CYCLIC THERMAL ENERGY HARVESTING BY ORGANISMS

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ABSTRACT

Photosynthesis requires complex chemical machinery, and converts only a few percent of incident sunlight energy to useful work. Few animals are photosynthetic. A possible alternative is to use the Carnot cycle, exploiting temperature differences. The maximum efficiency with which work can be extracted is then $\sim\Delta T/T$, where terrestrially $T\sim300$ K.

For a cold blooded animal which moves frequently between environments at significantly different temperatures, this energy can be substantial: its entire body can act as a thermal reservoir. The energy harvesting machinery might be hard to spot, much as ‘brown fat’ in human adults was overlooked until recently. It could be based on any temperature-sensitive chemical equilibrium, for example one that interacts with ATP formation.

In the temperate and tropical oceans, animals could harvest such energy very easily, by swimming repeatedly up and down through the thermocline. In so doing, they would transfer significant heat from near-surface waters to the mid-depths. Such behavior would be increasingly favored as surface waters become warmer, as has recently occurred. This could conceivably explain the recent ‘pause’ in the anthropogenic greenhouse effect.

At the origin of life, diurnal thermal harvesting by non-motile organisms could evolve far more easily than photosynthesis, and might have preceded both photosynthesis and the use of external chemical energy.

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1. INTRODUCTION

In human technology, the difficulty of turning sunlight into useful energy is reflected in the fact that the first practical solar cells were made only 60 years ago, and even then were inefficient. By contrast heat has been successfully harnessed for centuries and hydraulic pressure for millennia. Biological systems also seem to find direct light harvesting no easy feat. Photosynthesis is at best a few percent efficient relative to the energy available in the full spectrum of sunlight. Even to achieve that is chemically very complicated.

Given that various photosynthesis pathways appear to have evolved independently many times, it would be surprising if direct harvesting of heat energy from thermal cycling had never been explored by evolution. Due to the simpler chemical machinery required, it might have been the first energy harvesting mechanism at the origin of life.

Cold-blooded animals which move between significantly different temperatures could harvest such energy repeatedly, using their bodies as thermal reservoirs. The associated chemical machinery would not necessarily be easy to spot, just as brown fat in adult humans was overlooked until recently. Almost any chemical reaction whose equilibrium point varies strongly with temperature in the range ~10-30°C will do: one which interacts to promote the assembly of ATP is one obvious possibility.

This paper points out some ecological niches and specific organisms in which the phenomenon might be discovered.

2. MARINE ANIMALS

In the temperate and tropical oceans there is often a temperature difference of ~12°C across ~100m vertical distance. For an animal of any size, transiting this thermocline requires negligible energy and can be done often. Even the smallest animals could potentially transit multiple times per day: vast quantities of zooplankton are diel vertical migrators over ~1,000 m depth range.

An animal whose body experiences a temperature change 10°C has 40 J/g more thermal energy in its body tissue at the higher temperature. ΔT/T = 10/300 = 3.3%, so up to 1.3 J/g of this could ideally be extracted into chemical energy. A real system might do perhaps half as well, storing 0.65 J/g per cycle in the animal's tissue. Muscle ultimately converts this chemical energy to mechanical work at ~30% efficiency**[1]** for overall efficiency ~0.5%.

A 12°C temperature difference causes only ~3 kg/m^3 density difference, so assuming a constant density gradient, the ideal minimum work needed to transport one litre of water, or 1 kg of body tissue of the same density, across the thermocline is 1.5 J. Actual work done by an animal's muscles might be twice this, 3 J.

The thermal energy transported across the thermocline by moving one litre of water and allowing its temperature to change 10°C is 40 kJ: 13,000 times greater than the muscle work done. Dividing by 200 to take account of the low overall efficiency, there is still a 65:1 favourable ratio of muscle work made available to muscle work required.

An animal which can swim at about one knot and also exchange heat rapidly with the surrounding water could transit the thermocline at least a hundred times per day. The overall cyclic energy harvest obtained is then very substantial, equivalent to storing energy ~65 J/g = 15 kcal/kg of its bodyweight per day. From Kleiber's law**[2]**, a 1 kg poikilotherm requires ~0.5 kcal/hr = 12 kcal/day: energy consumption scales as bodyweight$^{\wedge 0.75}$. Thus a fish or reptile of body mass 1 kg could generate all the energy it needed by making 4 round trips per hour through the thermocline. A larger animal could generate all its energy with fewer transits, for example a quarter-tonne animal one cycle per hour.

Large fish such as rays and skates have a flat body plan with high surface area that would be ideal for rapid intentional temperature change by heat exchange despite their large size.

