WHAT IS THE EFFICIENCY OF A BIOREFINERY?

Fredrik Lind,
Stefan Heyne,
Filip Johnsson,
Department of Energy and Environment, Chalmers University of Technology*

* Division of Energy Technology (F. Lind, F. Johnsson), Heat and Power Technology (S. Heyne)
Reviewers: Staffan Jacobsson, Björn Sandén, Environmental Systems Analysis; Fredrik Hedenus, Physical Resource Theory, Simon Harvey, Heat and Power Technology; Energy and Environment, Chalmers.

6

INTRODUCTION

The thermal efficiency is a key characteristic of thermal processes, defining how much of the fuel input that is converted to desired energy services and products. The thermal efficiency is closely related to the cost, in both economic and environmental terms, of generating a specific energy service. Development of energy efficient systems has been a prerequisite of industrialisation and economic growth. A modern state of the art 1000 MW coal fired power plant may have a thermal efficiency of some 47% whereas the first Newcomen steam engine that set in motion the industrial revolution 300 years ago had an efficiency of less than 1%. Given the limited availability of biomass (Chapter 4), energy efficiency is now a key issue also for bioenergy based systems.

However, care has to be taken when comparing thermal efficiencies between processes since different assessments may have used different definitions of thermal efficiency and applied different system boundaries. This chapter concerns biorefinery processes for which the efficiency concept is associated with the additional difficulty of comparing different energy services and products. Biorefineries typically produce a variety of products such as fuels, heat, electricity, chemicals and materials (see e.g. Chapters 3 and 5). Consequently, different markets and users may value the output according to different standards. As an example, combined heat and power (CHP) may cause confusion since the thermal efficiency is often defined by adding the two energy services heat (for district heating) and electricity and dividing these with the fuel input to obtain the thermal efficiency of the CHP plant in spite of that such a ratio is not very informative (some would say incorrect) from a thermodynamics point of view. Yet, for a local heat market such efficiency gives important information on the extent to which the fuel is efficiently converted to heat and electricity. Furthermore, in a municipal energy system with district heating CHP units one typically considers heat to be the main product while the electricity is produced as a co-product that increases the income of the local utility. There are also examples of heat produced as a byproduct from a large power plant where the electricity is the main product. In the latter case, the relevant efficiency for the plant owner would instead be the electric efficiency.

In summary, it is difficult to define a standard expression for evaluating efficiencies for biomass conversion processes, especially for biorefineries producing several products and energy services. Thus, when evaluating and comparing different processes it should always be clear how the thermal efficiency is defined. If the definition is not clear, there is a risk that a process may be perceived as more favourable than it is, or the opposite. The aim of this chapter is to illustrate how the concept of thermal efficiency can be used to evaluate biorefinery processes and highlight risks of comparing efficiencies from different sources. Some commonly used definitions are illustrated and their advantages and drawbacks are discussed. Several examples are used to emphasize the importance of transparency and of clearly defining performance measures and system boundaries.

MEASURES OF ENERGY INPUT

A general expression for thermal efficiency is given in Eq. 1. As is clear from the introduction such a general expression can be given different meaning depending on context. In the following we will elaborate on different ways to quantify thermal efficiency.

(1)

$$\eta_{th}=\frac{\text{Useful energy services and products}}{\text{Fuel input}}$$

In this section we will start with the denominator in Eq.1 and discuss what can be meant by "fuel input". Biomass is a heterogeneous fuel (compared to natural gas, coal and oil) and may therefore vary substantially in composition and water content. Thus, it is important to consistently define its energy and water content.

The *moisture fraction* (f_M) of the fuel ($kg_{water}/ kg_{wet\ fuel}$) is defined in Eq. 2, where mdry is the mass of the dry part of the fuel (dry matter) and m_{wet} is the total mass of the wet fuel.

(2)

$$f_M=\frac{m_{water}}{m_{wet}}=\frac{m_{wet}-m_{dry}}{m_{wet}}=1-\frac{m_{dry}}{m_{wet}}$$

The heating value defines the chemically bound energy within a certain fuel (J/kg_{fuel}). The heating value is calculated from the heat release of the fuel when the fuel is reacting completely with oxygen and the products are returned to the initial temperature before heating (e.g. 25 °C). The value is given as *Higher Heating Value* (*HHV* also called higher calorific value) where the water is condensed or as *Lower Heating Value (LHV)* where the water is not condensed. The water that can be condensed comes partly from the water in the fuel (moisture) and partly from the reaction between hydrogen in the fuel and oxygen.

The heating value of a fuel can be specified for the dry matter of the fuel and for the wet fuel including moisture. While the former is a constant for a given fuel (LHV_{DM} and HHV_{DM}), the latter depends on the moisture fraction ($LHV(f_M)$ and $HHV(f_M)$). The former is simply the latter with a zero moisture fraction. In addition, depending on the process to be described the heating value of a wet fuel can be given specific to the dry fuel mass (index "dry" below) or the wet fuel mass (index "wet"). For example, during a drying process the mass of dry fuel will remain unchanged while the total (= wet) mass will change. It may therefore be more convenient in that case to define the heating value on a dry basis. It is important when stating efficiencies to clearly indicate what heating value has been used as well as the moisture content of the fuel it has been calculated for.

The *HHV* on a dry basis (HHV_{dry}) does not change with increasing moisture content but is always equal to *HHV*DM since the energy that is required to vaporize the moisture equalizes the energy that is later gained from the condensation (see definition above). The *HHV* on a wet basis (*HHV*wet) declines linearly with increasing moisture fraction since the mass fraction of the combustible part of the wet fuel decreases.

