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PNNL- 36992

Biomimicry in Clean Energy Futures

Workshop Report

November 2024

Rebecca S O'Neil
Pamela R Jackson
Rebe J Feraldi

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory
Richland, Washington 99354

Abstract

On July 25, 2023, PNNL hosted a workshop to explore the potential for biomimicry – looking to nature and biology for solutions to human engineering challenges – to support clean energy futures and associated research. Participants represented a range of technical expertise ranging from ecological modeling to cyber-security. Workshop supporting material featured a literature review of biomimetic approaches in all renewable energy technologies and inspired from all kingdoms of life. Participants noted clear contrasts between natural design strategies and clean energy deployment and the electric grid. They also agreed that biomimicry offered a rich area of research potential but lacked definitive benefits or results in commercialization phases.

Executive Summary

Why Biomimicry

Biomimicry is the "conscious emulation of life's genius." The term was coined by Janine Benyus in her seminal 1997 book. For the last twenty-five years, biomimicry has expanded as a design theory and discipline to include practicing professionals, academic coursework, and organizational purposes for research institutes.

> Biomimicry is learning from and then emulating natural forms, processes, and ecosystems to create more sustainable designs.
>
> *Biomimicry Resource Handbook*

Biomimicry refers to looking to nature as a mentor, model, or measure (Baumeister, et al. 2013). The methods of biomimicry are acutely relevant for envisioning energy futures and sustainable energy research. Today, we have introduced a colossal amount of nature into our engineered energy systems. The essential idea of renewable energy is leveraging natural forces and resources into an energy conversion process-- a universal practice in nature. Capturing natural resources over daily and seasonal cycles have become critical to a stable electric grid.

Applications of biomimicry extend beyond conversion of clean energy resources. Systems models are another opportunity to investigate nature's dynamics and consider how we engineer or envision prediction and controls. Concepts of energy resilience – diversity, decentralization, and managing extreme physical/climate conditions, with adaptive capacity for complexity and uncertainty – mirror naturally resilient ecological systems. Biology offers new formats and characteristics for sensors and data processing among other advanced technologies.

Workshop Investigation

To explore these ideas, PNNL staff conducted an internal workshop on July 25, 2023, to investigate the potential for biomimicry to advance research into clean energy futures, including conceptual designs and system architectures for the electric grid. This report provides an overview of the literature review presented at this workshop, discussion summaries, and outcomes.

Effective communication between design, engineering, biology or ecology experts is an important aspect of biomimicry success. Prioritized research strategies at PNNL include decarbonization, clean energy solutions, and energy resilience through capabilities in electricity infrastructure, earth systems, and energy processes. Participants for this workshop were selected across strategies and capabilities to explore potential biomimetic research at PNNL. A roster of workshop attendees is provided in Appendix A.

The workshop was organized into three sections: a presentation of the summary literature review including the results shown in Figure 1 (Section 2); breakout groups by technical topics (Section 3); and a discussion of next steps and key lessons (Section 4). An agenda is provided in Appendix B.

Key Takeaways

- **The initial literature review shows that biological "champions" for energy system mimicry likely span all kingdoms of life.** The diverse range and application of champions, functions, and energy types indicate biologists and ecologists of very diverse backgrounds will be needed to consider the full spectrum of potential solutions.

- **There is an enormous space for big ideas in natural models and solutions for clean energy mechanics, operations, design, engineering, and markets.** Participants identified many biological inspirations across several technical domains, with a group gravitation toward systems and resilient design. Systems discussed ranged from ecological systems (rivers) to social interactions (ant behavior) and mutualisms (mycelial networks) to internal functions of organisms (parasympathetic systems in human bodies, subconscious swarm movements). One participant proposed to study the natural property of system adaptation and graceful degradation in the face of large disruptive forces and decadal effects – a useful model for the challenge of energy operations under the stress of climate change.

