BIOMIMETICS & ENERGY

SUMMARY REPORT

EDITION 2022

Ceebios

"

The transformation of the electricity system is at the heart of the climate issue and the transformation of our society towards carbon neutrality. This energy transition must consider the impact on ecosystems, biodiversity and resources.

DFor several years, RTE has been interested in the potential of biomimicry to explore solutions that take all these dimensions into account. This opens a field of cooperation for all energy players, from operators to industrials committed to the energy transition, making biomimicry one of the pillars of the development of the energy products of tomorrow.

That is why we support this report, which marks the starting point for this hope for cooperation.

Olivier Grabette

General Delegate in charge of European Industrial Affairs

Member of the Executive Committee

Rte

This summary was produced thanks to the impetus and support of RTE

Le réseau de transport d'électricité

EDITO

Biomimicry can be a guiding principle for choosing the technologies to be developed, for building original, innovative expertise that will generate economic activity, and for inspiring future technologies that are compatible with the ecological transition. In this context, ADEME recognizes the value of biomimicry, particularly in terms of better integrating the energy industry into the life cycle of living beings.

It is to collectively take up this challenge that we wished to associate ourselves with this publication, which opens original questions, new perspectives and horizons, avenues for reflection, stimulating examples and possible achievements. Basically, biomimicry questions our objectives, our practices, and our requirements, which often overlook the need to integrate all our activities with the biological world and its major biogeochemical cycles, as well as with the preservation of ecosystem services.

Aware of these limitations, ADEME wanted to establish a national agreement with Ceebios in order to use the principles of biomimicry to implement a responsible ecological transition. The objective is to facilitate the appropriation of biomimicry by the greatest number of people, the sharing of best practices and, above all, the emergence and dissemination of the solutions developed. With this in mind, ADEME supports projects based on biomimicry, whether they involve research into new knowledge, innovation or industrial pre-deployment. This is notably the case for the wave membrane tidal turbine for recovering energy from marine currents, which is the result of research financed by the agency.

In the field of projects close to the market, we can also mention the s3 project, financed under the Investments in the Future program, which aims to deploy a wave motor prototype to harness wave energy. In the field of agrivoltaics, we can also mention the sun agri project, also funded by the Investments in the Future program, which will produce electricity while contributing to the resilience of agricultural crops in the face of climate change.

In addition to the research and innovation projects supported by ADEME, we have joined forces with Ceebios to produce a methodological guide on biomimetic eco-design so that project leaders can take into account the environmental impact of their innovations at a very early stage.

These few concrete examples in the energy field give a good idea of the innovation potential of biomimicry. Beyond the energy field alone, this observation also encourages us to encourage a strong dynamic of appropriation of biomimicry concepts within our organizations in order to develop our practices in all our fields of intervention. Biomimicry and energy invites us to take up this more global challenge by proposing avenues of reflection and proposed solutions.

Arnaud Leroy

Chairman and CEO of ADEME, 2021

ADEME, the French Environment and Energy Management Agency, supports all those who act to implement solutions, innovate, and prepare for the future in order to accompany the necessary transformation of our production and consumption methods.

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INTRODUCTION

REINVENTING OUR RELATIONSHIP TO ENERGY, BY OBSERVING LIVING THINGS

Towards a desirable energy model

Energy is at the heart of the ecological transition of this first half of the 21st century. Collecting "clean" energy, storing it massively to compensate for the variability of its availability without polluting, efficiently transmitting it to meet demand, optimizing its use and limiting losses are all elements that make up the specifications of tomorrow's energy systems.

This desirable energy model, supported at the international level by initiatives such as COP 21, the American and European Green Deal and at the national level by actors such as ADEME, may seem utopian. However, it can already be observed in the rest of the living world. For nearly 3.8 billion years, life has been built around locally abundant energy vectors to ensure its resilience and development while meeting its environmental and functional constraints.

Inspired by the management of energy in living organisms

Biomimicry consists in drawing inspiration from the strategies of biological systems to provide innovative solutions that reconcile technical and environmental performance. This approach applied to the energy field opens a wide field of potential innovations.

Through this report, the presentation of the issues of the energy sector will lead us to:

- study and analyse energy management in living organisms,
- present specific examples of biological models associated with short to medium term incremental biomimetic innovations,
- formalize a global synthesis of the strategic axes underlining the interest of biomimicry for a change in the energy paradigm, in the medium to long term.

> *"The objective of this paper is to present the opportunities of biomimicry in the context of energy management and to identify a set of key biomimetic innovation levers to be activated to accelerate the ecological transition."*

In this respect, our approach combines a technical-scientific axis and a societal and environmental axis. Without claiming to be exhaustive, we are drawing up a summary of the current situation to inform, inspire and structure the actions of the players in the energy sector.

This document is the synthesis of a more complete and detailed report, written by the same authors.

MODERN ENERGY ISSUES

THE LIMITS TO ENERGY GROWTH

In the course of its development, the human species has gradually gained access to an increasing amount of energy. More than food products, which feed the biological system that is the human being, it is above all the access to fossil vectors of organic origin (coal, oil, etc.), feeding non-biological machines, that has considerably accelerated the growth of the technological world. Humanity is a special species in terms of its relationship with energy. It is the only one that uses it mainly to power non-living systems (machines) and therefore not subject to natural selection or to the challenge of sobriety[1].

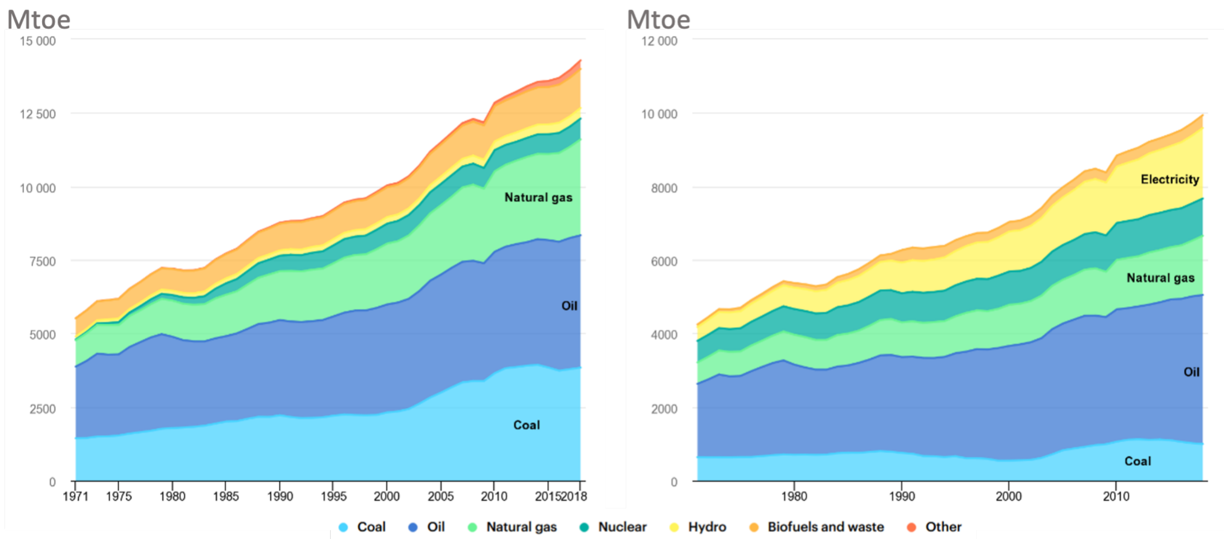


Figure 1: Total world energy production (left)[2] and final consumption (right)[3], by source.

In combination with the rising standard of living in OECD countries, the continuing demographic and industrial growth of many developing countries (China and India in particular) is leading to a continuous increase in the amount of energy used by humanity. This raises the central question of the limits and multiple impacts of this growth.

1 A. Gonzague, Le gaspillage énergétique, grand oublié de la COP21, L'OBS, 2015, https://www.nouvelobs.com/planete/cop21/20151210.OBS1135/le-gaspillage-energetique-grand-ou blie-de-la-cop21.html

2 IEA, World total energy supply by source, 1971-2018, IEA, Paris https://www.iea.org/data-and-statistics/charts/world-total-energy-supply-by-source-1971-2018

3 IEA, World total final consumption by source, 1973-2018, IEA, Paris, https://www.iea.org/data-and-statistics/charts/world-total-final-consumption-by-source-1973-2018

Four main axes can be identified to study the limits to this growth in global energy consumption[4]:

the limits of resource stocks used as energy sources

Scientific research on the composition of the planet Earth has made it possible to estimate the maximum exploitation time of the various fossil resources exploited at the current rate[5]: between 50 and 100 years of exploitation maximum. As these fossil resources represent 83% of the world's energy mix (excluding nuclear power[3]), maintaining a stable energy balance requires anticipating the end of stocks to prevent a drastic drop in fossil energy supplies.

the limits of the equilibrium of the planet Earth system[6,7]

The impacts of human activity on our planetary environment can lead to an imbalance in the environmental foundations on which our society is built (climate, biodiversity, atmospheric composition, etc.). It is therefore necessary to consider the limits to be respected to prevent such an imbalance.

the limits of our scientific and technological knowledge and know-how

Our inability to drastically reduce our impacts calls into question the scientific and technological response to planetary limits. While technology cannot be seen as the only answer, it does have a fundamental role to play.

political, socio-economic and societal limits[8]

Awareness of the three limits previously mentioned requires us to move away from an ever-increasing growth in energy use, based on our emancipation from the rules of sobriety intrinsic to the rest of life. Questioning our consumption patterns, re-examining the energy paradigm[9], rethinking societal objectives are all key components of a more desirable future. Only enlightened political choices in favour of a considered orientation of our societal growth, the axis of which remains to be (re)defined, will be able to guide us in the transition towards a sustainable energy model.

If the issues related to the limits of stocks and the limits of the earth's equilibrium emerge from natural constraints imposed by our planet, the technical-scientific and political-social issues depend on our capacity as a species to choose the right resolution levers.

Several decades of scientific work[10] have highlighted the link between our energy model and our impact on the environment. Societal sustainability is dependent on energy sustainability. This transition to a sustainable energy system is now, even more than before, a major international objective, as expressed in 2015 in the UN's Sustainable Development Goals[11], in particular SDG 7.

4 RTE, " Futurs énergétiques 2050 : les scénarios de mix de production à l'étude permettant d'atteindre la neutralité carbone à l'horizon 2050" [Online]. Available: https://www.rte-france.com/analyses-tendances-et-prospectives/bilan-previsionnel-2050-futurs-energetiques#Lesdocuments

5 https://www.edf.fr/groupe-edf/espaces-dedies/l-energie-de-a-a-z/tout-sur-l-energie/le-developpement-durable/l-epuisement-des-ressources

6 Meadows, D. H., Randers, J., & Meadows, D. L. (2013). The limits to growth. The Future of Nature: Documents of Global Change, 101-112.

