

Well-to-Wheel Studies, Heating Values, and the Energy Conservation Principle

Ulf Bossel
European Fuel Cell Forum
Morgenacherstrasse 2F
CH-5452 Oberrohrdorf / Switzerland
forum@efcf.com, www.efcf.com
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It has become standard practice to assess different options of energy conversion technologies with respect to overall energetic efficiency and emission of greenhouse gases by following the flow of energy from its source to its final use. Such studies are known as “Well-to-Wheel” or “Source-to-Service” analyses. They are useful and necessary. Optimal energy paths can be identified and selected to formulate energy strategies and energy policies. However, such analyses are helpful only if based on the fundamental laws of physics. Also, the results of similar studies can only be compared as long as a common base is used for input parameters, numerical procedures, technology standards and user behavior.

In the simplest case, different energy conversion technologies are compared, all using the same fuel from different sources and supplied via different routes. The analysis is reduced to a comparison of energetic efficiencies according to the first law of thermodynamics (energy conservation principle) and to a summation of greenhouse gas emissions at various stages of the energy chain. As long as the same source fuel is used (e.g. natural gas, heating oil, gasoline, hydrogen), the results are informative and meaningful. Different gasoline engines, different gas furnaces, or coal fired steam power plants from different manufactures may be compared with other products of the same category. Also, for energy equipment using the same fuel, the comparison may be based on either the Higher Heating Value HHV or the Lower Heating Value LHV.

However, a meaningful well-to-wheel analysis involving different chemical energy carriers must be based on the true energy content or the Higher Heating Value HHV of all fuels considered, not on the Lower Heating Value LHV. The one and only proper and physically exact reference would be the Heat of Formation of the respective energy carrier. The values are tabulated for all chemical substances and reactions. By definition, the Heat of Formation includes all sensible and latent energetic changes of a chemical reaction between the initial state at 25°C and the final state, also at 25°C. For energy engineering applications oxidation reactions with air are of prime importance. Therefore, engineers prefer the term “Higher Heating Value” HHV. Its definition is derived from the Heat of Formation, but it represents the heat released by oxidation of a fuel with air. Values are tabulated for fossil fuels from different sources as well as synthetic chemical substances like carbon monoxide or hydrogen. Examples are “natural gas from the North Sea, Russia, or The

Netherlands, or different types of coal from various countries: lignite, anthracite or coke from USA, South Africa, or Germany, gasoline [8].

Again, the Higher Heating Value HHV is experimentally determined by concealing a stoichiometric mixture of fuel and oxidizer (e.g. two moles of hydrogen and one mole of oxygen) in a steel container at 25°C. Then the exothermic reaction is initiated by an ignition device and the chemical reaction of the components is completed. If hydrogen and oxygen are combined, water vapor emerges at high temperatures. Subsequently, the vessel and its content are cooled down to the original 25°C and the "Heat of Formation" (or the "Higher Heating Value" HHV) is determined by measuring the heat released between identical initial and final temperatures.

In contrast, when the LHV is determined, the cooling is stopped at 150°C and the reaction heat is only partially recovered in the case of the "Lower Heating Value" LHV. The limit of 150°C, although a practical number on our temperature scale, is a totally arbitrary choice. Why not 200°C, or 300°F? The Lower Heating Value LHV is nothing but a practical number. It is not based on energy conservation, one of the fundamental laws of physics, but on convenience and the consent of a standardizing committee.

As a historic reminder, the Lower Heating Value LHV was created in the late 1800s when it became obvious that condensation of water vapor or sulfur oxide in smoke stacks lead to corrosion and destruction of exhaust systems. As it was technically impossible to condense flue gases of sulfur-rich coal, the heat below 150° was considered of no practical use and therefore excluded from energy considerations.

Recent applications in the area of Fuel Cells add further complications to the use of Lower Heating Values in energy studies. The energy content of fuels may be changed by endothermic or exothermic heat exchange during reforming reactions, by reaction of fuel compounds with nitrogen, etc. Waste heat may be transferred to the fuel to drive an endothermic reaction. Exothermic heat from partial oxidation reformers may provide useful heat. A true energy balance can only be established on the basis of the Heat of Formation or the Higher Heating Value HHV of the original. Lower Heating Values fails to provide correct answers.