Animals such as basking sharks might conceivably be sunbathing to raise their body temperature as high as possible for maximum thermal harvest.

A colleague points out that sailed fish might be able to increase their rate of heat exchange by deploying their sails, and that small sharks often rest on the seabed in very shallow water during the daytime, which should maximize their body temperature.[3]

If some marine organisms do indeed harvest thermal energy by repeatedly traversing the thermocline, for the thermodynamic reasons described above, they transport hundreds of times more energy downward than they output as muscle work. As an illustration, to export 1 W/m^2 heat downward requires thermocline-traversing marine animals to do only 80 W muscle work per square kilometre, for example 700 1 kg fish/km^2. It has recently been suggested that the estimated biomass of large mesopelagic fishes should be raised from ~1 billion tonnes (3 tonnes/km^2 ocean) to ≥10 billion tonnes (≥30 tonnes/km^2 ocean).[4]

Thermal harvesting organisms will tend to thrive and increase as surface waters become warmer, as has recently occurred, due to the greater efficiency of energy harvest possible as the $\Delta T/T$ ratio increases. This could conceivably explain the anomaly of the current global warming 'pause'. While not really a pause, a present slowdown in surface level warming appears to be due to thermal energy passing from shallow ocean water to the mid-depths at an unprecedentedly high rate.[5]

If this bio-feedback from ocean surface warming is a real effect, it is of tremendous importance, because the deep oceans have sufficient heat capacity to store centuries' worth of anthropic greenhouse energy before warming appreciably. This could defer the need for costly measures to counter the anthropic greenhouse effect. The mechanism may have been damping rapid surface temperature changes, from any cause, for a significant portion of the Earth's history. Total current anthropogenic radiative greenhouse forcing[6] is ~2.5 W/m^2, and would be balanced by a drawdown of ~5 W/m^2 in the temperate and tropical oceans. Especially if the new larger estimate of mesopelagic fish mass is correct, an even larger drawdown is ecologically feasible.

3. LAND ARTHROPODS

Insects and other arthropods can move from sun to shade very easily, and heat and cool very rapidly, due to their small size. Insect energy consumption will vary enormously with species and life cycle stage, but a thermal cycle contribution could be significant in many cases.

Beetles might plausibly use their elytra as thermal reservoirs for this purpose. Often coloured black, which gives optimal absorption and emission of radiant energy, the elytra temperature could be cycled very rapidly by moving in and out of direct sunlight, without affecting the insect’s core body temperature. These organs are normally assumed to serve mainly as wing protective cases, but have always seemed to me disproportionately massive structures for a flying insect to carry for this purpose.

Arthropods which spend a long time in a non-motile state, such as a pupa in a chrysalis, could harvest energy from the diurnal thermal cycle at a time no other source is available to them.

A colleague observed that on the Canadian farm where she spent her youth, monarch butterflies hang their chrysalises beneath milkweed whose shadow forms an intricate pattern of light and shade.[3] As the sun tracks across the sky, such a chrysalis would likely switch between full sun and full shade many times a day, providing a correspondingly large number of thermal cycles.

4. LAND REPTILES

Alligators are often observed to sunbathe in the morning, enter water in the middle of the day to cool, then sunbathe again in the afternoon. An alligator’s body temperature can vary by 14°C in a single day, twice as much as its average diurnal temperature varies over a year, strongly suggesting that it is deliberately maximising short-term thermal cycling.[7]

Taking a more typical cycle as 10°C: the animal then has 40 J/g more thermal energy in its body tissue at the higher temperature than the lower. ΔT/T = 10/300 = 3.3%, so up to 1.3 J/g of this could ideally be extracted into chemical energy. A real system might do perhaps half as well, storing 0.65 J/g in the animal's tissue: a twice daily cycle produces 1.3 J/g

A 70 kg alligator produces 72 kcal/day metabolic energy[8], 4.3 J/g. Thus thermal cycling could produce 30% of the animal's total energy requirement for a large part of each year.

Large crocodilians by contrast appear to have near-homeothermic body temperatures.[9]

Among small reptiles, the lizard Ameiva Exsul cycles its body temperature by ~7°C many times a day by shifting from sun to shade.[10] However Kleiber's Law suggests that with mass < 100g it will need too much energy for cyclic thermal harvesting to be of significant use.

5. BIRDS

The peacock's tail famously puzzled Darwin, and evidence for its value as a sexual ornament is not unequivocal. An arrangement of bird feathers could be alternately sun-heated and air-cooled in the shade in the same way as suggested above for the beetle's elytra. The mass of any bird's feathers is typically greater than that of its skeleton, a high fraction of its total body weight, and the feathers are thin and can be deployed in a large surface area to both warm (if exposed to the sun) and cool (if shaded and exposed to the wind) very rapidly.