7 Rockström, J., Steffen, W., Noone, K. et al. A safe operating space for humanity. Nature 461, 472-475 (2009).
https://doi.org/10.1038/461472a

8 Joakim Kulin & Ingemar Johansson Sevä (2019) The Role of Government in Protecting the Environment: Quality of Government and the Translation of Normative Views about Government Responsibility into Spending Preferences, International Journal of Sociology, 49:2, 110-129, https://doi.org/10.1080/00207659.2019.1582964

9 Spittler, N.; Gladkykh, G.; Diemer, A.; Davidsdottir, B. Understanding the Current Energy Paradigm and Energy System Models for More Sustainable Energy System Development. Energies 2019, 12, 1584. https://doi.org/10.3390/en12081584

10 https://www.ipcc.ch/reports/GIEC (FR) = IPCC (EN)

11 https://www.un.org/fr/chronicle/article/lobjectif-de-developpement-durable-relatif-lenergie-et-les-technologies-de-linformation-et-de-la (UN)

BIOMIMICRY

BE INSPIRED BY THE LIVING AND ITS ENERGY MANAGEMENT

The living world runs on solar energy. Matter flows are regulated and distributed in a circular fashion. Ecosystems are resilient to disturbances. Organisms can feed, communicate, develop, protect, and repair themselves in a sober and efficient way. Living organisms incorporate a multitude of responses to the challenges facing humanity today. These responses can be observed at many scales of time and space.

Biomimicry invites us to observe the principles that govern the biological world, to identify the rules that regulate it, to understand the organization that gives it its balance. It also invites us to study in detail the strategies for solving the technical challenges that such an organisation implies.

> "This is indeed the richness of the biomimetic approach, which questions our development structure and offers technical levers by proposing more sustainable alternatives."

Whether technical or biological, systems are subject to the laws of physics and, in the case of energy, to the principles of thermodynamics. The first of these principles emphasises that the quantity of energy is always conserved. The second explains that energy naturally dissipates and therefore inexorably decreases in quality.

These principles invite us to consider that energy is only available to an organism if it has been taken from its environment. Moreover, as this energy is dissipated, the living organism must use it continuously to maintain its organized structure and its vital functions.

In conclusion: the collection, storage, transfer and use of energy are crucial functions in the survival of species[12].

> "The convergence of the functional needs of the biological and technological worlds (moving, communicating, protecting, etc.) as well as the associated energy challenges (storing, transmitting, collecting, and using energy sustainably) (Figure 2) leads us to want to learn from how Life has articulated, for nearly 3.8 billion years, sustainable energy management."

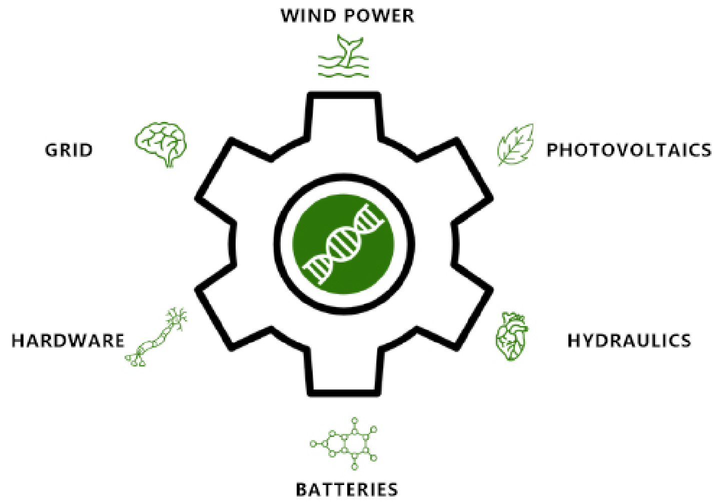


Figure 2: Illustration of convergences between technological and biological functional needs © Ceebios

12 Adapted from Humanité Bio-Inspirée - Une question de principes thermodynamiques - Christophe Goupil, 2020

The characterization of a desirable future for humanity is now at the heart of the societal transition process. Biomimicry offers a coherent framework for this transition by describing a set of foundations on which to build a sustainable balance.

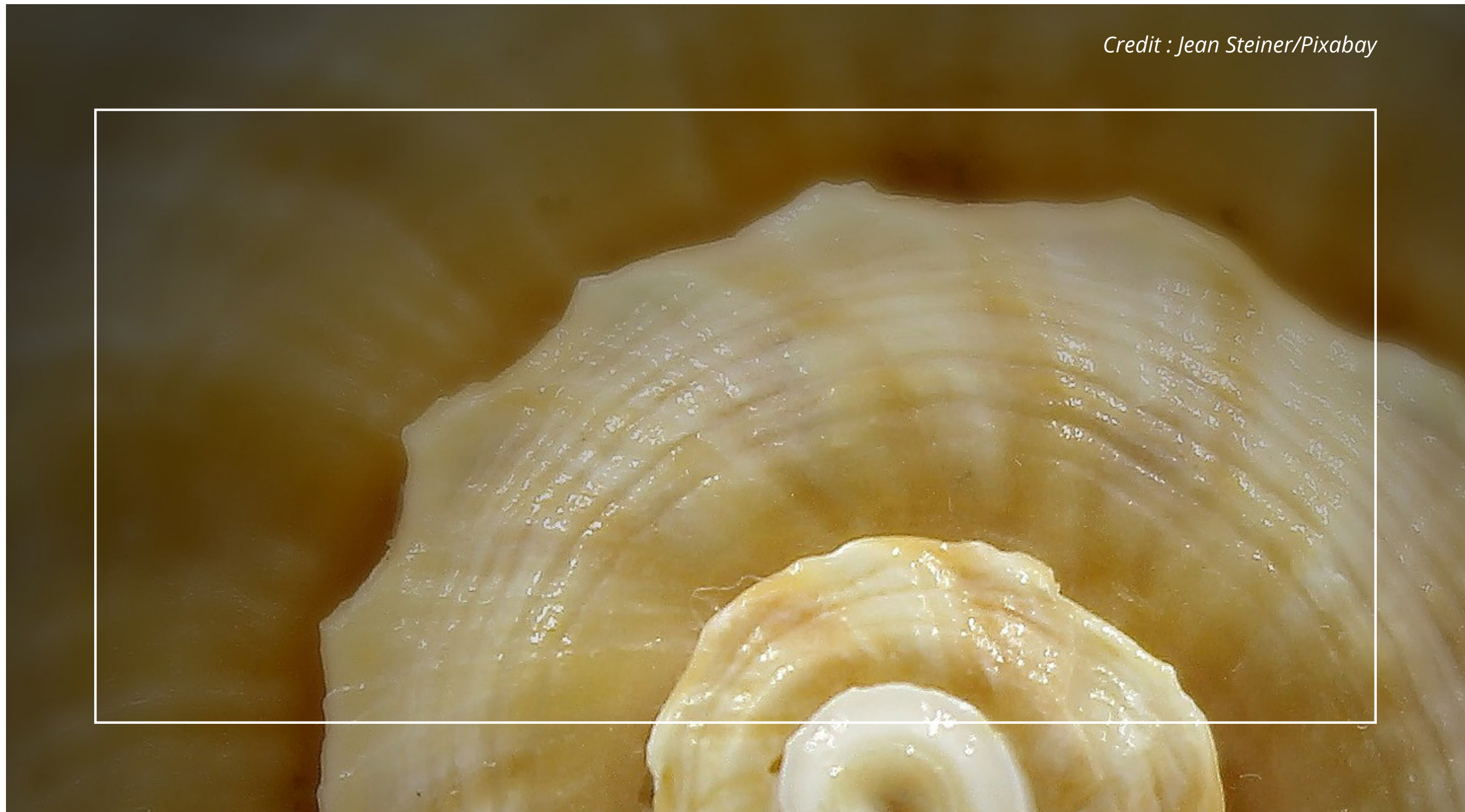
Comparing the technological and biological worlds on a set of criteria related to energy management makes it possible to identify possible major areas of biomimetic innovation, new constraints to be anticipated and new prisms of analysis. This rapprochement with the living world leads us to change our relationship with energy (Table 1).

ENERGY SOURCES & CARRIERS		
	WORLD TECHNOLOGICAL	WORLD BIOLOGICAL
Energy carrier majority	Hydrocarbons	Solar photon
Time to depletion of stocks of main energy carriers	A few tens to hundreds of years	Corresponds to the lifetime of the sun, i.e. about 5 billion years
Vector renewal rate	Several million years = fossil vectors	Continuous = renewable vectors
Vector mobility	Possible over long distances = stock energy	Locally limited = flow energy
Variability in availability of vectors	Low variability while stocks last	Permanent variability (season, time, climate, etc.)

ENERGY MANAGEMENT INFRASTRUCTURE		
	WORLD TECHNOLOGICAL	WORLD BIOLOGICAL
Materials & composition	Large amount of material, little recycled and presence of rare elements	Material efficient, fully recycled material based on abundant elements
Infrastructure assembly	Industrial assembly polluting and energy-intensive	Self-assembly in water, at ambient temperature and pressure
Disassembly of infrastructure	Energy-intensive disassembly, long and polluting	Rapid disassembly into biocompatible upgraded building blocks
Impact on the environment	Pollution, habitat destruction, soil artificialisation, etc.	Pollution control, creation of habitat, soil permeability, etc.
Operating range	Narrow operating range (operating under precise conditions), low resistance to changing conditions (single criterion optimization / maximization)	Variable operating range, from narrow to wide depending on the environment, strong resistance to conditions changing (multi-criteria optimisation)
System resilience	Even slight degradation can lead to a complete shutdown of the system	Degradation usually leads to a reduction in efficiency before returning to a steady state

ENERGY-RELATED PROCESSES		
	WORLD TECHNOLOGICAL	WORLD BIOLOGICAL
Vector extraction	Drilling in the underground	Directly available subject to sun exposure
Transport of vectors collection	Global transport from major producers to all countries	No or little transport of chemical energy carriers, under metabolic control
Transformation of collection vehicles in useful vector	Energy supply to refine the hydrocarbons into usable energy carriers or petro-sourced materials (e.g. plastics)	Use of the photon energy, CO_2 and H_2O to form usable chemical energy carriers
Uses	Allows the technical system to generate heat by combustion of hydrocarbons and to use (individual or collective heating) or convert this heat into mechanical energy (engine, turbine, etc.) to ensure a set of functions (mobility, electricity generation, etc.) Use of materials of interest in industry (e.g. textiles, food processing, etc.)	Enables living systems to perform their vital functions by oxidation of chemical energy carrier into unstable chemical carriers used to enable chemical reactions and conversion of chemical energy into mechanical energy (reproduction, nutrition, communication, etc.) Use for the assembly and structuring of the constituent material of organisms
End of life	Loss of energy in the form of heat, release of combustion products (including H_2O and CO_2), difficult degradation of petro-sourced materials	Loss of energy in the form of heat (used by some biological systems), release of complete oxidation products (H_2O and CO_2), biodegradation

Table 1. Comparison of energy management between the technological and biological worlds
© Ceebios



Credit : Jean Steiner/Pixabay

Today accepted as necessary to ensure the sustainability of human civilization, the transition to an energy system based on so-called renewable vectors is a transformation that has already been carried out by the living world during evolution.

Although the sun is now the primary source of energy, the scientific community accepts the hypothesis that the first organisms, which appeared at the bottom of the oceans, drew their energy from mineral molecules and not from solar radiation. This deduction is based in particular on the observation of contemporary organisms such as sulfo-oxidizing or methanogenic bacteria[13].

Indeed, Life, which uses mostly local resources, appeared in the oceans where solar radiation is scarce. Its energy system was then based on the molecules that surrounded it. It was only later, when Life emerged from the water, that the sun, which was widely available, was used as an energy source and took its central place in the management of energy by living organisms.

This evolution shows that Life always favours the use of abundant local resources, and that the transition that we must accomplish is not only possible, but that it follows the logic of the development of the living world: a global development on the surface of the globe requires to switch to a massively available energy, as does the living world.