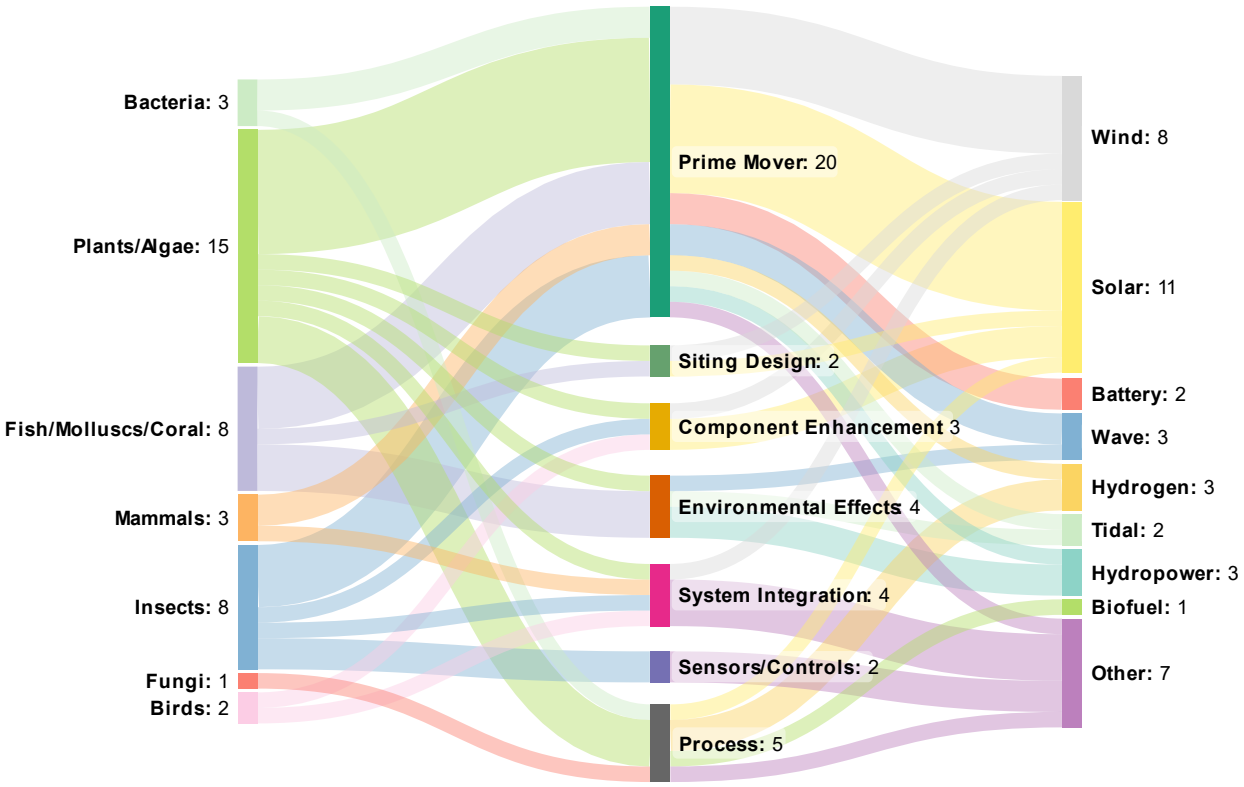

Figure 1. Biomimicry application flow from biological champion to element typology to energy type (original work).

- **There is skepticism among participants about whether biomimicry "works."** Participants expressed awareness of areas of biomimetic research (technology solution

companies, artificial photosynthesis) but noted that to our knowledge, they had not yet resolved successfully. The group discussed whether the biomimetic approach was the root cause of that lack of success, or whether the advancements or market environments had not progressed enough to bring the technology to commercialize effectively.

- **Characteristics of natural systems are highly relevant for electric grid futures strategies, in particular concepts of resilience.** Applications of resilience models included the greater bulk energy system; markets and transactional information; power restoration after a disruption; strategic deployment of scarce or limited energy; and building design. Many participants noted the inspiration of mycorrhizal fungi as nature's 'commodity trade experts', distributing resources where they are needed by utilizing bi-directional sensory and nutrient delivery networks.