The difference between the two heating values depends on the chemical composition of the fuel. In the case of pure carbon or carbon dioxide, both heating values are almost identical, the difference being the "sensible" heat content of CO₂ between 150°C and 25°C ("sensible heat" exchange causes a change of temperature. In contrast, "latent heat" is added or subtracted for phase changes at constant temperature. Examples: heat of vaporization or heat of fusion). For hydrogen the difference is much more significant as it includes the sensible heat of water vapor between 150°C and 100°C, the latent heat of condensation at 100°C and the sensible heat of the condensed water between

100°C and 25°C. All in all, the Higher Heating Value HHV of hydrogen is 18.2% above its Lower Heating Value LHV or in absolute numbers, 142 MJ/kg vs. 120 MJ/kg for the two cases. For hydrocarbons the difference depends on the hydrogen content of the fuel. For gasoline and diesel the HHV exceeds the LHV by about 110% or 107%, for natural gas about 112%, respectively.

The dependence of efficiencies on the choice of heating values is illustrated in the following tables.

Table A. Heating values for selected fuels [8]

Fuel	HHV (MJ/kg)	LHV (MJ/kg)	HHV/LHV	LHV/HHV
Coal 1)	34.1	33.3	1.024	0.977
CO	10.9	10.9	1.000	1.000
Methane	55.5	50.1	1.108	0.903
Natural gas 2)	42.5	38.1	1.115	0.896
Propane	48.9	45.8	1.068	0.937
Gasoline 3)	46.7	42.5	1.099	0.910
Diesel 4)	45.9	43.0	1.067	0.937
Hydrogen	141.9	120.1	1.182	0.846

- 1) Anthracite, average
- 2) Groningen (The Netherlands)
- 3) Average gas station fuels
- 4) Average gas station fuels

Table B. Reported LHV efficiencies and real HHV efficiencies based on the fundamental law of physics, the Energy Conservation Principle

Technology	Fuel	Reported LHV efficiency (convention)	Real HHV efficiency (physics)
Power plant	coal 1)	50%	48.9%
	natural gas 2)	60%	53.8%
Condensation boiler	natural gas 2)	105%	94.1%
IC engine car	gasoline 3)	25%	22.8%
	Diesel 4)	35%	32.8%
Fuel cell car	hydrogen	40%	33.8%

The results show that the LHV efficiencies of common power conversion technologies differ from the physically exact HHV efficiencies. However, the difference is most significant for pure hydrogen or hydrogen-rich fuels. This should be considered in the ongoing energy debate.

Also, in energy literature and found in the brochures of advanced technical equipment one can find LHV efficiencies above 100%. This certainly irritates any knowledgeable person with some experience in physics. In fact, it may be misleading, because energy efficiencies above 100% violate all laws of nature. The true HHV efficiency remains below 100% as it should according to the energy conservation principle. This by itself should be reason enough to depart

from the use of the Lower Heating Value LHV and base all energy engineering on the real HHV energy content of fuels.

For the synthetic energy carrier hydrogen the use of the Lower Heating Value is bordering on dishonesty. At minimum, the heat of formation or the Higher Heating Value HHV must be invested to produce hydrogen by electrolysis. It is certainly incorrect, mildly said, to base energy efficiency on the Lower Heating Value LHV as energy corresponding to the Higher Heating Value HHV was used to produce the synthetic energy carrier. One could also claim that the consumers are cheated by 18.2%.

But even for accepted efficiencies below 100% only the Higher Heating Value HHV can provide a fair base of comparison if different fuels are considered. A LHV efficiency of 50% corresponds to a true 50% HHV efficiency for carbon or carbon monoxide, to 45.5% for gasoline, to 44.8% for natural gas, and to only 42.3% for hydrogen. The efficiency of a hydrogen Fuel Cell looks much better if it is based on LHV standards rather than on the physically correct Higher Heating Value HHV.