Biomimicry allows us to target the compromises necessary for the current energy transition: adaptation to local resources, variability of production and access to energy, continuous renewal, the drop in conversion efficiency in favour of multifunctionality, etc. These compromises, which are essential for building a sustainable society in a finite environment, are all profound changes in the way we understand energy.

If biomimicry invites us, on a strategic axis, to take a step back to observe the major rules structuring the living world, it also allows us, on a technical axis, to respond to the problems inherent in rethinking our approach to energy. We can thus list a set of functional axes associated with energy and for which biomimicry has strong potential.

"A transition analogous to the one we wish to make
(from stock energy to flow energy)
has shaped the development of Life on the surface
of the Earth."

Illustration of the adaptations of living organisms according to local resources (cactus in arid zone).

13 Minic, Z., Serre, V., & Hervé, G. (2006). Adaptation des organismes aux conditions extrêmes des sources hydrothermales marines profondes. In Comptes Rendus - Biologies (Vol. 329, Issue 7, pp. 527-540).
https://doi.org/10.1016/j.crvi.2006.02.001

THE TECHNICAL POTENTIAL OF BIOMIMICRY

THREE EXAMPLES

Three prisms are chosen here to illustrate the technical potential of biomimicry:
- a structural prism
- a functional prism
- an organizational prism.

Illustration of the structuring of insect eyes, leading here to the superhydrophobia of dragonfly eyes

BIO-MATERIALS WITH PASSIVE FUNCTIONS THROUGH THEIR STRUCTURE

Biological materials are often highly structured at very small scales. These micro- and nanostructures, which are widespread at the interfaces of living systems, ensure the functionalization of biological materials (Table 2). The functions (self-cleaning, hydrophobicity, anti-reflection, etc.) are provided passively, by the shape of the material, with a zero-energy cost during the use phase.

Functions	Biological models
Concentration of solar radiation	Butterfly wing
Anti-reflection property	Insect eyes (Figure 4)
Light radiation guidance	Polar bear hair
Reflexion and emission promotion	Ant hair
Maintenance by self-cleaning	“Lotus Effect” type
Water protection	“Lotus Effect” type
Anti-biofilm protection	Cicada

Table 2. Example of the functional potential associated with the structuring of biological materials © Ceebios

Drawing inspiration from these models represents a strong potential for innovation for our energy systems with often comparable functional needs (self-cleaning of photovoltaic panels, protection against biofilms, etc.).

STRATEGIES OF THE LIVING, TO LIMIT ENERGY LOSS

Living organisms are chemical systems whose structural integrity and function are temperature dependent. They achieve their thermoregulatory function through a combination of materials, structure, processes and organization (Table 3). Drawing inspiration from these strategies can allow us to design new systems that prevent, limit and counteract temperature variations by combining active and passive solutions that reduce the overall energy cost.

Functions	Biological models
Heat generation	Brown grease
Valorisation of waste heat	Muscle contraction and metabolism
Thermal insulation	Plant trichomes
Limit solar radiation	Canopy
Controlling infrared emission	Morpho Butterfly wings
Passive ventilation	Termite mound
Thermal energy use	Sweating

Table 3. Example of functional potential associated with biological models of thermoregulation © Ceebios

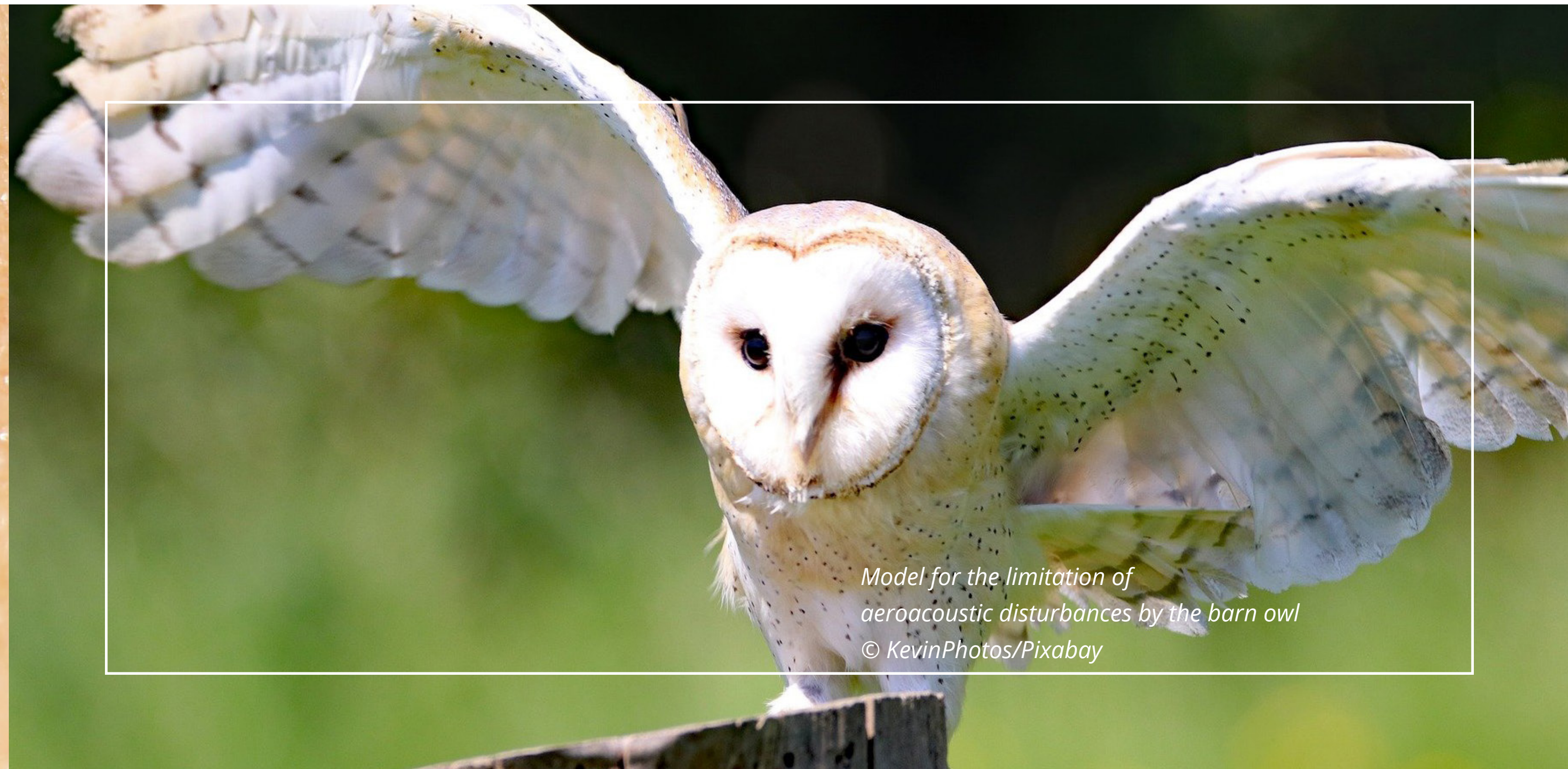
In the living world, as in the technosphere, heat is the main cause of energy losses, especially through the friction of structures in their fluid environment. While this energy constraint is very strong, it has led over time to the development of a series of hydro- and aerodynamic strategies aimed at limiting losses (Table 4).

Functions	Biological models
Surface friction reduction	Shark and dolphin skin
Turbulences management	Whale fins
Aero-acoustic disturbances limitation	Barn Owl (Figure 6)
Wave motion propulsion	Ripple in fish
Limitation of cavitation problems	Superhydrophobia of springtails

Table 4. Example of functional potential associated with biological hydro/aerodynamic models © Ceebios

Transposing the friction management strategies observed in nature to areas where the same environmental constraints apply, whether for similar functions (generation of mechanical energy for movement) or the opposite (collection of energy thanks to movement), opens the way to a large number of potential applications in the mobility (flow management, surface friction, etc.) and energy (turbine, oscillator, etc.) sectors.

Sweating as a thermal energy conversion process © Pixabay



Model for the limitation of aeroacoustic disturbances by the barn owl © KevinPhotos/Pixabay

LIVING ORGANISING ITSELF, TO SET UP NETWORKS

The organization of the living world into a network of matter and energy can be observed at different scales: the organism, the population, the ecosystem, etc. The living world develops through the co-evolution of different organisms in their respective environments, leading to the emergence of coordinated systems in a dynamic equilibrium under constraints, which can in some cases lead to efficient, sober and resilient situations.

The observation of the structuring of these systems then appears as a new source of inspiration, this time of an organizational nature (Table 5).

Functions	Biological models
Maintain a constant energy intake	Energy homeostasis
Prevent network disruptions	Adaptive behaviour swarms
Compensate for one-off accidents	Circulatory system of leaves
Direct flows within a complex system	Organization of the benches of fish (Photo)
Optimize the network architecture	Growth of the blob

Table 5. Example of functional potential associated with biological network management models © Ceebios

The examples presented in these three prisms (structural, functional and organizational) illustrate the technical potential of biomimicry. In addition to the paradigm shift that biomimicry proposes in our relationship with the living world, and more globally with our environment, it therefore provides a concrete response to the technical obstacles of the current transition.

These two levels of inspiration, strategic and technical, are at the heart of the biomimetic innovation process.

Our understanding of the key trends selected during the course of evolution, also known as the “principles of life[14]”, leads us to identify many areas of innovation for the energy sector.

14 Different formalisations of the principles of living exist in the literature, such as the Biomimicry 3.8 version or the KARIM guide. The original repository by Hoagland, B. Dodson & J. Hauck is the one used in this report. It should be noted that these principles are still being discussed and refined by the scientific community, including Ceebios and its academic partners. With this critical view in mind, the use of these principles of life in this synthesis aims at structuring a prism of analysis of living models that question our technological practices.

Model of collective behaviour in a school of fish © 123RF

AXES OF INSPIRATION

.01 .01 ENERGY SOURCES AND CARRIERS IN LIVING ORGANISMS

The living structures matter through energy and exchanges energy through matter. In living beings, even more than elsewhere, matter and energy are intimately linked. Both are vital to the survival of each organism, at the heart of biological processes.

From this observation, a first question emerges: the source and form of energy. How does the system obtain energy and in what form is the energy collected, transmitted and/or used?

The primary source of energy for the living world is the sun. Solar energy (electromagnetic energy) is converted by photosynthesis into chemical energy. Through a chain reaction, photon energy is used to carry out the photocatalysis reaction of H2O (which releases O2) and the reduction of inorganic CO2 (which stores CO2) to sugars (organic matter) (Eq. 1).

$$6\,CO_2 + 6\,H_2O \xrightarrow{\text{☼}} \text{Glucose} + 6\,O_2$$

Eq. 1 Global reaction balance of photosynthesis

This ability of photosynthetic organisms (green plants, phytoplankton, and some bacteria) to use energy to convert inorganic matter (CO2) into organic matter (sugars) has earned them the name “primary producers”. This process of linking flow energy (solar radiation) and storage energy (organic matter) is the basis for energy input into the biosphere[15] . These synthesized sugars are part of the metabolism of organisms and represent the main energy vectors of use: “living organisms run on sugar[14]”.

However, most animals are unable to use the sun as a direct source of energy. If this source of flow energy is not available to them, the energy remains vital to them and must be collected elsewhere.