(3)

$$HHV_{wet}\,(f_M)=(1-f_M)\cdot HHV_{DM}$$

The calculation of the lower heating values is somewhat more complicated. First, the energy that is not recovered from condensation of the water from the reaction between hydrogen and oxygen (Q_H) needs to be deduced from the *HHV*, second the energy required for vaporization of the moisture content (Q_M) needs to be deduced.

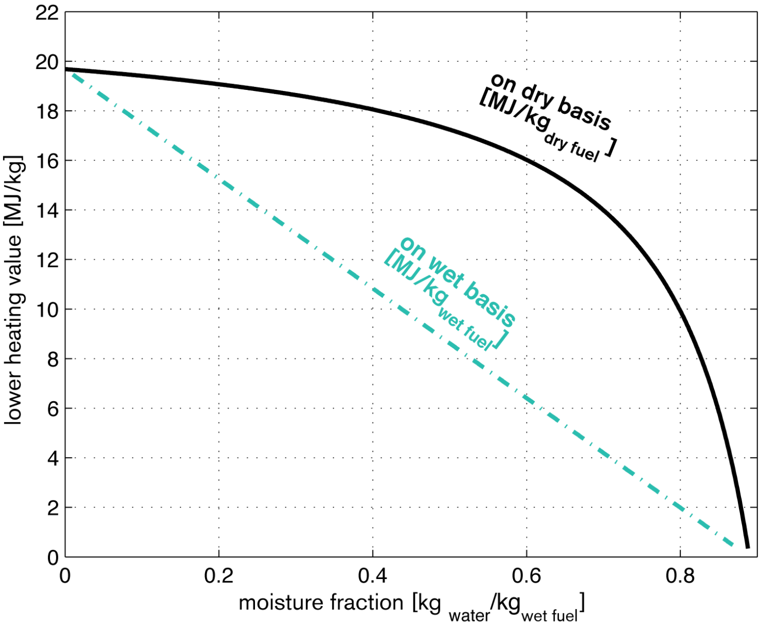

Figure 6.1 Lower heating value as a function of fuel moisture content

The *LHV* of a given fuel as a function of moisture fraction can then be expressed either on dry fuel basis (MJ/kg$_{\text{dry fuel}}$).

(4)

$$LHV_{dry}\ (f_M)=HHV_{DM}\text{-}Q_H\ \text{-}Q_M=$$

$$=HHV_{DM}\text{-}H_{evap}\left(w_H\cdot\frac{M_{water}}{M_H}+\frac{f_M}{1\text{-}f_M}\right)$$

or on wet fuel basis

(5)

$$LHV_{wet}\ (f_M)=LHV_{dry}\cdot\frac{m_{dry}}{m_{wet}}=LHV_{dry}\cdot(1\text{-}f_M)$$

where H_{evap} is the latent heat of vaporization of water at 25 °C (2440 kJ/kg$_{\text{Water}}$), w_H is the mass fraction of hydrogen in the dry fuel and Mwater and MH is the molar mass for water (0.018 kg/mol$_{\text{water}}$) and hydrogen (0.002 kg/mol$_{\text{hydrogen}}$), respectively.

The moisture fraction of fresh wood-chips typically ranges from 40 to 60 %. This means that only half of the fuel is combustible. Thus, part of the energy content should provide the energy needed to heat and evaporate the free and bound water in the fuel. Figure 6.1 plots the *LHV* of stem-wood with a typical *HHV*$_{\text{DM}}$ of 21 MJ/kg$_{\text{dry}}$[1] as a function of moisture fraction. It can be seen that the *LHV* on dry basis can be increased by 22% if the fuel is dried from f_M of around 0.7 to 0.5. But if the fuel is further dried from f_M of 0.5 to 0.2 the increase in *LHV* is only around 9%. For biomass combustion processes it is usually advantageous to dry fuels to around 40-50% moisture content.

In Sweden it is common to use the *LHV* to rank fuels. An argument for this is that it is not always feasible to make use of the energy that potentially could be gained from condensing the water vapour. However, in other countries it is common to use the *HHV*. Since both *LHV* and *HHV* are used it is obviously important to clearly state which one that is used when the energy content in the fuel is specified (i.e. not only using the term “heating value”).

---

[1] Strömberg, B. (2005). Bränslehandboken, Värmeforsk, Stockholm.

THE THERMAL EFFICIENCY OF A BIOMASS CHP

When interpreting a figure of the thermal efficiency of a biomass fuelled process it must be clear if it is based on the *HHV* or the *LHV*. In the following example, a biomass fired CHP plant is used to illustrate how the thermal efficiency differs depending on which heating value is used to define the energy content in the fuel.

The thermal efficiency of a stand-alone biomass fired power plant, which produces only electricity (as opposed to a CHP plant), is in the order of 35-40%. This can be compared to a biomass boiler for heat production, e.g. hot water for industrial use or for district heating, where the thermal efficiency is in the order of 95%.[2] If we instead define the efficiency of a CHP plant which can be seen as a "biorefinery" in that two products are produced (see Chapter 2 for alternative definitions), namely heat and electricity, we can illustrate both the influence of the choice of heating value (*LHV* or *HHV*) and the effect of combining two different products.

