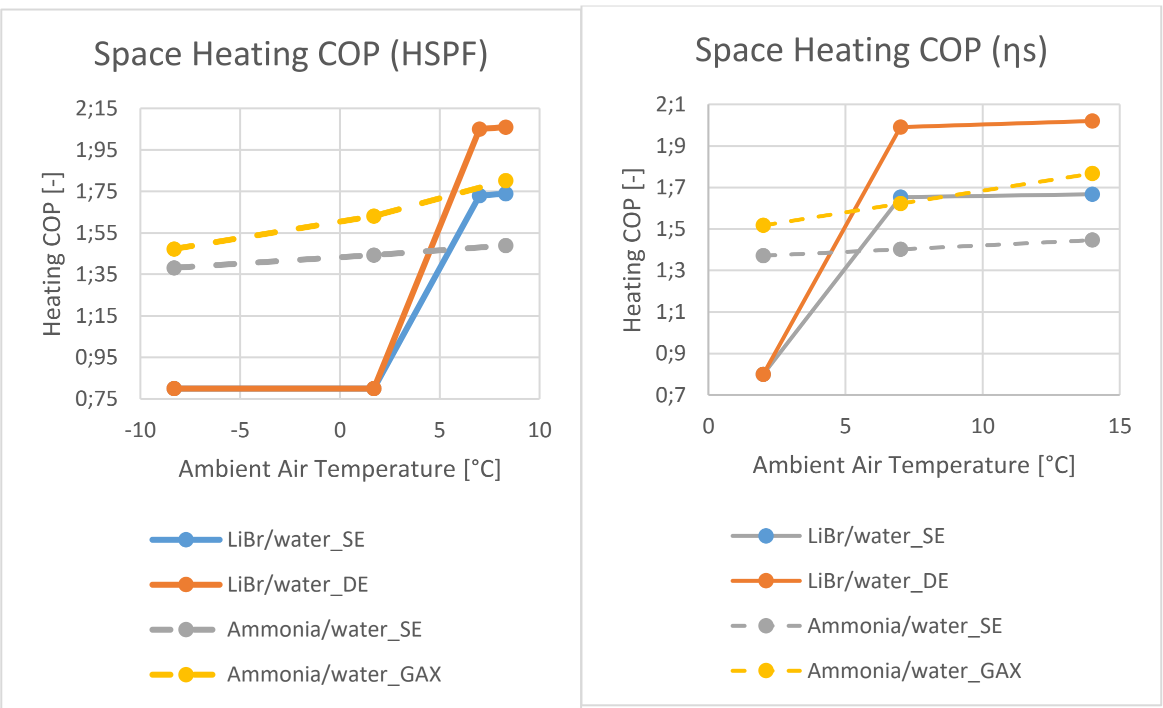

Fig. 3. COP curves of LiBr/water and ammonia/water absorption heat pumps at operation condition of space heating

6. Evaluation of EES&L metrics based on COP curves for selected technologies

Finally, selected EES&L metrics are combined to evaluate the values of the EES&L metrics. Evaluation required making assumptions about the various system parameters as well as COP. The feasible ranges of system parameters are shown in Table 3.

Table 3. Values of parameters used to evaluate selected metrics

Parameter	Parameter description	Feasible range	Value used in Table 4	Notes
η_b	Burner efficiency	0.75 – 0.98	0.8	Below 0.82 represents non-condensing; above 0.90 is condensing
η_{grid}	Grid efficiency	0.3 – 0.4	0.3: UEF, AFUE, HSPF 0.4: η_s	Depends on local grid primary energy factor
η_{ph}	Post-heater efficiency	0 – 0.24	0.12	If η_b is low, leftover flue heat can be transferred to process water. The sum $\eta_b + \eta_{ph}$ is always less than 1.
λ	Loss factor	0.7 – 1.0	0.82: UEF 0.95: AFUE, HSPF, η_s	For steady state metrics, this includes steady state losses from the system. For transient metrics, it also accounts for cyclic degradation.
COP	Cycle COP	1.2 – 2.0	According to technology curve	See technology-specific curves as a function of temperature in this section
ECOP	Electrical COP	10 – 50	25	Depends on fans, pumps, combustion blower

Table 4. Approximate evaluations of selected metrics for selected technologies

Product category	Standard		SE water/LiBr	DE water/LiBr	SE ammonia/water	GAX ammonia/water
Water heater	US 10 CFR 430 B	UEF =	1.15	1.34	1.02	1.22
Space heating furnace	ANSI/ASHRAE 103	AFUE =	1.17	1.36	1.02	1.17
Space heating heat pump	AHRI 210/240	HSPF =	0.96	1.05	1.04	1.23
Space heating heat pump, except low temp	EU 811/2013	η_s =	1.19	1.39	1.05	1.17
Space heating heat pump, low temperature	EU 811/2013	η_s =	1.71	2.11	1.65	2.14

Compared with the values presented in Table 4, developments in individual technologies could influence the values. Nevertheless, Table 4 provides reference values against which such developments can be compared.

7. Conclusions

A simplified and approximate method is presented to translate COP results into energy efficiency metrics commonly used in minimum efficiency standards and labeling. Examples are provided for single and double effect water/LiBr, and single effect and GAX ammonia/water, for space heating and water heating. The EES&L metrics are generally 15-35% lower than the cycle COP, and are most sensitive to burner efficiency. For primary energy-based EES&L metrics, the electrical efficiency is also a critical parameter to translating cycle COP into system-level performance.

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Nomenclature

η_b	the amount of cumulative energy flowing out of the burner (to the desorber) divided by the cumulative energy flowing in.
η_{ph}	the fraction of remaining flue gas heat that is transferred directly to the process water.
η_{grid}	the primary energy factor of grid electricity production.
η_s	seasonal space heating energy efficiency
λ_{loss}	the fraction of energy that is lost to surroundings by cyclic and standby losses
AFUE	average fuel utilization efficiency
COP	the cycle thermal coefficient of performance of the heat pump: the ratio of useful heat energy produced, per unit heat energy received from the burner/HX.
ECOP	the ratio of useful heat energy produced, divided by the electrical energy consumed by the heat pump (to run fan(s), pump(s), and controls).
EES&L	energy efficiency standards and labeling
PH	post heater, a heat exchanger which heats process fluid using flue gas heat leftover by the main burner
Q_{amb}	heat transferred from ambient to heat pump
$Q_{delivered}$	heat delivered to end use
$Q_{desorber}$	heat transferred to desorber of heat pump
Q_{HP}	useful heat produced by heat pump
Q_{flue}	heat remaining in flue gas after extraction for use by the desorber
Q_{gas}	chemical energy in fuel delivered to burner
$Q_{PE,grid}$	primary energy consumed by grid to produce electricity consumed by the heat pump
Q_{ph}	heat delivered by post-heater to process fluid
UEF	uniform energy factor

Subscripts

amb	ambient
b	burner
ph	post-heater

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