It is through a diet based on the consumption of other living beings, which are rich in chemical energy vectors (stock energy), that these inputs are ensured. Organisms that consume primary producers are thus called “primary consumers”. They themselves feed so-called “secondary consumers” and so on. A third category of organisms completes the picture of the network of matter and energy of Life: the “decomposers”. These organisms also feed on organic matter, but do so when an organism dies[16] . They break down matter into the inorganic molecules that are essential for primary producers. If one of these links is broken, the entire chain is affected: “life is interconnected and interdependent[14]” (Figure 3).

15 C. Goupil, H. Ouerdane, E. Herbert, Cl. Goupil and Y. D’Angelo. Thermodynamics of metabolic energy conversion under muscle load. New J. Phys.21 023021 -2019

16 Allan, J. D., & Castillo, M. M. (2007). Primary producers. Stream Ecology, 105-134. https://doi.org/10.1007/978-1-4020-5583-6_6

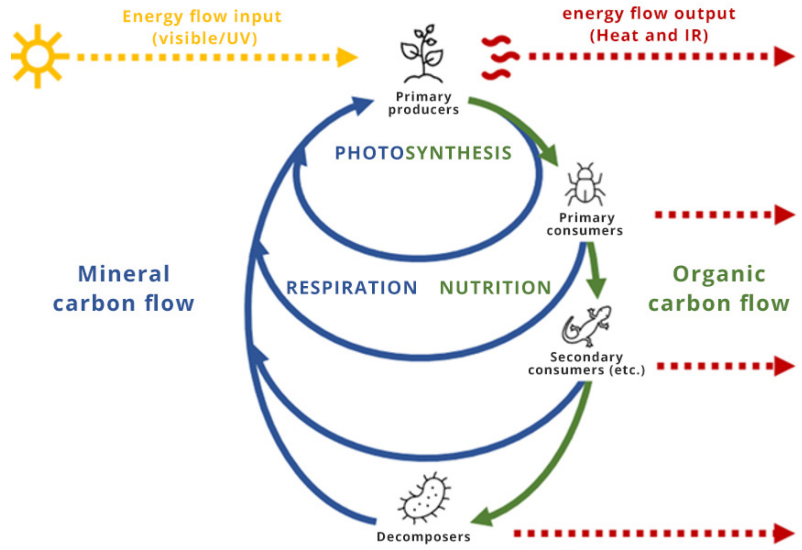


Figure 3: Principle of interconnection and interdependence through the example of trophic relationships at the ecosystem scale © Ceebios

If organisms are interconnected within ecosystems, their level of dependence varies, and a second observation emerges. If a consumer organism disappears, then the chain is impacted but not broken. On the other hand, if the primary producers or decomposers are removed from the equation, then the flow stops. Matter and energy become trapped in one compartment. To avoid this destructive scenario, ecosystems are naturally structured as a pyramid with a broad base (the primary producers) and a narrow top (the final consumers).

Formalized in 1942 by Lindemann’s law, this structuring of life shows that, in each ecosystem, a factor of about 10 separates the energy flows of two successive strata of consumers: “life builds from the bottom up”[14] (Figure 4).

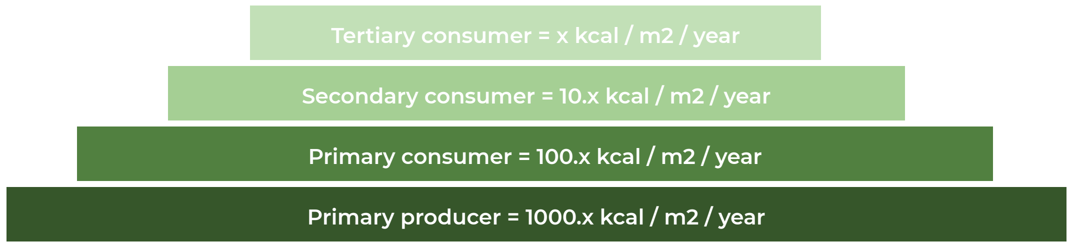


Figure 4: Illustration of the bottom-up construction principle / through the example of trophic pyramids and Lindemann’s law

This construction principle, which recommends a bottom-up approach, does not only apply to the establishment of ecosystems. It can be observed at all scales, including that of organisms, constructed from cells associated with tissues, themselves associated with organs, etc.

Once energy enters the living world, it must be able to be transmitted, stored, and used.

This diversity of functional needs associated with the management of energy in chemical form leads to a variability in the characteristics of the vectors considered (mobility, reactivity, stability, etc.). Thus, simple sugars such as glucose, formed by primary producers, are the "crossroads" molecules in the network of biochemical transformations required for the functional needs associated with energy management (Figure 5).

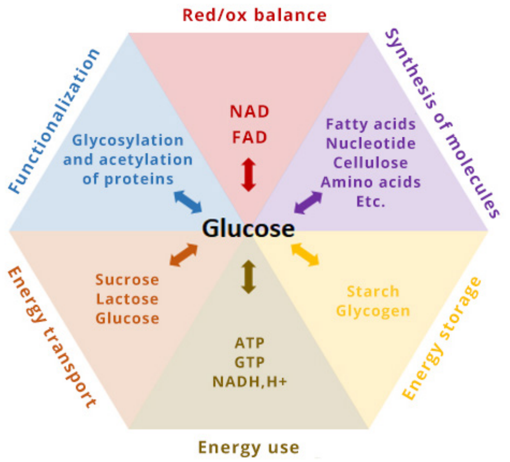


Figure 5: Illustration of the principle of sugar functioning

When a cell needs energy, it uses glucose as a reagent for cellular respiration. This biological mechanism leads to the synthesis of Adenosine TriPhosphate (ATP), the"molecular unit of currency".

Energy is produced in the cells by oxidation of this sugar (Eq. 2). It is ATP, not sugar, which is the energy carrier directly usable by the cells.

$$\text{Glucose} + 6\,O_2 \rightarrow 6\,CO_2 + \text{ATP} + \text{Heat}$$

Eq. 2 Global reaction balance of aerobic respiration

When the supply exceeds the demand, the energy carriers are stabilized before being transported and/or stored. Living organisms use the polymerization of matter as a regulatory lever. Thus, the more glucose is polymerized (assembled into molecular chains), the more stable it is.

This greater stability favours its transport (sucrose), and then its storage (starch) and can even provide structural functions (cellulose). When energy carriers must be stored for a long time, sugars are transformed into lipids (fats), which are even more stable and more energy dense (Figure 6).

The central role of the polymerization reaction in the management of energy carriers by living organisms underlines the fact that "living organisms are assembled in chains[14]". In particular, it is the variability in the length of these chains that allows the emergence of the diversity of functions for the management of energy carriers: their storage, transport and use.

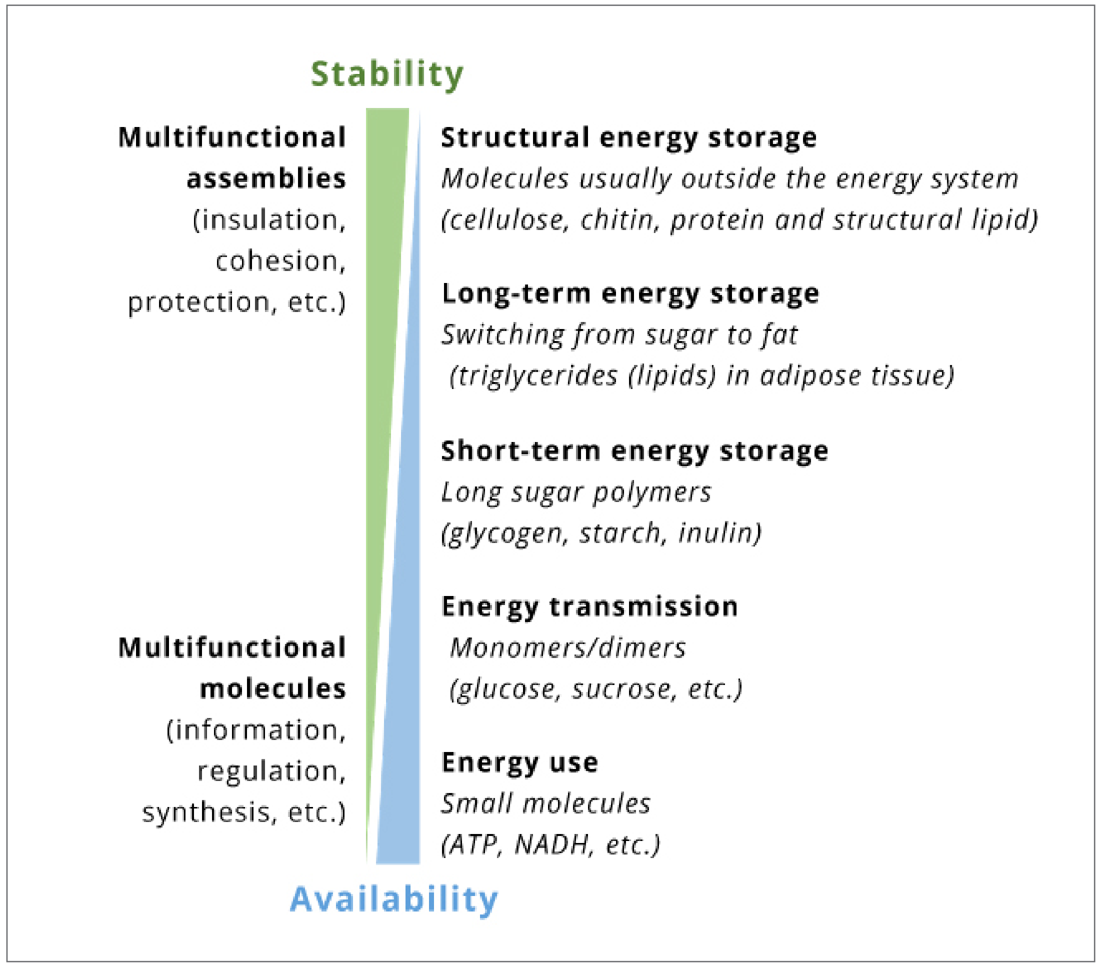


Figure 6: Illustration of the principle of molecular-scale chain assembly to ensure the stability of energy storage carriers © Ceebios

The analysis of the energy sources and vectors of the living world leads us to emphasize one last element that is fundamentally rooted in the management of these resources. As stated in the second principle of thermodynamics, the quality of energy only degrades over time, from highly structured forms such as chemical energy, to a disorganized form: thermal energy.

The living world is thus composed of a set of systems that constantly degrade the quality of the energy that passes through them to structure their own matter and perform their functions.

While the quality of energy therefore only evolves in a linear fashion, the flow of matter, and therefore of energy carriers, is in contrast profoundly circular. The balances of photosynthesis and respiration speak for themselves: for matter, life on Earth functions essentially in a closed circuit (Figure 7).