Figure 6.2 gives a simplified process scheme for a biomass CHP-plant. The process consists of a boiler with a convection part (including a flue gas condenser) for steam production, a back pressure steam turbine, an electricity generator and a heat exchanger for distributing the produced heat to the district heating system. Here, the efficiencies in Fig. 6.2 are calculated according to Eqs 6-8, were ηB is the efficiency of the boiler.

(6)

$$\eta_B = \frac{\text{Heat to process}}{\text{Fuel to boiler}}$$

The efficiency for electricity production is calculated according to Eq. 6, where η_M is losses due to mechanical friction e.g. in bearings, which is typically a few percent, implying that η_M is in the range of 0.98-0.99. The η_G is coupled to losses in the generator and is usually in the range of 0.96-0.98. The turbine efficiency η_T is here put to 0.25 which is a typical value for combined heat and power operation.

(7)

$$\eta_{El} = \eta_M \cdot \eta_G \cdot \eta_T \cdot \eta_B$$

The total thermal efficiency η_{Tot} when both heat and power production is combined is then calculated according to Eq. (7)

(8)

$$\eta_{Tot} = \eta_{El} + \eta_Q$$

where η_Q is the efficiency of heat transfer to the district heating system.

In this example, the boiler is fired with wood chips that contain 50% moisture (f_M). The mass fraction of hydrogen wH is 6% and the HHV_{DM} of the fuel is 21 MJ/kg. The total thermal efficiency when both electricity and heat is included is 87% (η_{El} = 22%, η_Q = 65%) based on the *HHV*. What would the total thermal efficiency of the plant be if the efficiency is based on the *LHV* instead of the *HHV*?

The *LHV* of the wet fuel is obtained by combining Eqs. 4 and 5:

$$LHV_{wet} = \left(HHV_{DM} - H_{evap} \left(w_H \cdot \frac{M_{water}}{M_{hydrogen}} + \frac{Mf}{1-Mf} \right) \right) \cdot (1-f_M) =$$

$$= \left(21 - 2.44 \left(0.06 \cdot \frac{0.018}{0.002} + \frac{0.5}{1-0.5} \right) \right) \cdot 0.5 = 8.62 \left[{}^{MJ}\!/_{kg_{wet}} \right]$$

Using Eq. 3 and the energy efficiency based on *HHV* to derive the energy output in the numerator, the total efficiency of the plant based on the *LHV* of the wet fuel can then be calculated:

$$\eta_{total,LHV} = \frac{\eta_{total,HHV} \cdot HHV_{wet}}{LHV_{wet}} = \frac{0.87 \cdot 21 \cdot 0.5}{8.62} = 1.06$$

---

[2] Note that we here discuss efficiency in energy terms and do not take into account the quality of the energy. Exergy is a concept that captures the difference in quality between chemical energy in the biomass and electricity (high exergy content) and heat (low exergy content). Hence, the conversion of bioenergy to heat only would have an exergy efficiency at the same level as that for electricity production or lower, depending on the temperature of the heat. w_H

Thus, for the CHP unit the total thermal efficiency becomes 106% based on the *LHV* of the wet fuel. The question is how can we reach an efficiency above 100%? This can be explained from the definition of *LHV* and the fact that this plant is equipped with a flue gas condenser as indicated in Figure 6.2 (convective part + condenser). The heat of vaporization is not included in the definition of *LHV*, but in this plant the heat of vaporization from the condensing water in the flue gases is used. In fact, from a theoretically point of view for the *LHV*, the efficiency of this plant will increase with increased moisture content in the fuel as shown in Figure 6.3. However, the ratio between produced heat and electricity it is not shown in Figure 6.3.

What actually occurs is that the combustion temperature decreases as the moisture content in the fuel increases. A consequence of this is that less high-grade steam is produced resulting in less electricity and more heat. This is shown in Fig. 6.4. The decrease in electricity production corresponds to the increase in heat production as more water is fed into the boiler.

THERMAL EFFICIENCY OF A BIOREFINERY PROCESS

The above example shows that thermal efficiency of a CHP plant, that produces the two products heat and electricity, is crucially dependent on the exact measures used. Hence, it is of great importance to specify how the thermal efficiency is calculated. This also provides an illustration of the difficulty of defining a standard measure of conversion efficiency, especially for biorefineries that produce several products and energy services at the same time (see also discussions on multiple outputs in Chapters 3 and 5, and on system expansion and allocation of emissions between products in Chapter 7).

Figure 6.5 shows a general representation of input and output of a biorefinery process. There may be several biomass fuels used within the process and several products and services may be produced at the same time. For example, electricity and heat might be co-generated from a process having a biofuel as main product. In the thermal energy efficiency definitions proposed in the following, it is assumed that the biorefinery