- **Participants noted clear contrasts between natural design strategies and clean energy deployment and the future grid.** Examples of contrasts include industrialization and economies of scale in place of diversity, and centralization of very large energy resources in a simplified model rather than complex decentralized and distributed resource networks. Participants noted many models of highly looped, highly meshed functions in nature. Distinctive concepts of efficiency in nature were also noted, where natural systems typically lack waste and choose to use materials that easily break down. Participants questioned how (and whether) human economics has a parallel in the natural world. Common research in the energy transition space focuses on confirming feasibility of future states, which leads to identification of highly optimal but brittle states which may not be achievable. Learning from nature might mean searching out and mitigating failure modes, investigating self-assembling, self-propagating and self-correcting systems.

- **There is a missing link in education and mental models between traditional human engineering, and formats for successful "engineering" in the natural world.** Participants noted that simply examining successful natural models shifts the range of possibilities, goals and methods. One participant recommended creating an educational bridge between energy system engineering and natural systems, to facilitate early thinking and integration for future biomimetics.

- **Research communication strategies would facilitate more biomimicry connections.** Biomimicry opportunities would be easier to identify with intentional word choice and functional framing. Currently it is difficult to draw connections to biomimetic potential unless research or research products are explicitly named as nature-inspired or biomimetic. Similarly, fundamental research into ecological or biological forms, processes, or systems must be described in abstracted ways, such as a function or property, in order to be accessed for biomimetic approaches.

Recommended Actions

1. **Conduct a more thorough internal review of biomimetic research activities.** PNNL already conducts biomimetic research in multiple enterprises and at least three directorates. Participants pointed to a previous convening exercise several years ago facing national security that led to advanced coating technologies (LeFevre, et al. 2023); “ant-inspired” cybersecurity software (Haack, et al. 2011); materials science and additional efforts in fundamental biology research groups. One potential next step is to gather this work under one roof and look across for common approaches and values, create a community of practice.

2. **More targeted scoping for opportunity areas is needed.** It is challenging to hunt for specific biomimicry opportunities at a large sector scale. Advanced practices for identifying biomimetic opportunities typically use a “function” as a main unit of design and analysis. First identify the functional gap, the problem we are trying to solve, and then second, look through the great index of biological functions to investigate how nature solves that gap. In the immediate inquiry, the group discussed large complex problems with many potential models for solutions. Before the group could come up with discrete opportunities for potential solutions, more scoping of areas of interest will be needed to get closer to the functional gaps.

3. **More foundational material is needed.** Participants recommended a “manifesto” to explain the connection and potential of biomimicry in grid and clean energy futures.

Acknowledgments

This work is sponsored by PNNL internally-directed funds to explore innovative ideas from the Energy and Environment Directorate, CSTO Office. Direct workshop contributors are listed in Appendix A. Several staff contributed to the literature review. The authors wish to thank external advisors, especially Nick Heier at Biomimicry 3.8.

Since the workshop took place in July 2023, staff have iterated on the findings and updated the literature review with a publication of a conference poster (Jackson 2024). The content presented in this report is updated to reflect the most current perspective on the literature review.

Contents

Figures

Tables

1.0 Introduction

Studying nature's biological strategies for inspiration in solving human challenges, or biomimicry, has led to innovative designs for clean energy. Several areas involving clean energy conversion and integration into the electric grid have been identified as fertile ground for biomimetic work through this workshop. Clean energy is increasingly introducing natural phenomena such as sunlight and wind into the human engineered grid and energy supply. Over billions of years, nature has developed efficient and sustainable methods to solve problems, which can be a useful reference point for considering the potential of engineered systems, science, and technologies.

1.1 Workshop Overview

The workshop was designed to bring together experts with diverse backgrounds in biology, engineering, and sustainability to explore what work has been done in biomimicry for clean energy and future areas of inquiry and investment.

Workshop goals:

(a) Build consensus about the state of play in combining biomimicry/energy across pre-identified topics in clean energy.

(b) Improve and validate the literature review.

(c) Identify potential areas of future research and opportunity (e.g. sensors), or practices that can facilitate future biomimetic thinking.

(d) Identify possible external partners.

(e) Determine opportunities and recommendations for next steps.