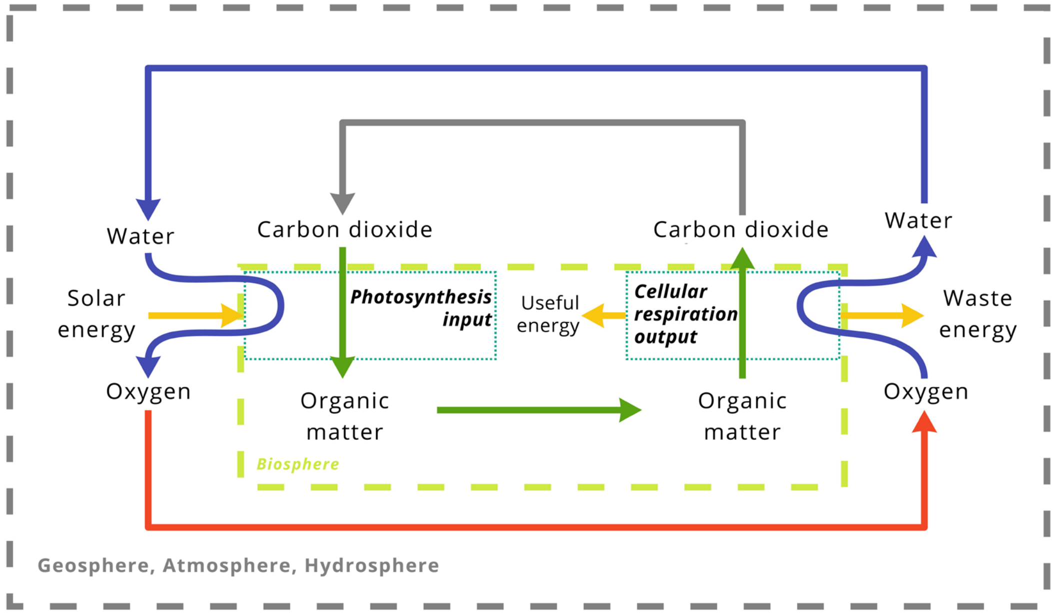


Figure 7: Illustration of the principle of recycling in living organisms through the example of the balance between the mechanisms of respiration and photosynthesis, the foundations of energy management © Ceebios

Thus, the atoms and molecules that compose us and carry our energy are the same as those that composed the plants at the time of the dinosaurs. The flow of matter ensured by the "primary producers/decomposers" couple constitutes the basis of the durability of the mechanism by which living beings can supply themselves with energy without exhausting the stock of resources: "living beings recycle what they use[14]". In this respect, the construction and degradation phases are equally important in guaranteeing the ability of the living world to persist.

A close link between matter and energy emerges from these flows. In general, with few chemical elements (C, H, N, O...), living beings assemble unitary blocks into superstructures which, through their architecture and their arrangement at all scales, become functionalized. Where the technosphere uses rare elements (such as metals) or energy to process the material (for example, the manufacture of glass at high temperatures), "living organisms use information[14]". This is the variability of genetic information, which leads to a diversity of arrangements of only 20 amino acids in several hundred thousand proteins with their own functions[18] .

18 Vincent, J. F. V., Bogatyreva, O. A., Bogatyrev, N. R., Bowyer, A., & Pahl, A. K. (2006). Biomimetics: Its practice and theory. Journal of the Royal Society Interface, 3(9), 471-482. https://doi.org/10.1098/rsif.2006.0127

.02 FUNCTIONS AND ENERGY CONVERSION IN LIVING ORGANISMS

Every organism is permanently subjected to many environmental constraints that require a complex multifunctional response. This response relies on the conversion of energy to do work and perform functions. The main energy carrier used by cells is ATP (see "Inspiration axis 1"). This universal molecule is the agent for the use of energy in living organisms. By analogy, we can compare this molecule to a battery with two main forms: adenosine diphosphate (ADP, discharged) and adenosine triphosphate (ATP, charged).

The binding of the third phosphate group is said to be "high potential" in that it requires a significant amount of energy to be maintained. ATP, which is very unstable, tends to quickly revert to its more stable form, ADP, by reacting with its environment to transfer energy and release the third phosphate group (Figure 8).

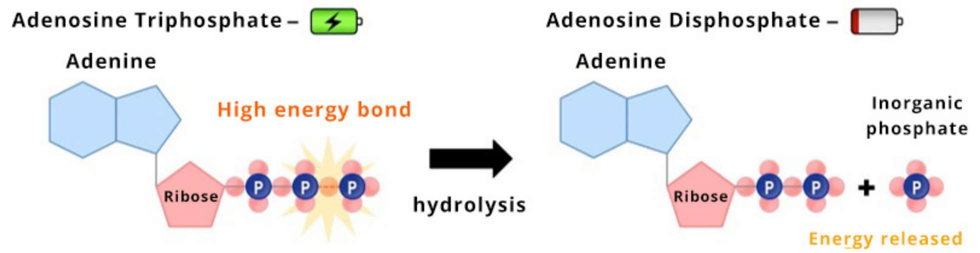


Figure 8. ATP hydrolysis reaction that allows the use of energy in living organisms in a universal way

As a result, ATP is formed locally and continuously by the organism[19] . The cell constrains the return of ATP to the ADP form by coupling it with other reactions to take advantage of the resulting free energy. This is how almost all endergonic reactions (requiring energy to occur) in the organism are carried out.

For example, ATP is used to enable the conformational change of the myosin molecule, resulting in its movement on a molecular scale, which, when multiplied, leads to the slippage of muscle fibers and the contraction of muscles that enable locomotion[20] .

The functions of the living world are thus based on the supply of energy made possible by the charge/discharge cycles of ATP[20]. The ability of functional subsystems (ATP, muscles, bioluminescent complexes, etc.) to return to their initial state ensures that organisms are able to repeatedly perform their various functions, "life works cyclically[14]".

19 Törnroth-Horsefield, S., & Neutze, R. (2008). Opening and closing the metabolite gate. In Proceedings of the National Academy of Sciences of the United States of America (Vol. 105, Issue 50). https://doi.org/10.1073/pnas.0810654106

20 https://planet-vie.ens.fr/thematiques/animaux/systeme-locomoteur/la-contraction-musculaire

"Moreover, every organism constantly performs several functions in parallel, requiring fine and balanced energy management:"

Nutrition

To incorporate matter and accumulate chemical potential energy to grow, reproduce, divide, proliferate, maintain the integrity of the organism.

Homeostasis

Maintaining physiological constants (temperature, blood sugar, etc.) to allow for optimal metabolic activity. For example, thermal homeostasis uses radiation (thermal energy, electromagnetic energy) to cool the body.

Intra-organism communication

Transmitting information between the systems that make up a given biological organism. It takes place within the organism, notably through the release of chemical messengers (e.g. hormonal communication) or an osmo-electric potential leading to the propagation of an electric current (nervous communication).

Communication with other organisms

Transmitting information between two distinct biological organisms. It can be carried out by movement (chemical energy → mechanical work), sound (chemical energy → mechanical energy, sound wave), light by bioluminescence in particular (chemical energy → electromagnetic energy) or even the exchange of pheromones.

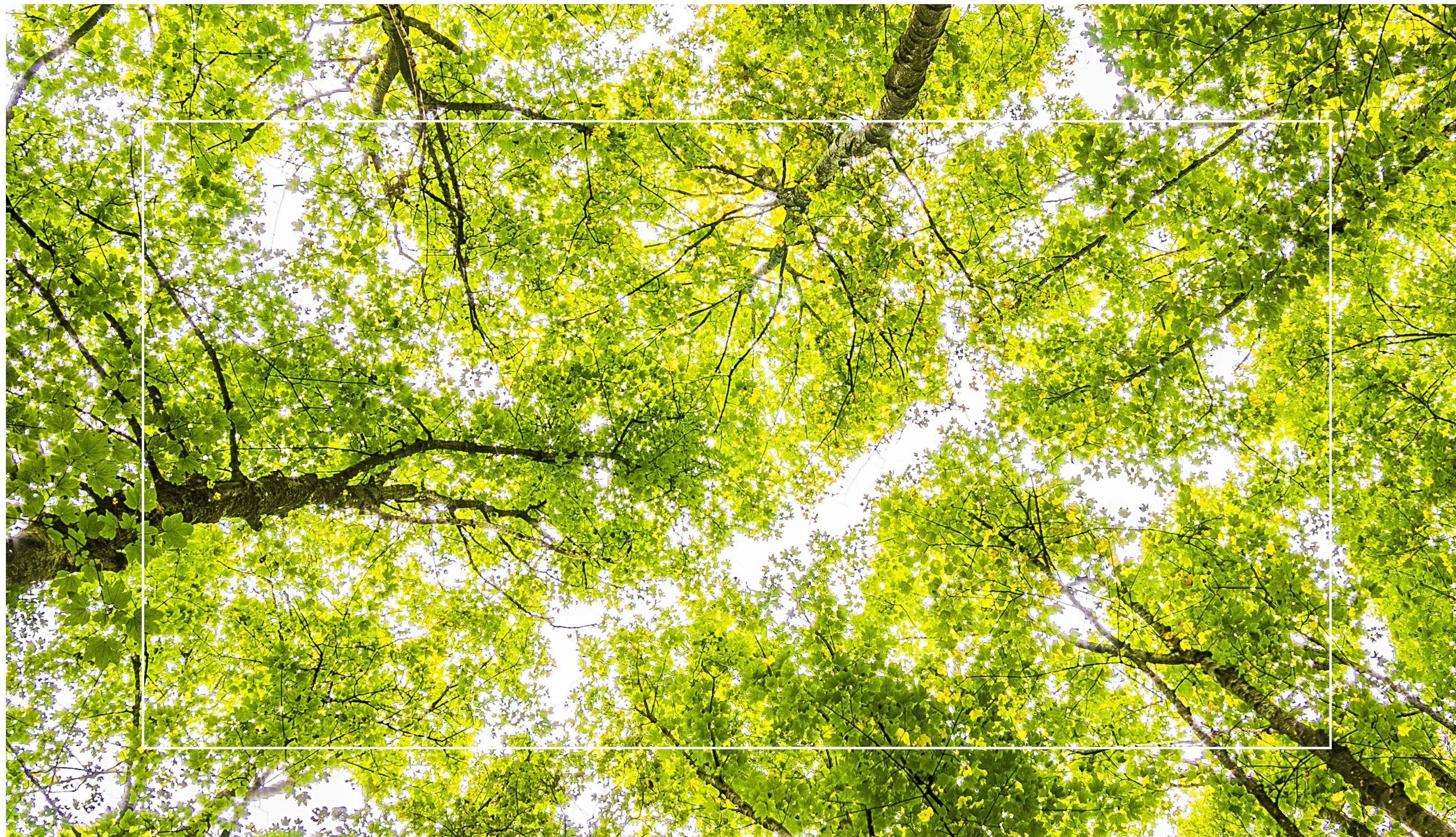
Locomotion

Moving (walking/swimming/jumping/flying/climbing) by converting chemical energy into mechanical, kinetic, or gravitational potential energy.

Faced with these multiple needs, living organisms do not maximise the functions they perform, but adopt the "good enough" rule to ensure their survival. This dynamic can be observed in particular from the point of view of natural selection, which leads to the adaptation of organisms towards functional equilibria, compromises, which respond to the environmental constraints to which they are exposed.

Furthermore, recent work has shown that some organisms minimize the amount of waste they produce when they reach their optimal operating conditions[21] , raising the question of the generalization of such an observation. In addition to the adaptation of species over time through natural selection, leading to these functional trade-offs, organisms continuously manage their internal distribution of energy according to their needs while respecting the basic functional balance that ensures their survival. In conclusion: "living organisms tend to find the best compromise rather than maximizing[14]".