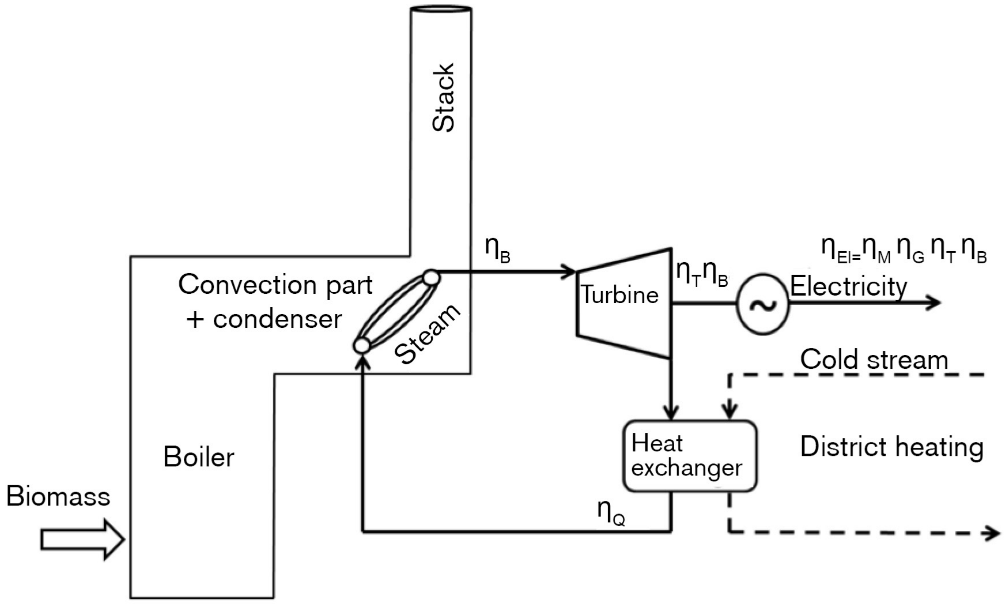

Figure 6.2 Biomass fired combined heat and power plant

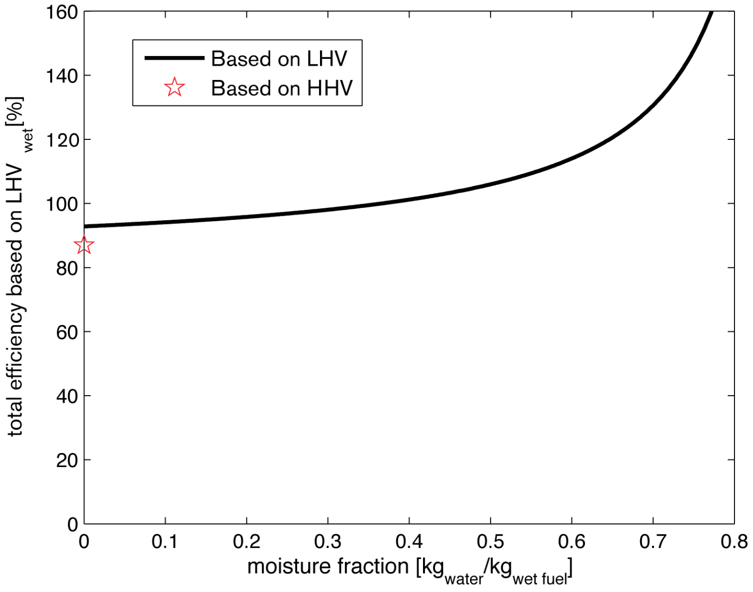

Figure 6.3 Total efficiency of CHP-plant, based on the LHV on wet basis

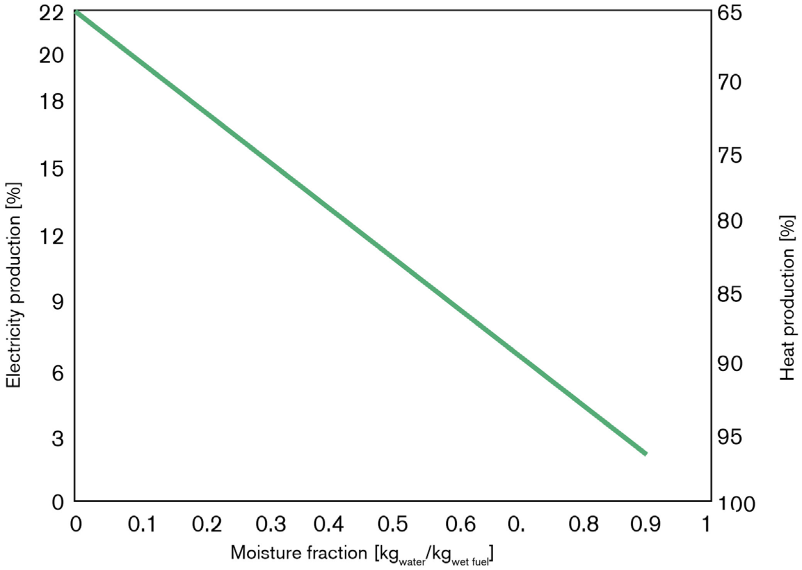

Figure 6.4 Electricity and heat production as a function of the moisture fraction in the fuel

process is supplied with one or several fuels and that it produces one main product (product 1 in Figure 6.5) and possibly several by-products. Depending on the process, electricity and heat are inputs or outputs.

The evaluation of the thermal efficiency of a biorefinery process can be done in various ways. It is difficult to point out an efficiency definition that is superior and applicable to all kinds of biorefinery concepts and processes. The aim of this section is to illustrate several alternatives for the thermodynamic process evaluation and to, once more, stress the importance of clearly defining the way the evaluation is done. Different definitions for the thermal efficiency aim at illustrating different process aspects, but care has to be taken when different measures are compared. In order to be able to recalculate one efficiency number into another one must know the underlying assumptions and the definitions used. Unfortunately, published information on efficiency figures often lacks this clarity, making it very hard to compare results from different sources.