There were 19 attendees at the workshop from communications and multiple areas within Energy and Environment Directorate (EED) (see full list in Appendix A). Participants belonged to divisions in coastal and earth systems sciences, electricity infrastructure, and program development. Representation came from teams working in systems, control design, renewables, grid resilience, sustainability, ecosystems, and biogeochemistry. The expertise of the contributors stemmed from engineers (electrical/environmental/systems), researchers (botany/renewables/power systems), scientists (computer/earth/quantitative ecology), a communications professional, advisors, team leads, a subsector lead, and a division director. Several participants had previous professional or academic experience with biomimicry.

The workshop began with participant introductions including their expertise, familiarity with biomimicry, biomimicry projects they found applicable to their professional interests, and some thoughts on the future of biomimicry. Staff presented a summary of biomimicry research programs, principles, and differences between biological and engineering solutions.

Staff presented the literature review and discussed initial findings and impressions. Additional sources for inclusion into the literature review were adopted during and after the workshop.

The following three breakout sessions were planned to proceed after the literature review presentation to discuss biomimicry application for different topics. Due to participant interest, the breakout groups for energy conversion and resilience combined into one group.

- Energy Conversion and Storage Technologies
- Sensors and Environmental Effects
- Resilience, Ecology, and the Grid

The workshop concluded with an all-participant brainstorm about where biomimicry could be applied to greatest impact and what partnerships could move research interests forward. The workshop closed by discussing the next steps to be completed following the workshop and possible future PNNL involvement in biomimicry for clean energy.

1.2 Participant Reactions to Biomimicry as a Concept

Participants shared biomimicry projects or biological studies they found that were applicable to their areas of research. Topics included resource distribution, system management and restoration, communication, diversity, and emergency response.

Participants found the positive potential for biomimicry in clean energy to be inspirational and overwhelming. However, there were concerns about success of biomimetic work which included start-up biomimetic companies that had short lifespans, projects that show potential but do not pass from “the learning to the doing,” stagnation of long-researched topics such as artificial photosynthesis, and how to go from a one-off project to large-scale implementation.

Following the participant introductions and discussion, information was provided on available biomimicry-inspired research programs for perspective on definitions and PNNL ambition in this space. The notion of sustainability in nature – that life produces conditions conducive to life – was weighed against principles of grid resiliency and reliability. A presented study detailed how nature tends to develop elegant solutions using structure and information, whereas human engineering solutions tend to be energy and materials-intensive (Figure 2) (Vincent 2006).

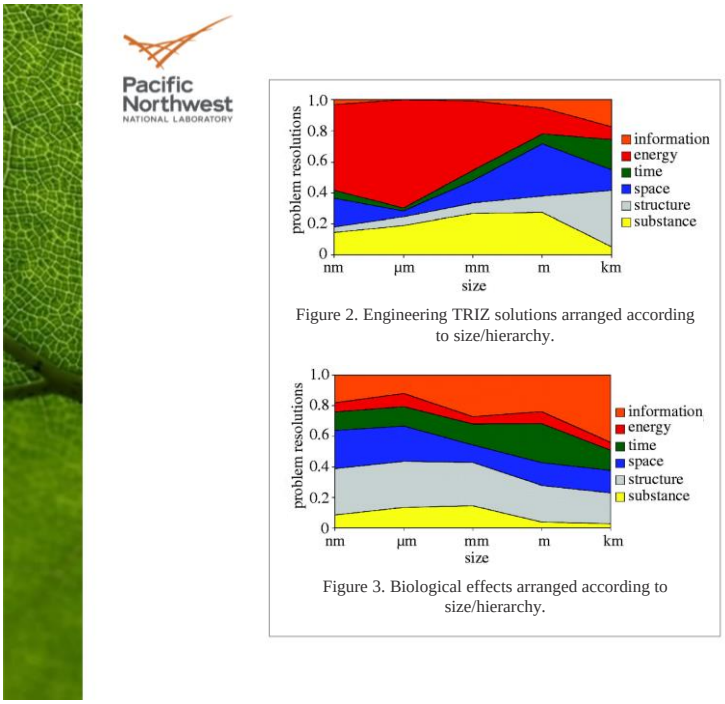

Figure 2. Engineering TRIZ solutions arranged according to size/hierarchy.