21 Herbert, E., Ouerdane, H., Lecoeur, P., Bels, V., & Goupil, C. (2020). Thermodynamics of Animal Locomotion. Physical Review Letters, 125(22), 228102. https://doi.org/10.1103/PhysRevLett.125.228102



AXES OF INSPIRATION

.03 SPECIALIZATION OF BIOLOGICAL SUBSYSTEMS

Among the functions performed by an organism, energy management relies on a set of organs and tissues structured in a distribution network feeding energy collection, storage and utilization subsystems.

Leaves are a remarkable example of a model for the study of solar energy collection infrastructures. Indeed, because of their interface role, these organs are constantly exposed to environmental constraints (sun, wind, insects, etc.[22]). Over time, these constraints have led to the selection of traits that provide multiple functions such as self-repair, protection against aggressors, reduction of wind resistance, etc. It is from this functional diversity that the resilience of these energy-harvesting structures emerges[23] , which are themselves associated with a foliage with its own multifunctional character such as self-shading (multiscale multifunctionality) (Figure 9).

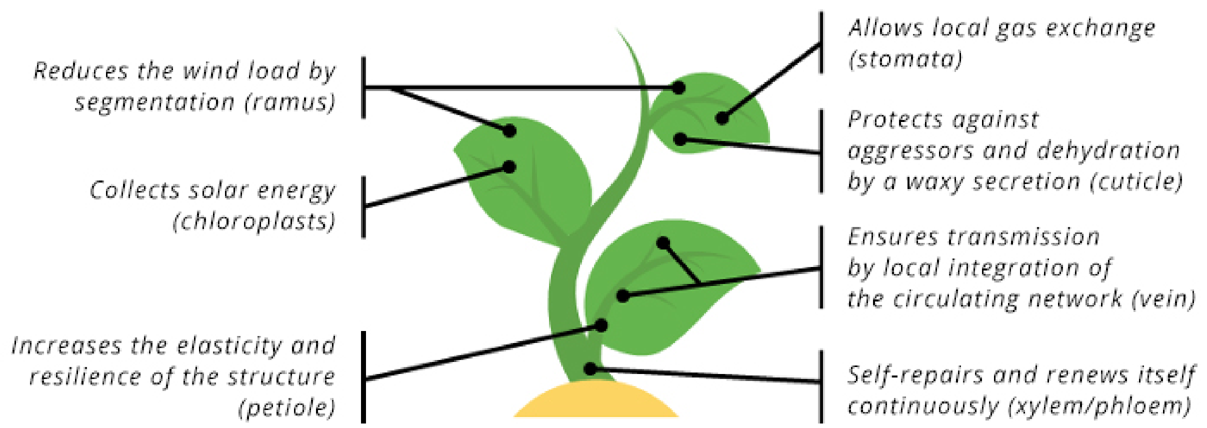


Figure 9: Illustration of the principle of managing trade-offs related to multifunctionality, the example of the leaf
© Ceebios © Icon by DynosoftLabs / Flaticon

Globally, the collecting organs generate an energy flow initially directed to meet the needs of basal metabolism and in particular the most consuming organs, such as the brain in animals. The surplus energy in circulation is stored in the so-called "reserve" organs, such as tubers in plants or adipose tissue in vertebrates.

This storage is carried out by the accumulation of energy carriers and by their transformation into denser carriers (from carbohydrates to lipids). When there is a strong increase in demand and/or a decrease in the inflow, a secondary energy flow is established, from the reserves to the user organs carrying out the biological functions.

22 Barthlott, W., Mail, M., Bhushan, B., & Koch, K. (2017). Plant surfaces: Structures and functions for biomimetic innovations. In Nano-Micro Letters (Vol. 9, Issue 2, p. 23). SpringerOpen. https://doi.org/10.1007/s40820-016-0125-1

23 C. GoupiL, E. Herbert H. Benisty," LINKS série 5-6, Penser la résilience. Un regard thermodynamique : 1 du concept de resilience" P 48-53, 2: de la résilience des organismes à celle des sociétés, P 156-163 - 2021

On the scale of an organism, the energy distribution system is essentially the circulatory system. It is through circulating fluids (haemolymph in invertebrates, sap in vascular plants, blood in vertebrates, etc.) that energy carriers are transported, along with information molecules and other blood components, from the organs of collection or storage to the organs of use. The structure of these networks is based on fractal branching rules. The number of segments increases as their diameter and length decrease. This fractal structure, selected during evolution, leads to an increase in the total surface area of the interface and allows the multiplication of local energy supply points. The body is "irrigated" with energy vectors by the circulatory system.

Thermal energy is transported by this circulatory system but also distributed, by a passive but very controlled conduction, through the biological structures.

Both at the ecosystem and organism levels, living systems remain deeply interdependent and interconnected.

Note that all these systems remain multifunctional, and the notion of "specialization" represents the variation in their functional equilibrium with respect to other systems, following the principle of compromise rather than maximization. For example, storage devices also use and transport energy but in a more localized and limited way than other systems. In addition, they have many other functions that also require energy conversions or are provided passively such as insulation or mechanical protection (Table 6).

Examples of specialized systems	Management function of energy	Example of other functions
Foliage of plants	Collecting vectors and ensuring energy supply	Hydraulic circulation motor (evapotranspiration), support for seed formation/dissemination (self-replication), shade for the local ecosystem, etc.
Circulatory system of plants	Transmit vectors and ensure energy distribution	Transport of waste, transport of immune agents, use as an information system (e.g. hormones), etc.
Adipose tissue (fat) in mammals	Storing vectors and ensuring the constitution of energy reserves	Thermal insulation, heat generation (brown adipose tissue), mechanical protection, internal communication (secretion of hormones), etc.
Animal muscle tissue	Use energy and ensure the generation of work	Heat generation (thrill), mobility, physical protection, external communication (e.g. deterrence), etc.

Table 6. Illustration of the multifunctional character of biological systems specialized in energy management © Ceebios

Living beings are organized around subsystems concentrating specific energy management activities. This architecture, polarized and connected by a network, is associated with a regulation system closely linked to the notion of information and intra-organism communication. Organisms must therefore be able to measure their internal energy to anticipate or respond to energy stress, if necessary. These mechanisms allow decisions to be made to ensure the survival of the organism in its dynamic environment.

.04 STRESS MANAGEMENT AND ENERGY BALANCE REGULATION

Within each biological system, the evaluation of the available energy appears central in order to modulate the incoming/outgoing flows and to ensure an efficient energy management. This evaluation is done by:

- direct measurements of stored (glycogen, starch, etc.) or free (glucose, sucrose) sugar concentrations. This is done locally (e.g. photosynthetic cells), but also centrally in animals via organs specialised in the regulation of glycaemia such as the pancreas, the liver or the brain; indirect measurements of the quantity of available reserves, particularly in lipid form.
- In animals, adipose tissue secretes molecules such as leptin and insulin. The blood concentration of these molecules is then proportional to the amount of lipid reserves. It is the brain (hypothalamus and solitary tract) that perceives these molecules and causes the global adjustment of the flows to maintain the energy balance.

At the scale of the biological organism, the regulation of energy distribution is carried out by a multifactorial process directed, depending on the species, by the nervous, humoral and hormonal communication systems. At the cellular level, regulation is under the control of signal molecules that direct the transformation processes of energy carriers. The transmission and regulation system, but also the setting up of new storage structures, are thus intrinsically linked to the information system: once again, "life is organized with information[14]".

Through its role as an energy transport network, the circulatory system is at the centre of the regulatory mechanism.

This energy regulation:

- **based on physiological set points.**
  This basal level of organ consumption is variable and constitutes a reference energy switch. For example, it is estimated that at rest, the brain accounts for about 20% of the total energy consumed[24] , while the heart uses only 8%[25] .
- **considers specific local energy needs.**
  In animals, muscular activity induces a rapid and local stimulation of the vasodilation/vasoconstriction of the vascular network (respectively the increase or reduction of the diameter of a blood vessel) leading to a more or less important blood flow, and thus of energy carriers, towards a given area.
- **is subject to unpredictable and/or seasonal environmental factors.**
  This is the case, for example, in plants with the phenomenon of the "rise of the sap" which can only be observed at the end of winter, during which a very rich sap goes up the network reserved for the poor sap to bring energy to the buds from the root reserves.
- **is associated with survival mechanisms.**
  For example, in animals, the perception of imminent danger causes a spike in adrenaline that leads to an almost instantaneous redirection of blood flow to the muscles of the motor limbs. This is the so-called "fight-flight" reflex response, which ensures that the organism has the energy available to carry out one or other of these defence strategies[26] .

24 Magistretti, P. J., & Allaman, I. (2015). A Cellular Perspective on Brain Energy Metabolism and Functional Imaging. Neuron, 86(4), 883-901. https://doi.org/10.1016/J.NEURON.2015.03.035

25 Brown, D. A., Perry, J. B., Allen, M. E., Sabbah, H. N., Stauffer, B. L., Shaikh, S. R., Cleland, J. G. F., Colucci, W. S., Butler, J., Voors, A. A., Anker, S. D., Pitt, B., Pieske, B., Filippatos, G., Greene, S. J., & Gheorghiade, M. (2016). Mitochondrial function as a therapeutic target in heart failure. Nature Reviews Cardiology 2016 14:4, 14(4), 238-250. https://doi.org/10.1038/nrcardio.2016.203

26 Jansen, A. S. P., Nguyen, X. Van, Karpitskiy, V., Mettenleiter, T. C., & Loewy, A. D. (1995). Central Command Neurons of the Sympathetic Nervous System: Basis of the Fight-or-Flight Response. Science, 270(5236), 644-646. https://doi.org/10.1126/SCIENCE.270.5236.644

Thus, a set of signals and molecular sensors allows organisms to perceive their situation in real time and to ensure the maintenance of energy constants (homeostasis), particularly in the event of stress.

Energy stress may be due to a one-time, unanticipated imbalance between incoming and outgoing energy flows, or to the cyclical and intermittent nature of living energy resources.

Whether we consider the daily sunshine cycle for electromagnetic energy or the seasonal cycle for chemical energy, the energy available varies over time.

Strategies	Punctual non-anticipable	Daily anticipable	Seasonal anticipable
Storage external	Degrading food bowl in animals	Regurgitated food for the offspring	Honey reserve in bees
Storage internal	Circulating and cellular vectors: ATP, phosphocreatine, glucose, etc.	Polysaccharide and triglyceride reserve	Long-term reserve in the form of fat
Separation temporal processes	Non-photochemical phase of photosynthesis	Overnight CO_2 storage in cacti	Annual development cycle in insects
Alternative metabolic	Lipid degradation and structural proteins	Plant respiration and photosynthesis	Degradation of brown fat in polar bears
Metabolic slowdown	Cryptobiosis in tardigrades	Sleep in animals	Hibernation, Sleep
Solving the constraint	Feeling of hunger leading to hunting in carnivores	Heliotropism in sunflowers	Seasonal migration in many animals

Table 7. Energy stress response strategies
© Ceebios

Faced with vital energy constraints, life presents a large number of possible adaptations, making its development possible on most of the planet.

This ability to acclimatize and evolve to meet a multitude of constraints highlights how "living things are opportunistic[14]".

From an energy perspective, this principle is best illustrated by the diversity of trophic types (ways in which an organism meets its material and energy needs) present in the living world and the diversity of functions that result from them[27] (Table 8).