The most general form of the thermal efficiency is provided in Eq. 1. For a biorefinery process this equation can be expressed more explicitly as:

(9)

$$\eta_{th}=\frac{\sum_i \dot{Q}_{prod,i} + (P_{el}^{-}-P_{el}^{+})+(\dot{Q}^{-}-\dot{Q}^{+})}{\sum_j \dot{Q}_{biomass,j} + (P_{el}^{+}-P_{el}^{-})+(\dot{Q}^{+}-\dot{Q}^{-})}$$

where and are the energy values of the resulting product(s) and biomass input(s), respectively. Pel represents the electricity and the useful heat (often in the form of e.g. district heating) that either is exported (superscript “–“) or imported (superscript “+”). For electricity and heat only net flows are accounted for, meaning that the terms only can appear either in the numerator or the denominator. The thermal efficiency rates all energy services at the same level, not taking into account their quality (see footnote 4). A certain amount of energy available as excess heat from the process () is valued equally to the corresponding amount of electricity export () or product energy (). This reveals the ambiguities with the thermal efficiency use that have been illustrated in the example of the CHP plant above (see also Chapter 8 on the value of excess heat).

For biorefinery concepts producing biofuels (e.g. ethanol, bio-diesel, dimethyl ester (DME) or synthetic natural gas (SNG)) another commonly used form of thermal energy efficiency definition is the biomass-to-fuel thermal efficiency (for

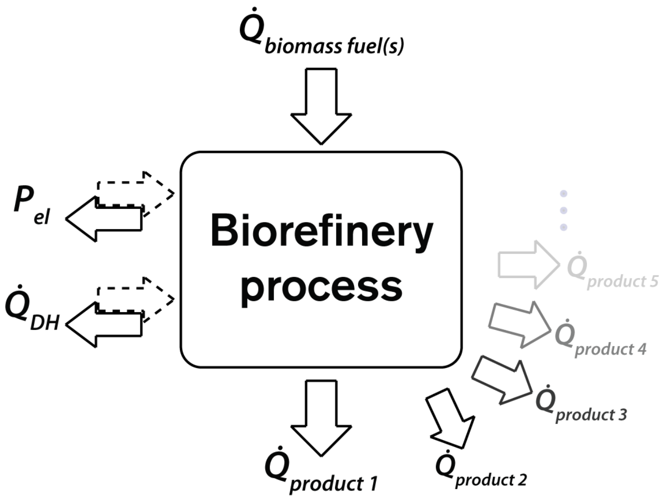

Figure 6.5 Energy input and output of a biorefinery process

gasification-based processes sometimes also referred to as cold gas efficiency) comparing the energy input in form of biomass only to the energetic value of the produced biofuel. This gives a good indication on how much of the biomass energy that is conserved in the final product, but may of course be misleading in case there is a significant input of electric energy to the process, since this is not accounted for. The biomass-to-fuel thermal efficiency hbtf can be defined as:

(10)

$$\eta_{btf} = \frac{\dot{Q}_{prod}}{\sum_j \dot{Q}_{biomass,j}}$$

SYSTEM THERMAL EFFICIENCY

The definitions in the previous section provide estimates of the thermal efficiency of a process as such, but they leave out crucial aspects linked to the evaluation from an overall system perspective. If a process, for example, is a net user of electricity it is important to have an idea about how the imported electricity is produced and how this influences the overall thermodynamic performance. In order to be able to account for such facts, it is necessary to expand the system and take the surrounding energy system into account as illustrated in Fig. 6.6.

Taking into account the surrounding energy system, it is possible to recalculate all energy services supplied and consumed by a process to primary energy using the corresponding reference conversion technology (see also the discussion on reference system in Chapter 7).

The overall system efficiency hsys of a biorefinery process defined in Eq. 11 compares all primary energy inputs into the process to the energetic value of the all outputs. This represents an adaptation of the thermal efficiency definition in Eq. 7.

(11)

$$\eta_{sys} = \frac{\sum_i \dot{Q}_{prod,i} + \frac{P_{el}^{-} - P_{el}^{+}}{\eta_{el,bg}} + \frac{\dot{Q}^{-} - \dot{Q}^{+}}{\eta_{q,bg}}}{\sum_j \dot{Q}_{biomass,j} + \frac{P_{el}^{+} - P_{el}^{-}}{\eta_{el,bg}} + \frac{\dot{Q}^{+} - \dot{Q}^{-}}{\eta_{q,bg}}}$$

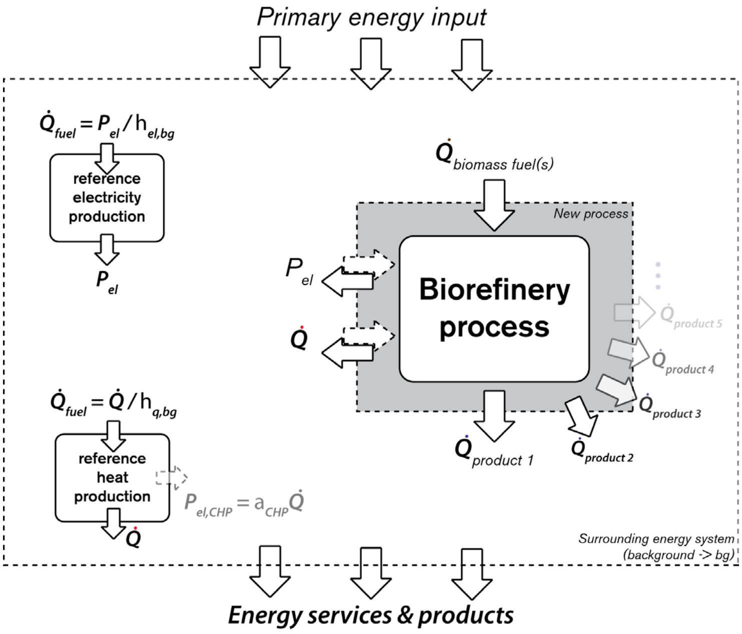

Figure 6.6 Schematic illustration of system boundary and energy flows involved in a biorefinery process.

