ENERGY CONVERSIONS IN THE BIOLOGICAL WORLD: EFFICIENCIES, ABUNDANCES AND LIMITS. S. J. Bartlett[1], [1]Earth Life Science Institute, Tokyo Institute of Technology, Tokyo 152-8550, stuart.bartlett@elsi.jp

Introduction: In this work I present an overview of all the interconversions of energy that are observable in the biological world. It is no longer in doubt that a defining feature of life is its requisite ability to produce entropy, i.e. it requires a supply of free energy (useful energy, e.g. photons), and outputs whatever energy it takes in, in a less useable form (higher entropy, e.g. heat) [1]. While equilibrium systems are relatively amenable to thermodynamic analyses, life is fundamentally a driven system, sustained by flows of energy and material through its components. Much of the complexity we see in the biological world is linked to the fact that life uses and converts energy of essentially all forms: light, heat, chemical, mechanical, electromagnetic, etc. In this work I will assess the various interconversions of energy types that are carried out in the biological world. I will make use of literature data to summarise or estimate the efficiencies of these conversions and also compare the abundances of the abiotic source energy. I hope to present a physical perspective on the ways in which life has chosen to drive itself and speculate as to how optimal the extant conversion processes are. We can even ask the question: If we were to try to redesign a given organism to make better use of its niche, to what extent could we improve on its energetics?

Diverse forms: There are realtively few energy conversions that life does not, or cannot, carry out. At large length scales, complex heterotrophs tend to convert chemical energy into mechanical work, heat, and alternative forms of chemical energy. If we instead turn to prokaryotes and protists, we find that almost every conceivable transformation is performed somewhere. There are examples of electrotrophic organisms, capable of transducing electron flows into metabolic cycles [2], and even radiotrophic fungi, which seem to be able to utilise high frequency ionising radiation (including that found at the Chernobyl reactor site) as a source of energy [3].

A Staple of Life: The most widespread conversion is arguably chemical to chemical transformations, including bond re-arrangements and redox reactions. However an essential element of almost all metabolisms is the conversion of a proton diffusion gradient into chemical bond energy, i.e. using a proton motive force to synthesise ATP from ADP and phosphate. This energy conversion is so essential and widespread that its converting device has evolved to become nothing short of a marvel of nanoengineering, vastly superior to even the most advanced man-made molecular machines [4]. It has been suggested that this device, the ATP Synthase molecule, works at near perfect efficiency [5,6].

Limits: For many energy conversions, near-perfect efficiency is, in principle, achievable (consider for example, electricity to heat conversion). The most notable exception to this is of course the conversion of thermal gradients to mechanical work (which could then be converted into other forms of energy in a hypothetical organism). Heat to work conversion is bound by the Carnot efficiency limit, which for temperature gradients that are typical of Earth's surface, prevents devices being much more efficient than approximately 50% (most would likely be significantly less efficient than this). Interestingly, there is no known example (as far as I'm aware) of an organism which is able to use a pure thermal gradient to power its metabolism. This is particularly poignant given the revolutionary impact that heat engines had on the technological evolution of our own species (though heat engines would have been futile in the absence of the abundant hydrocarbon fuels that power them). It is perhaps their inherent macroscopic size that prevented life from discovering them, in contrast to the molecular discoveries that formed the foundation of the biological world.

Summary: This work will draw together the above examples with other biological energy conversions to present an overview of the diversity and effectiveness of life's energy transformations. I will then use this comparison to discuss the apparent exploitability of different energy sources and the ease with which life has found ways to perform different energy transformations. Analysing the problem of bioenergetics in this way could help us refine our ideas of habitability and perhaps even inspire more abstract, physically-based definitions of the general role that life plays in the universe.

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