27 Schuldt, A., Assmann, T., Brezzi, M. et al. Biodiversity across trophic levels drives multifunctionality in highly diverse forests. Nat Commun 9, 2989 (2018). https://doi.org/10.1038/s41467-018-05421-z

Source of energy	Electron source	Source carbon	Type trophic	Main examples
Light Photo-	Compound organic -organo-	Organic - heterotrophic	Photoorganoheterotrophic	Some bacteria
		Mineral (CO_2) - autotrophic	Photoorganoautotrophic	Some bacteria (athiorhodaceae...), chlorophyllous plant hemiparasites
	Inorganic -litho-	Organic - heterotrophic	Photolithoheterotrophic	Some bacteria (thiobaca...)
		Mineral (CO_2) - autotrophic	Photolithoautotrophic = mineral nutrition	Chlorophyllous plants, some bacteria
Oxidation of a chemical compound reduced, organic or mineral Chemo -	Compound organic -organo-	Organic - heterotrophic	Chemoorganoheterotrophic	Animals, fungi, most bacteria
		Mineral (CO_2) - autotrophic	Chemoorganoautotrophic	Rare, some bacteria (mixotrophy)
	Inorganic -litho-	Organic - heterotrophic	Chemolithoheterotrophic	Some bacteria (Bosea, Albibacter)
		Mineral (CO_2, CH_4) autotrophic	Chemolithoautotrophic	Some terrestrial or marine bacteria (hydrothermal ecosystems). The energy source is inorganic

Table 8. Illustration of the principle of opportunism of living organisms with regard to local resources Source: Wikipedia

"Whether it is a question of sources and vectors, conversion processes, system organization or responses to energy stress, studying living organisms allows us to draw up specifications for biomimetic energy systems that will be able to respond to the ecological, technical-scientific and political-societal challenges of our time."

SYNTHESIS AND PERSPECTIVES

This report explores the potential of biomimicry to address modern energy challenges. Drawing inspiration from the way the living world manages energy invites us to consider two synergistic axes:

- A strategic axis that underlines the principles structuring the relationship between life and energy and leads us to rethink our relationship with energy in a systemic way;

- A technical axis that describes how life can help us identify concrete levers for the transition to responsible and efficient energy systems.

Studying the link between the living world and energy thus leads us to pose a set of structuring reflections on the way in which Life has maintained a dynamic balance for 3.8 billion years, guaranteeing its development.

These observations are structured during the report through the prism of the principles of living as formalised by Hoagland, Dodson & Hauk (Table 9).

	Material	Organization
Living beings tend to optimize rather than maximize	Multifunctional	Made up of repetitions, adaptable to the variations of the environment and adapted to its main constraints
Living things recycle everything that they use / works cyclically	Degradable into universal unit blocks that can be recovered in the ecosystem	Based on the balance of flows
Living things come together chained	Made up of unit blocks assembled from functional polymers	Structured by interdependence biological systems (e.g. food chains)
The living is organized with information	A complex and functional architecture	Setting up in association with an information network
The living built from bottom to top	Self-assembly of unit blocks	Based on producers of organic matter
Life is interconnected and interdependent	Whose components are part of the metabolism	Ecosystem
Living things work with sugar	Structural, energy vector, information vector etc.	Based on sugar flows

Table 9. Summary illustrating the principles of life at different scales © Ceebios

The clear shift that emerges from the confrontation of the principles of life with the technological world leads to a set of perspectives, lines of thought and potentialities to be explored:

- Living organisms invite us to consider an energy collection system based on flows (water, air, radiation, heat) and not on stocks (hydrocarbons, gas, uranium, etc.) of vectors. What if we were to draw inspiration from living organisms to size our energy use systems according to the local availability of energy flows? To rethink the scales from which to consider our infrastructures as autonomous energy systems? To design the organization of our systems in a way that is similar to the way organs, organisms and ecosystems are structured?

- Living beings invite us to consider a distribution and storage system in the form of stock vectors and not of flows[15] . In this way, the vectors transported or stored are temporarily stabilized before being made available when needed. These observations may even call into question the place of electricity in our energy system. What if we were to draw inspiration from the living world and make this form the last link in the chain, the vector of use, the equivalent of ATP in the living world? To generalize the mobilization of physical networks of matter (such as water networks) for the transport of energy vectors in the image of biological circulatory systems?

- Living things invite us to question our view of energy efficiency. The collection efficiency of a leaf is about 2%, which is almost 20 times less than our best solar panels (around 35%[28]). On the other hand, they are produced from abundant elements in a few weeks and therefore for an infinitely lower total cost. They are also organized in a wind-resistant, self-cleaning, self-repairing, and continuously renewing foliage. What if we were to take inspiration from living organisms and redirect our innovations towards the search for compromises[29 ,23]? To build systems with a stable architecture but whose parts can be continuously renewed? To look at any use of energy as a directed loss?

- Living beings invite us to face the trade-off between adaptability and adaptation. An adapted system is not very adaptable and an adaptable system is not very adapted[30] . What if we were to take inspiration from life to design systems whose adaptability depends on the variability of their environment? To design electricity networks made up of highly adaptable portions to respond to strong variations in a collection of flows and highly adapted portions to ensure a constant supply from the storage systems to the systems of use? To propose tomorrow systems with an operating range adapted to their environment, like cars adapted to city speed limitations?

...

28 Blankenship, R. E., Tiede, D. M., Barber, J., Brudvig, G. W., Fleming, G., Ghirardi, M., Gunner, M. R., Junge, W., Kramer, D. M, Melis, A., Moore, T. A., Moser, C. C., Nocera, D. G., Nozik, A. J., Ort, D. R., Parson, W. W., Prince, R. C., & Sayre, R. T. (2011). Comparing photosynthetic and photovoltaic efficiencies and recognizing the potential for improvement. Science (New York, N.Y.), 332(6031), 805-809. https://doi.org/10.1126/SCIENCE.1200165

29 J. F. V. Vincent, The trade-off: A central concept for biomimetics, Bioinspired, Biomimetic and Nanobiomaterials, vol. 6, no. 2, pp. 67-76, Jun. 2016, doi: 10.1680/jbibn.16.00005.

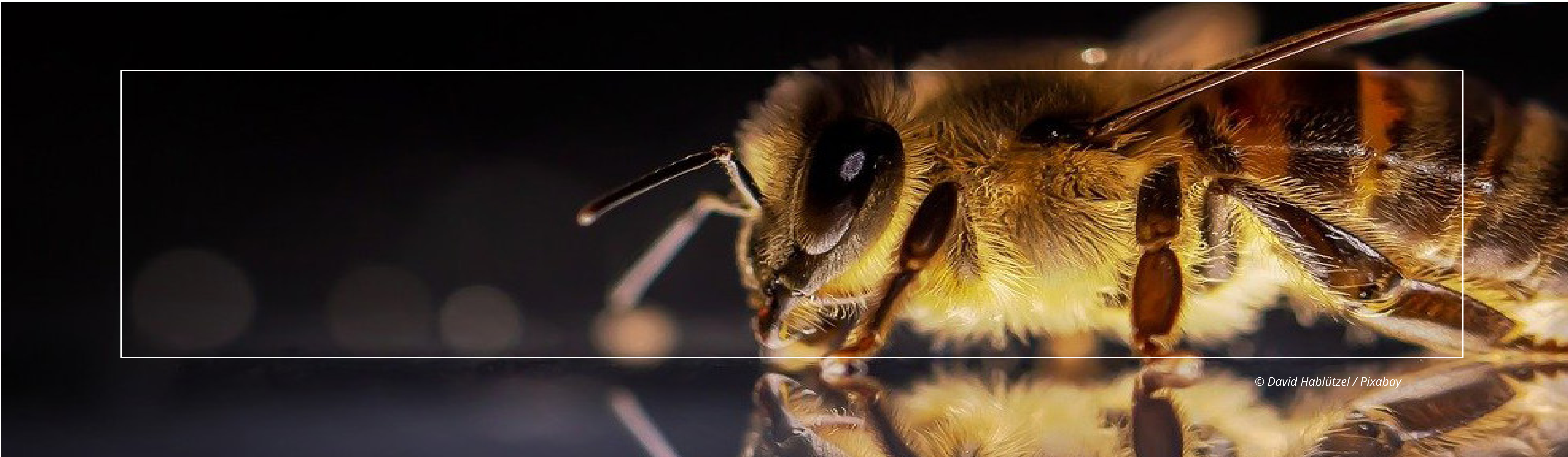
30 C. Goupil, E. Herbert Adapted or Adaptable: How to Manage Entropy Production, Entropy, 22(1), 29 - 2020

Living organisms invite us to consider the autonomy of energy systems (self-assembly, self-organization, self-cleaning, self-repair). What if we were inspired by living organisms to design tomorrow's self-cleaning solar panels without chemical treatment? To develop self-healing networks? To reorganize the fields of wind turbines or solar panels according to the exposure to flows or environmental constraints?

Living organisms invite us to make our energy systems cooperate with each other. What if we were to draw inspiration from living organisms to manage fields of wheat, barley, windmills and solar panels as sub-systems of the same operation and to compensate for the variations of each other? To develop a network that produces energy? To make possible the generalization of the association between agricultural production and energy collection (agrivoltaics, methanizer, etc.)?

The living invites us to build our systems only from biocompatible and reusable elements in a modular way. What if we were to draw inspiration from living organisms to reorganise our system to manage matter in a closed circuit? In order to achieve tomorrow a decoupling of performance from the quantity of material used?

"So many reflections that can change the way we think about the energy sector and rethink our practices. The abandonment of fossil fuels is only a question of time and the transition to a profoundly different system must be anticipated in a systemic manner. The coming energy transition represents the transition from a technological world with the status of final consumer to a technological world with the status of primary producer. This is a profound emancipation and a considerable reduction in the weight now carried by the biosphere."



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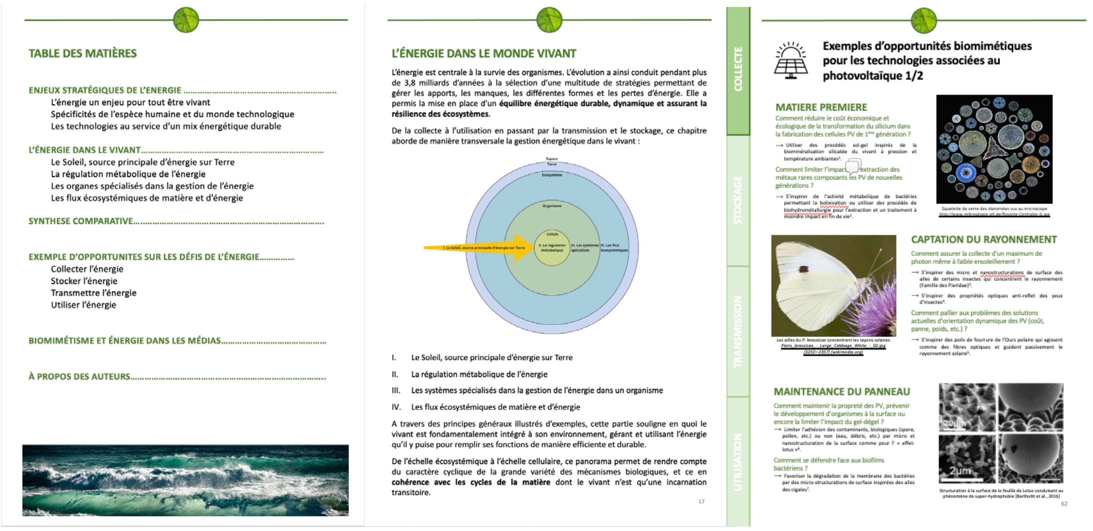
TO GO FURTHER

WORKING GROUP & LITERATURE REVIEW



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L'ÉNERGIE DANS LE MONDE VIVANT

L'énergie est centrale à la survie des organismes. L'évolution a ainsi conduit pendant plus de 3,8 milliards d'années à la sélection d'une multitude de stratégies permettant de gérer les apports, les manques, les différentes formes et les pertes d'énergie. Elle a permis la mise en place d'un **équilibre énergétique durable, dynamique et assurant la résilience des écosystèmes.**

De la collecte à l'utilisation en passant par la transmission et le stockage, ce chapitre aborde de manière transversale la gestion énergétique dans le vivant :

I. Le Soleil, source principale d'énergie sur Terre
II. La régulation métabolique de l'énergie
III. Les systèmes spécialisés dans la gestion de l'énergie dans un organisme
IV. Les flux écosystémiques de matière et d'énergie

A travers des principes généraux illustrés d'exemples, cette partie souligne en quoi le vivant est fondamentalement intégré à son environnement, gérant et utilisant l'énergie qu'il y puise pour remplir ses fonctions de manière efficiente et durable.