Only net flows are considered, meaning that only heat and electricity import or export is accounted for. The efficiencies for electricity and heat production, $\eta_{el,bg}$ and $\eta_{q,bg}$, in the surrounding energy system need to be specified. If heat is a useful product that should be accounted for again depends on the surrounding energy system, i.e. on the availability of a district heating network or any other heat demanding process such as drying that actually can act as a sink for the available excess heat from the process (see Chapter 8 on the value of heat).

An adaption of Eq. 8 to the system level is possible by accounting for all fuel inputs that is necessary for the production of the main product of the biorefinery (product 1) – that is the biofuel in this case. The by-products (product 2,3...n) are in this case accounted for as a reduction of primary energy input, i.e. their energy values are deduced from the energy input. Electricity and heat input (and) are converted to primary energy input based on the reference technology for the system under consideration.

(12)

$$\eta_{btf}=\frac{\dot{Q}_{prod,1}}{\sum_j \dot{Q}_{biomass,j}-\sum_{i=2}^{n} \dot{Q}_{prod,i}+\frac{P_{el}^{+}}{\eta_{el,bg}}+\frac{\dot{Q}^{+}}{\eta_{q,bg}}}$$

This definition gives an idea about how much energy is needed for the biofuel production. However, co-generation of power and heat are not accounted for. However, this can (and should) be done. Taking into account the decrease in use of primary energy at the system level in case electricity is co-generated within the process, a fuel system thermal efficiency $\eta_{sys,fuel}$ can be defined according to:

(13)

$$\eta_{sys,fuel}=\frac{\dot{Q}_{prod,1}}{\sum_j \dot{Q}_{biomass,j}-\sum_{i=2}^{n} \dot{Q}_{prod,i}+\frac{P_{el}^{+}-P_{el}^{-}}{\eta_{el,bg}}+\frac{\dot{Q}^{+}-\dot{Q}^{-}}{\eta_{q,bg}}}$$

It needs to be stated that heat export () should only be accounted for if there actually is some suitable heat sink available.

SOME ILLUSTRATIVE EXAMPLES

To illustrate the difference between the efficiency definitions and the importance of clearly stating the underlying assumptions when presenting efficiencies, a number of biofuel conversion processes are evaluated (compare the processes presented Chapter 2). The examples are taken from a report available in Swedish.[3]

The different process alternatives evaluated are: wood pellet production; lignin pellet production; torrefied wood pellet production; pyrolysis oil production; ethanol production via hydrolysis followed by fermentation of the sugars; methane production via hydrolysis and fermentation ; methane production via gasification; DME (dimethyl ether) production via gasification and methanol production via gasification.

The evaluation is based on the *LHV* on a dry-mass basis and a biomass moisture-fraction of 0.5 (LHVDM = 18.6 MJ/kgdry) corresponding to average values for wood fuel. The reference technologies in the assumed reference (or background) energy system (according to Figure 6.5) have an efficiency of □el,bg = 0.4 and $\eta_{q,bg} = 0.9$ for power and heat production, respectively. (See Chapter 7 for an illustration of what might happen when reference system parameters are changed.)

In Figures 6.7 to 6.9 the above listed processes are characterized by means of the different efficiency definitions presented in Eqs. 9-11 and 13.

A number of observations can be made from these figures. First, the pellet processes stand out as most efficient regardless of which efficiency definition that is used. In a sense, it is true that the energy conservation is most efficient for these processes but it has to be taken into account that the product resulting from the processes basically still is a solid biofuel not much different from the biomass input.

---

[3] Thunman, H. et al. (2008). Inventering av framtidens el- och värmeproduktionstekniker, Elforsk, Stockholm. For details about the production pathways and technologies the reader is referred to this report. In the report, overall energy balances are set up for the different process alternatives and in some cases for varying plant sizes.

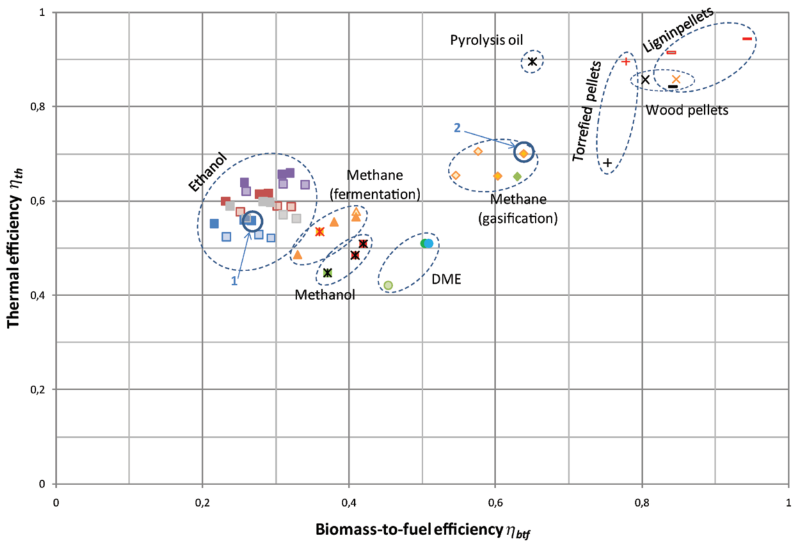

Figure 6.7 Overall thermal efficiency (Eq. 9) of the biofuel process alternatives versus biomass-to-fuel efficiency (Eq. 10). Both heat and electricity are accounted for as useful by-products.