Most well-to-wheel studies are based on the Lower Heating Value LHV. Many fuel options are compared with each other: liquid or gaseous hydrocarbons, coal and hydrogen. All results reflect the choice of energy reference. Hydrogen is more affected by the choice of heating values than hydrocarbons. On average, hydrogen looks about 10% better than liquid hydrocarbon fuels. The results of most published well-to-wheel studies -- only a few of a long list shall be referenced here [1, 2, 3, 4] -- are fail to correctly represent the true energy content of the considered fuel options. In fact, the results are biased towards hydrogen-rich fuels with the highest efficiency gains for hydrogen.

There are even attempts to justify the use of the Lower Heating Value LHV by philosophical arguments. In the study "Twenty Hydrogen Myths" by a renowned private research organization [1] the following remarks can be found: "This article expresses hydrogen's energy content at its Lower Heating Value (LHV), 120 MJ/kg, as is appropriate for low-temperature Fuel Cells. Hydrogen used in a condensing boiler or furnace can yield 18% more energy (the Higher Heating Value HHV, 142 MJ/kg) because the difference -- the latent heat of vaporizing the resulting water into steam -- can also be recovered." Energy assessment standards are tailored to suit the application. Energy losses are eliminated by philosophical arguments, not by improved technology. Laws of physics are twisted to obtain attractive results. One could also argue that hydrogen Fuel Cells operate below 150°C in a temperature range in which, according to the choice of our forefathers, hydrogen has no "useful" energy left at all.

The inappropriate choice of heating values has certainly lead to embellished results and may be one of the reasons why hydrogen has gained so much attention among environmentalists and political groups. With minimum effort the existing computer programs could be re-run with Higher Heating Values HHV to put the comparative analyses on a sound base of physics. Fortunately, there

are exceptions to the rule. The analysis by "The Hydrogen Report" by TMG/The Management Group [5] is based on the higher heating value and should therefore be considered for reference and energy policies. The results of this study show that hydrogen offers no convincing alternative to some other energy carriers, and that much of the hydrogen euphoria is not backed by the fundamentals of physics.

In their recent study "The Future of the Hydrogen Economy: Bright or Bleak?" [6, 7] the authors present a thorough energetic analysis of the Hydrogen Economy based on the laws of physics. It is symptomatic for the ongoing discussion that this work has been criticized by groups whose analyses are based on Lower Heating Values LHV and many "soft" arguments. If a hydrogen economy is established, it must be in agreement with the fundamental laws of physics. The promoters of hydrogen would do better to observe the laws of nature than to engage in missionary activities.

Reference:

[1] Amory B. Lovins; Twenty Hydrogen Myths. Rocky Mountain Institute, 20 June 2003, corrected and updated 02 September 2003.

[2] Raj Choudhury et al.; Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – A European Study. L-B-Systemtechnik GmbH, Ottobrunn / Germany, 27 September 2002, <http://www.lbst.de/gm-wtw>

[3] Malcolm A. Weiss, John B. Haywood, Andreas Schafer, and Vinod K. Natarajan; Comparative Assessment of Fuel Cell Cars. Massachusetts Institute of Technology (MIT), February 2003, MIT LFEE 2003-001 RP

[4] Michael Wang et al.; Well-to-Wheel Energy Consumption and Greenhouse Gas Analysis – An American Analysis. Report by Argonne National Laboratory for General Motors Corporation. June 30, 2001.

[5] John R. Wilson and Griffin Burgh; The Hydrogen Report, An Examination of the Role of Hydrogen in Achieving U.S. Energy Independence, TMG/The Management Group, July 2003 (www.tmgtech.com)

[6] U. Bossel, B. Eliasson and G. Taylor; The Future of the Hydrogen Economy: Bright or Bleak? Final Report of 15 April 2003, European Fuel Cell Forum (www.efcf.com/reports)

[7] U. Bossel; The Physics of the Hydrogen Economy. European Fuel Cell News, Volume 10, Number 2, July 2003.

[8] D. Castorph, M. Kollera and P. Waas; Brennwert und Heizwert (www.fm.fh-muenchen.de/labore/waas/skripten/kap11.pdf)