De l'échelle écosystémique à l'échelle cellulaire, ce panorama permet de rendre compte du caractère cyclique de la grande variété des mécanismes biologiques, et ce en **cohérence avec les cycles de la matière** dont le vivant n'est qu'une incarnation transitoire.

17

COLLECTE
STOCKAGE
TRANSMISSION
UTILISATION

Exemples d'opportunités biomimétiques pour les technologies associées au photovoltaïque 1/2

MATIERE PREMIERE
Comment réduire le coût économique et écologique de la transformation du silicium dans la fabrication des cellules PV de 1ère génération ?
→ Utiliser des procédés sol-gel inspirés de la biominéralisation silicatée du vivant à pression et température ambiantes.
Comment limiter l'impact … extraction des métaux rares composants les PV de nouvelles générations ?
→ S'inspirer de l'activité métabolique de bactéries permettant la bolixivation ou utiliser des procédés de biohydrométallurgie pour l'extraction et un traitement à moindre impact en fin de vie.

Squelette de verre des diatomées vus au microscope

CAPTATION DU RAYONNEMENT
Comment assurer la collecte d'un maximum de photon même à faible ensoleillement ?
→ S'inspirer des micro et nanostructurations de surface des ailes de certains insectes qui concentrent le rayonnement (Famille des Pieridae).
→ S'inspirer des propriétés optiques anti-reflet des yeux d'insectes.
Comment pallier aux problèmes des solutions actuelles d'orientation dynamique des PV (coût, panne, poids, etc.) ?
→ S'inspirer des poils de fourrure de l'Ours polaire qui agissent comme des fibres optiques et guident passivement le rayonnement solaire.

Les ailes du *P. brassicae* concentrent les rayons solaires

MAINTENANCE DU PANNEAU
Comment maintenir la propreté des PV, prévenir le développement d'organismes à la surface ou encore la limiter l'impact du gel-dégel ?
→ Limiter l'adhésion des contaminants, biologiques (spore, pollen, etc.) ou non (eau, débris, etc.) par micro et nanostructuration de la surface comme pour l' « effet-lotus ».
Comment se défendre face aux biofilms bactériens ?
→ Favoriser la dégradation de la membrane des bactéries par des micro-structurations de surface inspirées des ailes des cigales.

Structuration à la surface de la feuille de Lotus conduisant au phénomène de super-hydrophobie [Bartholt et al., 2016]

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Figure 10. Full report "Biomimicry & Energy

This Biomimicry & Energy synthesis document prefigures actions aiming at the development of biomimetic practices within the energy sector.

In the continuity of its actions of structuring and coordination of the working groups Bio-inspired Urban Project, Bio-inspired Materials, Information Management and Marine Biomimicry, Ceebios and its partners wish to gather the actors of the sector to set up a new working group: Biomimicry & Energy.

The launch of this working group is accompanied by the availability to the cooperators of the SCIC Ceebios[31] and to subscribers to the Biome+ offer of Ceebios of an in-depth report (for now only available in French) presenting, in particular, a review of the scientific literature associated with the subject, a set of thematic sheets describing existing innovations or those under development (TRL 3-4). Approximately 200 bibliographical references addressing the main innovation issues of some fifteen technological systems (photovoltaic panels, batteries, lamps, etc.), on cross-cutting themes (thermoregulation, raw material recycling, maintenance, etc.) are presented (Figure 10).

31 Ceebios has been a cooperative society of collective interest since 1st January 2021

DRAWING INSPIRATION FROM THE LIVING / FOR ENERGY MANAGEMENT

EXAMPLES OF CONCRETE ACHIEVEMENTS

Rheticus project by the German groups Evonik and Siemens aiming at the implementation of a plant that performs the electric electrolysis of CO_2 and H_2O to produce H_2 and CO used as reaction substrates for fermenters. Potential products are bio-fuel, bioplastic or food additives.

Biome Renewables is marketing bio-inspired wind turbines based on the kingfisher and the maple samaritan. Their shape guides the air flow to improve its capture and ensure better turbulence management. These adaptations reduce noise pollution and increase annual energy production by up to 13%.

Whether through mathematical models describing the alternating positioning of leaves on their stems (phyllotaxis), which allows for the optimization of sunlight (natural lighting and thermal energy supply), or the ability of termite mounds of the species *Macrotermes michaelseni* to passively regulate their temperature, the architectural firm In Situ draws inspiration from living beings to rethink the habitat.

Prophesee markets neuromorphic cameras and algorithms, i.e. they imitate the functioning of the human eye and brain. Unlike conventional cameras, which refresh all the pixels at regular intervals, event-based cameras only record changes in brightness, pixel by pixel, continuously. This makes these cameras particularly energy-efficient.

Encycle develops technology to improve the energy efficiency of air conditioning. Its flagship product is SwarmLogic®, a system of wireless controllers that communicate with each other like a swarm of bees and control the transmission of energy within the building's air conditioning network as needed.

Whylot has developed electric motors that are lighter and smaller than reference motors thanks to several innovations, including a thermoregulation system inspired by honeycomb architecture.

Glowee takes advantage of the bioluminescence capacity of microorganisms and thanks to biotechnology offers a less energy consuming alternative to conventional lighting systems.

Wavera adapts this fluid movement mechanism to its hydraulic pumps with a weight and volume saving as well as 30% less energy consumption.

By reversing the wave propulsion mechanism, Eel Energy is developing a wave turbine technology that respects the seabed and is not subject to cavitation. Unlike offshore wind turbines, this energy source has the advantages of being renewable, predictable and regular.

Push4M revises the current robotic solutions with a technology that allows to gain in energy efficiency, lightness, precision and compactness in the implementation of a mechanical movement. This cobotics solution can be applied to the manufacturing, handling, construction and public works sectors, while safely integrating the human operator nearby (cobotics).

The locomotion of marine organisms is mainly based on the propulsion of a fluid by membrane undulation and not on the rotation of propellers. Based on this observation, many deeptech startups have developed innovative technologies:

DRAWING INSPIRATION FROM THE LIVING / FOR ENERGY MANAGEMENT

EXAMPLES OF NATIONAL/ & INTERNATIONAL EXPERTISE

Laurent Billon, IPREM - University of Pau and Pays de l'Adour, eSCALED project coordinator

The eSCALED project is a European-level contribution through research training and innovation capacity to the development of an artificial leaf device operating on the principle of photosynthesis. It aims to produce "solar fuels" such as H_2 hydrogen or raw materials in stable and storable chemical form, from solar energy, H_2O water and CO_2, for the generation of renewable and sustainable energy.

SolHyCat Team Artero Research Group, CBM-LAB

Led by Vincent Artero, this research team studies the electro-catalysis of multi-electron redox reactions, and their integration within electrode nanostructures. An important feature of the group is to place the principles of bio-inspiration at the heart of the design of the catalysts developed, in particular to obtain efficient systems using non-noble metals (Fe, Co, Ni, Mn, Cu, Mo, W...).

GDR 3422 Organizations Photosyntheti

The role of the GdR *"Photosynthetic organisms*" will be to federate the efforts of all French laboratories that take into account the functioning of a light energy capture and transformation apparatus in their work on photosynthetic organisms. The network has 41 members (laboratories or teams).

GDR ACTHYF 3270

Created on January 1, 2007, the laboratory develops original and innovative research in the fields of chemistry and materials science, as well as at the interfaces with physics, engineering and biology, in order to respond to major societal challenges in the cross-cutting themes of energy, transport, environment, sustainable development and health.

Center for Bio-inspired Energy Science

The centre seeks to develop the next generation of flexible materials by designing structures inspired by the many properties observable in biological systems. Our vision is that basic scientific research in this area can lead to engineered materials that rival living materials in the remarkable and useful way they manage energy.

French Bioenergetics Group

The French Bioenergetics Group (GFB) is an association under the French law of 1901 whose objective is to support the development of scientific research in bioenergetics and to federate all laboratories working in this field. The main activity of the GFB is the organization of a biennial congress.

International Society of Photosynthesis Research

The objectives of the ISPR are: (1) To encourage the growth and promote the development of photosynthesis as a basic and applied science. (2) To facilitate the publication of research on photosynthesis. (3) To sponsor the organization of a triennial International Congress on Photosynthesis. (4) To promote international cooperation in photosynthesis research and education.

Christophe Goupil, LIED -/ Université Paris-Diderot

The research activity of the laboratory is based on a non-equilibrium thermodynamic approach to energy and matter conversion processes, where the conditions for optimizing the efficiency of the latter are considered, as well as strategies for allocating resources and waste. These works are declined in the fields of Physics, Macroeconomics, Biology, and Medicine in the service of sports performance and functional rehabilitation. The whole of this activity is based on a bio-inspired approach to energy, in which the aim is to learn how nature makes use of the first and second principles of thermodynamics.

GDR Solar Fuels

The objective of the "Solar Fuels" research group is to structure the French community working in the fields of solar fuel production. The production of such fuels or energy carriers of solar origin by photo-catalysis, photoelectrocatalysis, artificial photosynthesis or via process coupling is now a fast-growing, cross-disciplinary field. It is organized around six research areas and is supported by a consortium of nearly 50 French academic research teams.

Arcane Project

The ARCANE project is guided both by fundamental research ambitions and by the need to respond to critical and societal issues. Thus, chemists and biochemists combine their expertise in protein chemistry, synthetic chemistry, catalysis and photo/electrochemistry in order to better understand the functions of these systems, especially when they interact in complex multi-protein structures to produce synergistic effects, and to exploit the basic chemical principles on which these biological systems are based to generate artificial and bio-inspired multifunctional analogues.

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Engineer in biology (AgroParisTech) and doctor in biomimetic design engineering (Arts & Métiers), Eliot's objective is to create bridges between sciences. Within Ceebios, he uses his skills to support industrial partners in their biomimetic innovation processes, to support academic/professional training and to participate in the development of the methodological framework of biomimicry.

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He studied at AgroParisTech in life and environmental sciences and then did a double degree at the École Nationale Supérieure des Arts & Métiers specifically in aeronautical sciences and aerodynamic simulation. Félix joined Ceebios after a consulting experience within Myceco. He participated in the drafting of the report on the state of the art of biomimicry in 2020 in France (France Strategy report).

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With the participation of Christophe Goupil,
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