A second interesting aspect is to compare the thermal efficiency figures for the ethanol process alternatives. Both the overall system efficiency hsys and fuel system efficiency $\eta_{sys,fuel}$ rank the process alternatives with combined heat and power production (filled squares in Figures 6.8 to 6.9) higher than the stand-alone ethanol processes (semi-transparent squares). The simple definition of the thermal efficiency η_{th} cannot account for the differences as can be seen in Fig. 6.7.

Finally, when comparing methane production via gasification and ethanol production one can observe that the overall system efficiency hsys points out the ethanol process as performing equally well as or even better than the methane process, while the fuel system thermal efficiency $\eta_{sys,fuel}$ gives results in favour of methane production. To explain the difference, two cases are depicted for a more detailed investigation of the influence of efficiency definition.

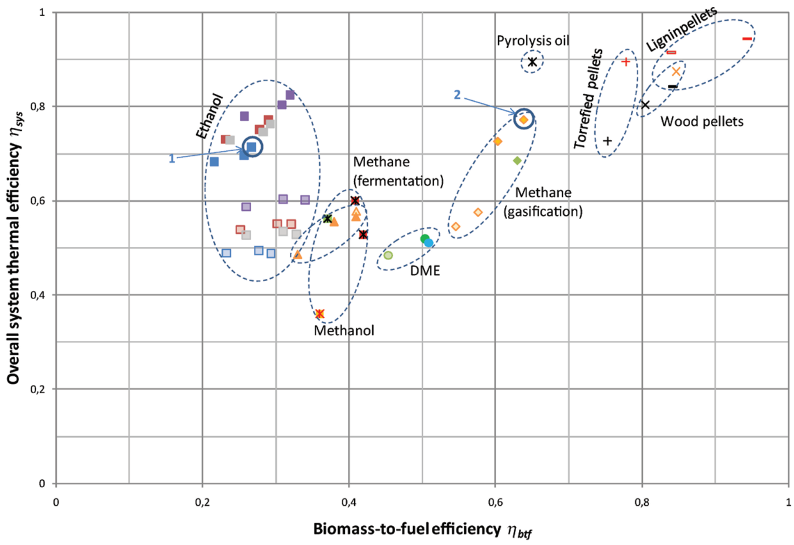

Figure 6.8 Overall system thermal efficiency (Eq. 11) of the biofuel process alternatives versus biomass-to-fuel efficiency (Eq. 10). Only electricity is accounted for as useful by-product while excess heat is not accounted for as useful product.

In Case 1, *methane is produced via gasification* with methane being the only fuel product. In order to make use of the large amounts of excess heat available from gas cooling and fuel synthesis a CHP steam cycle is used to co-generate both electricity and heat. The process is a net exporter of heat and electricity.

In Case 2, *ethanol via hydrolysis* is the main product, but considerable amounts of by-products (lignin and sugars) are generated as well. The process has a large heat demand (mainly for ethanol distillation). This heat demand is covered by a CHP steam cycle that needs extra fuel input. The size of the CHP plant is adjusted to cover the ethanol processes heat demand, resulting in a large production of electricity but no net heat export from the overall process.

The overall energy efficiencies are highlighted for the two cases in Figures 6.7-6.9 with the corresponding number. The energy flows of the two processes are illustrated in Figure 7.10. Table 6.1 provides the energy figures as well as calculated efficiencies. What process is considered being the more efficient one depends on whether the biofuel yield or overall energy efficiency is in focus. The methane production process (case 1) has a substantially higher yield of biofuel compared to the ethanol process (case 2) resulting in better figures for ηbtf and ηsys,fuel. When looking at all energy services provided (hsys) the picture changes drastically with both processes performing about equally well and the ethanol process even having the potential to outperform the methane process (when energy by-product 2 (sugars) are accounted for hsys becomes 0.79). So again, simply stating efficiency numbers without clear definition may therefore result in misleading conclusions on the process performance.

Table 6.1 Energy performance analysis of the two process examples of methane and ethanol production.

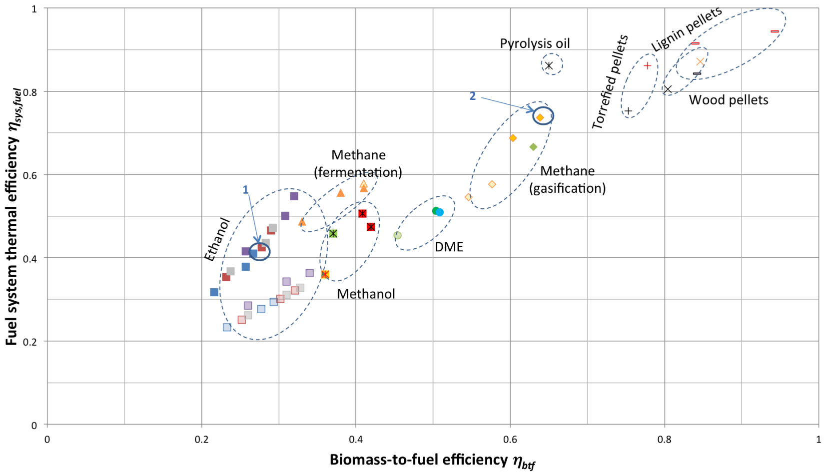

Figure 6.9 Fuel system thermal efficiency (Eq. 13) of the biofuel process alternatives versus biomass-to-fuel efficiency (Eq. 10). Only electricity is accounted for as by-product.