It is normally assumed that a fully grown feather is effectively dead tissue which doe not exchange material with the rest of the bird's body. But if the energy from thermal cycling is converted into hydrocarbons in situ, since the energy from burning hydrocarbons can be ~40 kJ/g, an unnoticeably tiny amount of oil flowing from the feather back into the bird's skin could convey the energy harvested. Alternatively, the secretions from the uropygial gland might be converted to a chemically more energetic form before being combed off the feather and eaten.

While the peacock's tail could be a formidable energy-harvesting array, many more ordinary birds spend a considerable portion of their day perching time adjusting areas of feathers with respect to the sun. The usual assumption is that the purpose of this behavior is to cause parasites to congregate so the bird can easily remove them, but it could also be to maximise energy harvesting by thermal cycling.

A colleague points out that while the extreme of the male peacock's tail may indeed now serve principally as a sexual ornament, and may have been further enhanced by selective breeding by humans, the fantail of the American wild turkey, which comprises black feathers suitable for maximum absorption and emission of radiant energy, could comprise a purer example of a thermal harvesting organ.[3]

6. DINOSAURS

Ancient cold-blooded animals could have harvested thermal energy. The sail of Dimetrodon could have helped this comparatively large animal to cycle its body temperature rapidly: blood circulated through it could be heated and/or cooled by adjusting the angle of the sail with respect to sun and wind. Some modern lizards have a similar sail-like feature.

Dinosaurs were likely warm-blooded. However external features of dinosaur anatomy otherwise hard to explain could be thermal harvesting organs. Thermal cycling of significant masses of external bone which could be exposed to the sun and wind would be possible. For example the back plates of stegosaurus, the tail club of ankylosaurids, or the head ornamentation of many dinosaurs.

Large warm-blooded dinosaurs could nevertheless not have used thermal cycling nearly as effectively as creatures which could either thermally cycle their entire body mass, like alligators, or thermally cycle a substantial part of their body mass very rapidly, like birds. This might help explain why, when dinosaurs became extinct, these related creatures survived.

7. NON-MOTILE ORGANISMS

Particularly in regions where the ground surface temperature undergoes a large diurnal cycle, static organisms which have energy needs beyond carbon fixation might use thermal harvesting. This applies to plants which manufacture sugars for animal lures such as fruits or nectar, or high-energy fuel for their seeds as contained in nuts. Organisms incapable of photosynthesis such as fungi might also use this energy source.

The energy might be harvested as previously described, using the diurnal temperature cycle. Alternatively, a spatially extended organism can span a range of temperatures at a single instant: for example a tropical or desert plant with deep roots will have a large temperature differential between its above-ground and below-ground portions at the hottest part of the day and coldest part of the night. Chemicals circulated in its sap could readily perform thermal harvesting. Cacti, tubers and trees are plausible candidates.

8. ORIGIN OF LIFE

Cyclic thermal harvesting could evolve far more easily than either photosynthesis or the use of external chemical energy. Temperature affects essentially every chemical equilibrium between reactants. Even stationary organisms, or ones which drift randomly, experience temperature variations: for example the diurnal temperature cycle. Thermal cycling might be the original form of energy gathering, used by the first lifeforms.

Thermal harvesting mechanisms in modern animals might or might not be related to such ancient ones. Either way, functional harvesting mechanisms of ancient origin or non-functional remnants might be found in single-celled organisms or larger ones. Almost any part of the kingdom of life, with the possible exception of mammals because almost their entire body mass is homeothermic, can harvest thermal energy in the right circumstances.

9. CONCLUSION

The cyclic thermal harvesting hypothesis can be tested with comparatively straightforward experiments.

Behavioural observations and tests might be highly suggestive, and easier to do in the first instance than biochemical investigations.

The actual mechanism of energy harvesting may be more difficult to detect, as it need not necessarily involve either a distinct cell type, or more than a fraction of a percent of the animal's total mass, explaining why it has been overlooked. A solid-to-liquid phase change, such as water to ice, can have specific endothermic energy of several hundred J/g with negligible temperature change. It is not clear to me what the maximum specific endothermic energy of organic substances optimised by evolution could be with ~10°C temperature change available: possibly an order of magnitude greater, as exothermic reactions providing ~10 kJ/g reactants are widely used. Material making up a fraction of a percent of total body weight could then do the harvesting proposed.

If the hypothesis is correct, a significant portion of the energy available to life on earth may always have come not from photosynthesis, but from cyclic thermal harvesting. The implications, theoretical and practical, will be enormous.

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