Figure 3. Biological effects arranged according to size/hierarchy.


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REVIEW

Biomimetics: its practice and theory

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Vincent, J. F., O. A. Bogatyreva, N. R. Bogatyrev, A. Bowyer, and A. K. Pahl. 2006. "Biomimetics: Its Practice and Theory." *J R Soc Interface 3 (9): 471-82.* https://doi.org/10.1098/rsif.2006.0127. *PMCID: PMC1664643.*

Figure 2. Slide with diagram from presented study and source (Vincent 2006).

2.0 Literature Review

Staff conducted an initial literature review in advance of the workshop. The statistics and impressions from the review were presented at the workshop and participants were able to add more sources during and after the workshop. Before the workshop, attendees were asked to review videos about biomimicry and the website AskNature.org for examples of clean energy bioinspiration (The Biomimicry Institute 2021). A request was also made for biomimetic examples associated with the participants' expertise that was not already on AskNature.org.

Literature regarding biomimicry was compiled and categorized by clean energy resource type and element. The biomimicry topics did not include energy efficiency through building materials, which would broaden the scope past the intended clean energy focus. To the authors' knowledge, no other comprehensive literature review on the combination of biomimicry and clean energy exists.[1] Relevant literature that did not use critical words such as biomimicry or clean energy may not have been found. There are several ways to describe biology inspiration and aspects related to clean energy without explicitly using those terms. This exemplifies a need for framing research communication to be recognizable by interested parties.

To connect biology with energy engineering, staff created intermediate categories ("elements") listed in Table 1. This made it possible to see how one biological champion could influence many clean energy technologies. For example, both solar and wind facilities could benefit from the same sensors inspired by multiple biological champions.

Table 1. Clean energy typology for literature review (original work).

Element	Description
Component Enhancement	An inspired adjustment to an element of a clean energy system
Environmental Effects	Interactions between the clean energy system and its operating environment
Siting Design	Strategies for clean energy system physical design and placement within a site or landscape
Process	Resource production and delivery
Prime Mover	Essential energy conversion technology. Includes adjustments to established energy conversion processes to new energy capture technologies (solar energy conversion, energy storage).
Sensors/Controls	New methods, signals, and mechanisms for sensing and actions based on that signal
System Integration	Interactions between clean energy systems and the electric grid

[1] The authors note the discovery of one biomimicry literature review regarding solar and one about storage, but nothing more comprehensive of the field.

Of the sources found before and the workshop and added to by the attendees, four were PNNL projects, one was a DOE competition winner, and five were startup companies. Only one company exhausted funding and was decommissioned while the others had current projects.

The sources spanned various bioinspiration, or biological champions, including plants, insects, fish, birds, mammals, fungi, and bacteria. Most projects were inspired by plants, followed by insects. All sources had at least one unique champion except for photosynthesis, trees, and ants. Photosynthesis was the catalyst for three different applications involving solar, syngas generation, and batteries. Trees inspired pumpless water movement and optimal power network structure. Ants exemplifies optimized microgrids and decentralized systems.

To illustrate the literature review, Staff created a double Sankey diagram (Figure 3) to show relationships in the data from biological champion (left column), functional element (center), and energy technology (right).