Table 6.1 Energy performance analysis of the two process examples of methane and ethanol production.

Property	Variable	Units	Case 1 (methane)	Case 2 (ethanol)
Primary fuel supply	$\dot{Q}_{fuel,1}$	kW	1000	1000
Secondary fuel supply	$\dot{Q}_{fuel,2}$	kW	0	708
Process electricity demand	P_{el}^{+}	kW	43	35
Process electricity co-generation	P_{el}^{-}	kW	96	212
Process heat demand	Q^{+}	kW	20	460
Useful process excess heat	Q^{-}	kW	29	460
Energy value main product	$\dot{Q}_{prod,1}$	kW	638	340
Energy value by-product 1	$\dot{Q}_{prod,2}$	kW	0	440
Energy value by-product 2	$\dot{Q}_{prod,3}$	kW	0	(120)*
Thermal efficiency (eq. (9))	η_{th}	-	0.700	0.560
Biomass-to-fuel efficiency (eq. (12))	η_{btf}	-	0.638	0.268
Fuel system thermal efficiency (eq. (13))	$\eta_{sys,fuel}$	-	0.735	0.412
Overall system thermal efficiency (eq. (11))	η_{sys}	-	0.771	0.716
Overall system thermal efficiency (heat export possible)	η_{sys}	-	0.781	0.716

* not accounted for in efficiency calculation

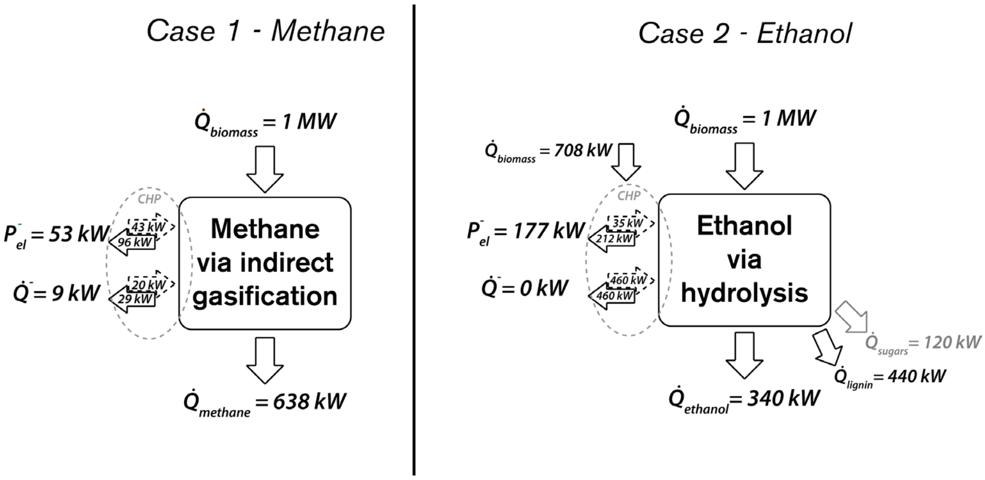

Figure 6.10 Overall energy balance for two biorefinery cases (heat losses during conversion not specifically shown)

CONCLUDING REMARKS

Due to the nature of biorefinery processes having a large spectrum of possible products it is hard to define a common thermal energy definition that can be applied to all processes. The aim of this chapter is to illustrate the difficulties in judging published efficiency figures and point out important factors that affect efficiency calculations. There are certain aspects that apply to all thermal energy efficiency definitions. First, it is of utmost importance to be clear about the underlying assumptions in the definition. What heating value is the efficiency based on? What services and products are accounted for? Are all forms of energy equally valued or is there any recalculating done using conversion factors? If numbers from different studies are to be compared, the underlying assumptions need to be harmonized. Thermal efficiencies that are stated without a clear description of assumptions and definitions are not too seldom used in a way which favours a certain process and should be taken with care.

When trying to classify the introduced efficiency definitions it can be stated that the simple thermal efficiency η_{th} does not give sufficient information on the process performance within an energy system as all energy services and products are valued equally in this definition. The overall system efficiency hsys gives a good idea on how efficient all primary energy input to the process is converted to products and services. This is generally a good indication of the process performance as it indicates how well primary energy input is converted into useful products. A drawback is the necessity to specify the surrounding energy system and conversion efficiencies of several processes. Varying the assumptions about the surrounding energy system may result in quite different numbers for the overall system efficiency hsys. When the production of a single product is in focus the fuel system efficiency $\eta_{sys,fuel}$ is a good choice, indicating how much primary energy is required for producing a specific fuel.

Finally, there are of course more dimensions to biomass conversion efficiency than energy efficiency, which is the focus of this chapter. As the biorefinery concept is closely related to sustainability issues, one could name the economic, environmental and social dimensions of sustainability and, not at least, the climate benefit of different types of biomass production system associated with the biomass fuel used in the biorefinery. While conversion efficiency is linked to environmental and economic aspects, the environmental and economic dimension of sustainability involves a great deal more.