Why We "Waste" Energy: The Second Law of Thermodynamics Explains--UPDATED 8/7

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This is a guest post by John Schmitz. John E.J. Schmitz holds currently a senior management position in semiconductor technology research. He was awarded his Ph.D. in Chemistry in 1984 from the Catholic University of Nijmegen (Netherlands). He holds six patents in the semiconductor field and has published over 45 scientific articles and one technical book in the field of integrated circuit technology. Before, Schmitz was the Chief Operating Officer Manufacturing Technology of SEMATECH (Austin, Texas) a consortium that develops semiconductor manufacturing technology, materials, and equipment for their member chip maker companies. Schmitz has dealt with thermodynamics and entropy for 25 years on a professional level. He currently lives in a small town in Belgium with his wife, Pieternel, and his children; Lucas, Juliette, Emmeline, and Jasper.

There are many instances that we can see that in our attempts to transform energy into as much as possible usable work, we are always left with this "rest" amount of heat that we can not use anymore to generate even more work[1]. Clear examples of these imperfect transformations are the coolant radiators in our cars and the cooling towers of many factories or power plants. In powerplants that use fossil fuels we can have an efficiency as poor as 50% or often even lower, meaning that only 50% of the energy enclosed in the fuel is converted into electrical power, by means of burning fuel, heat generation that leads to steam and steam that will drive then turbines and generators. 50% or less is that not a shame? Of course the question arises why that is the case?

Why can we not convert for the full 100% the energy enclosed in the fuel into utile work? Well it is here that the Second Law of thermodynamics kicks in, also known as the entropy law. But before we go deeper into this entropy law first a bit more about the First Law of thermodynamics. The First Law is nothing more than the law of conservation of energy. Energy can be present in many forms (chemical, heat, work, electrical, nuclear etc etc) and the total amount of all this energy in the universe is constant. The First Law will not object to convert a given amount of energy *fully* into work. Unfortunately we *never* observe this attractive situation. The answer why that is so can be found from an analysis of the entropy law.

What is entropy? Entropy is a concept discovered while people were answering "simple" questions such as why heat only streams from warm to cold places. Another question that came up around 1800 was caused by the growing popularity of steam engines. Steam engines can also be called heat engines because they convert heat into work. Another example of a heat engines is a car engine. Steam engines where used in England to pump water out of the coal mines, a job that was done by many workers day and night before steam engines became available. To keep the steam engine running, fuel (such as wood or coal) was burned to generate the steam. While the steam engine was gaining ground, many improvements (for instance James Watt was able to improve efficiency with about 25%) were done that increased the efficiency of the steam engines considerably. Therefore much more work could be obtained from a given amount of fuel.

While this went on there was a young French military engineer, Sadi Carnot, who asked himself the question whether there was perhaps an upper limit to this efficiency. To answer that question he carried out a careful analysis around 1825 using a simplified of a steam engine[2]. The result of his analysis was that the upper limit of the efficiency was only determined by two factors: the temperature of the heat source (the steam) and the temperature of the heat sink (the location where the steam was condensed, for all practical matters the outside air). More precisely he found that the amount of heat, Qh, taken from the heat source at temperature , Th, is related to the amount of heat given up at the heat sink, Qc, at temperature Tc, as: $Qh/Th = Qc/Tc$. Although he did not coined the factor Q/T as entropy (that was done by Rudolph Clausius around 1850) he clearly laid the foundation for scientists such as Clausius who came to the conclusion that "something was missing" and was needed in addition to the First Law . That something became later the Second Law of thermodynamics.

The best possible efficiency of the steam engine was then shown by Carnot to be equal to (Th-Tc)/Th (an atmospheric steam engine efficiency is therefore limited to about (373-272)/373 = 25% efficiency).

The work of Carnot showed very clearly that in order for a heat engine to work you MUST have a heat source at high temperature and a heat sink at colder temperature and that the heat disposed at the heat sink can NEVER generate any work anymore unless you have another heat sink available at an even lower temperature. Also, from the fact that Qh/Th = Qc/Tc, it becomes clear that in an heat engine you MUST give up an amount of heat, Qc, to the cold sink no escape. That is the fundamental reason for having the efficiency of the heat engines less than 100%! We can also see now that the efficiency of heat engines will increase if we make the temperature difference between the heat source and heat sink as large as possible.

Note added on August 6th:

In the orginal post I used an example of the efficiency of a refridgerator (a heat pump) for which I used the wrong equation as was clearly pointed out in many reactions. I apologize for this problem. I have removed this part of the post since it will sent the reader in the wrong direction.

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1. With work we mean here the ability to lift weights, or to to turn wheels which in turn can rotate shafts.

2. That is well known as the Carnot cycle.