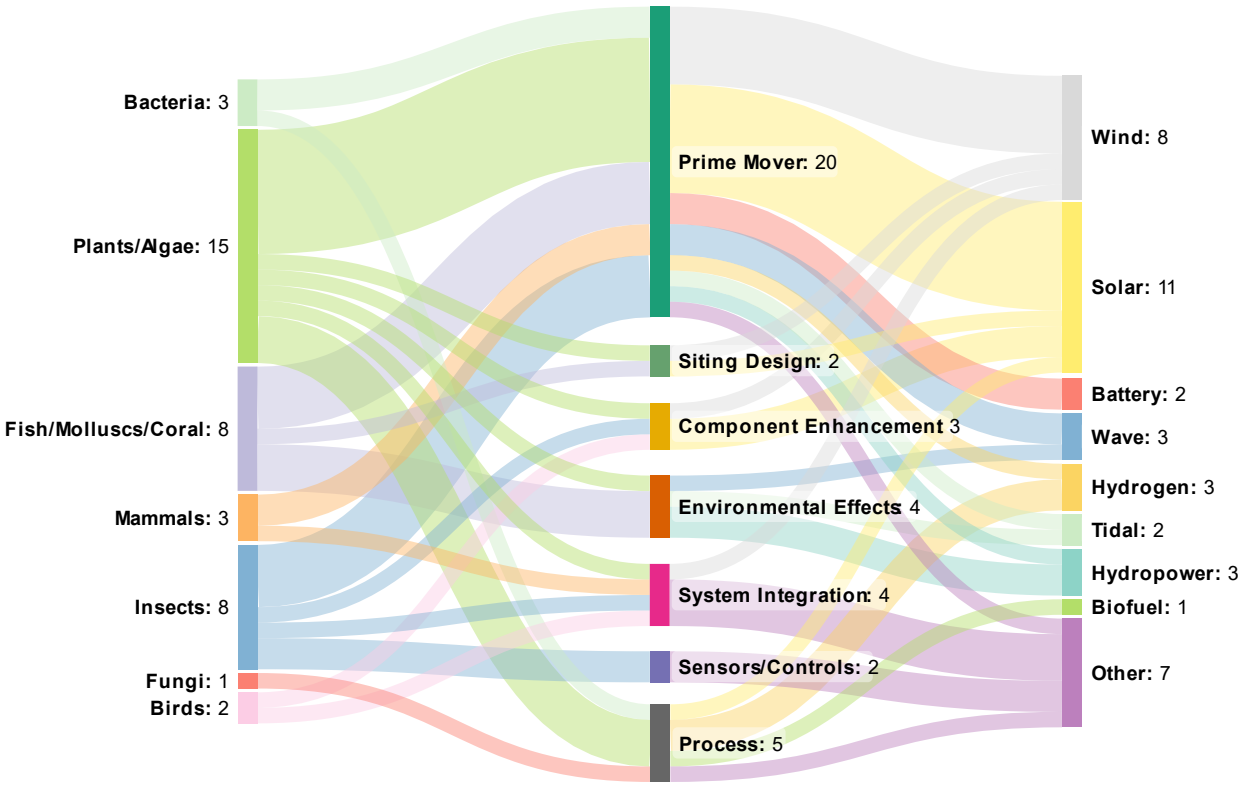

Figure 3. Biomimicry application flow from biological champion to element typology to energy type (original work).

The relationships from biological champion to the element typology were shown as a flow in Figure 3 from left to center. A breadth of relevance is shown in how types of champions, such as plants and insects, can be applied to multiple functions. The flow from the typology functions in the center to the energy types on the right show how a common function such as processes have been applied to multiple energy sources. Flows from the energy types to the typology demonstrate benefits from multiple functions to a given energy source. The diverse range and application of champions, functions, and energy types indicate expertise from multiple biology and ecological disciplines are useful to capture the full range of biomimicry.

The timeline of when these biomimicry projects were published show a general following of market interest (Figure 4). Most projects have been applicable to solar and wind. The number of studies per year trended an increase with the majority being published since 2017 when considering only the latest research date for a project. There is no peak and decline visible in the timeline.

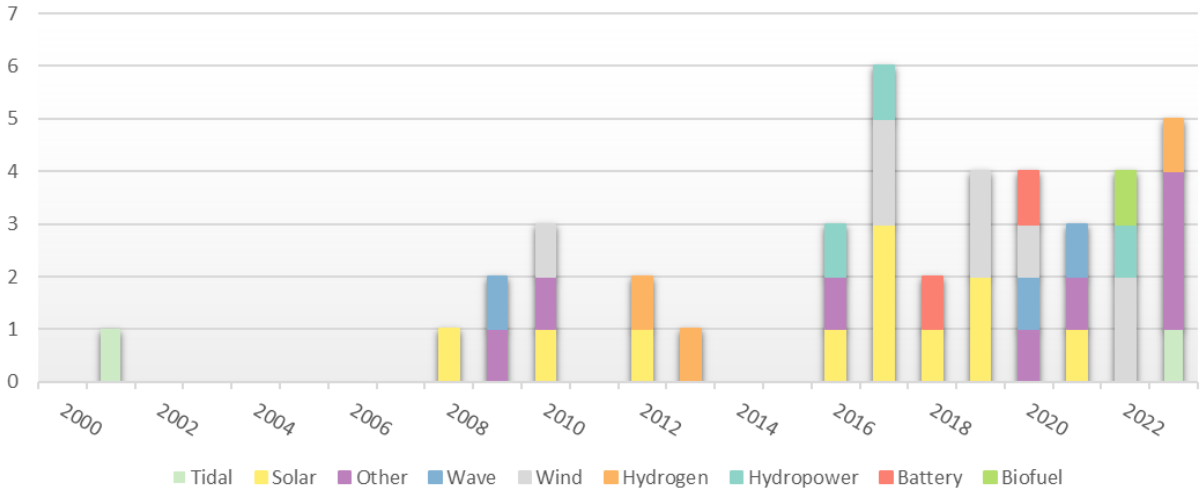

Figure 4. Timeline of biomimicry application energy type by year of most recent publication (original work).

3.0 Breakout Groups

The participants were broken into three groups based for breakout discussions. Each group was provided with guiding questions and examples to draw upon in the discussion (see Figures 5-7). Desired outcomes from group discussion were descriptions of the opportunity space and compelling areas of future work. Based on the number of interested participants in each topic, the energy conversion and resilience groups combined into a single group.

3.1 Energy Conversion, Storage Technologies, Resilience, Ecology, and the Grid

There were several areas identified for possible profitable connections between biomimicry and the breakout group topics. Ideas discussed in this breakout session included:

- An expansive database similar to AskNature (The Biomimicry Institute 2021) but modified for pattern recognition or clustering could be used to make connections of ecological processes and the grid for engineering, policy, and economic tools and modeling.

- Human engineering speeds work faster than evolution over generations. The rate of change from climate drivers and clean energy policies forces us to move faster. How can nature help us think through rates of change, adaptation into evolution?

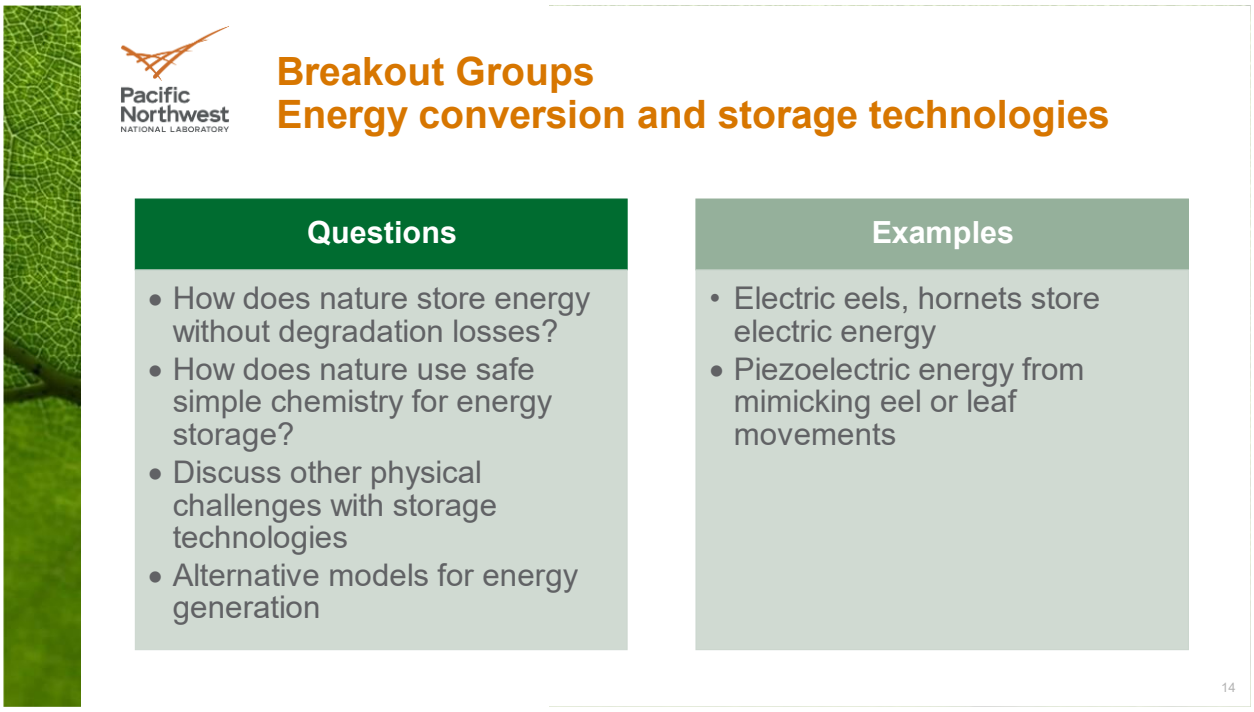

Figure 5. Slide with breakout group prompt for energy conversion and storage technologies.

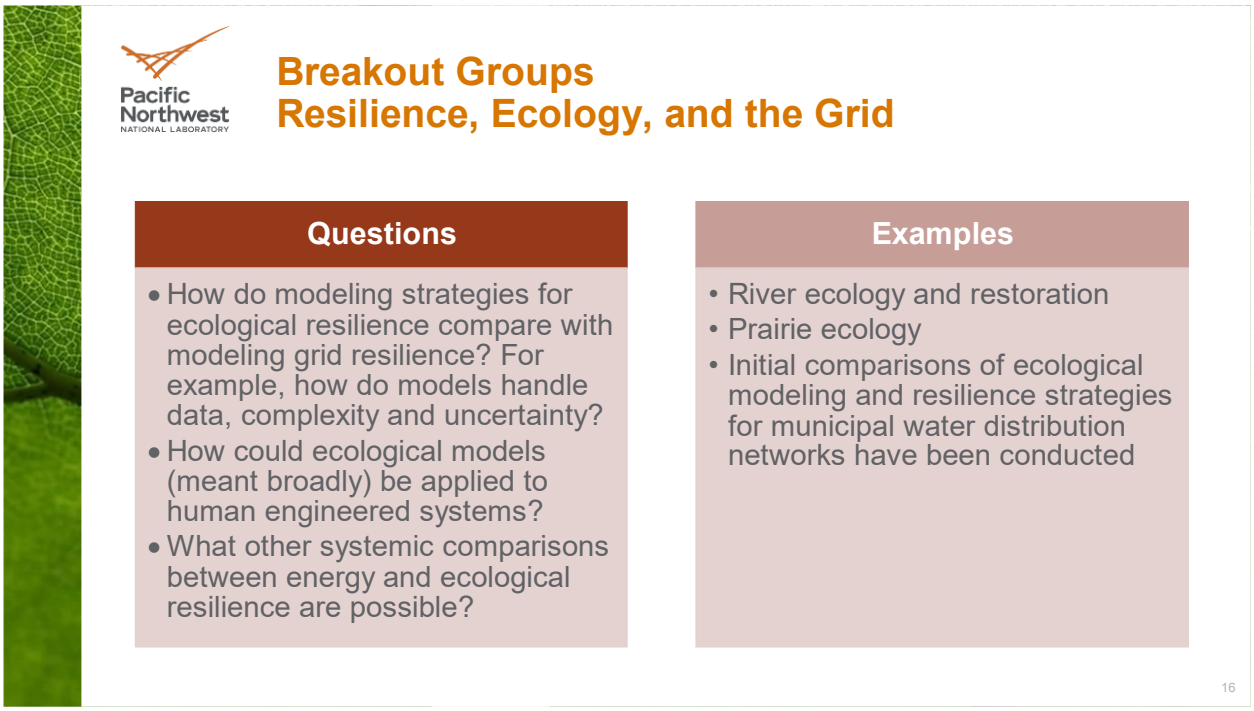

Figure 6. Slide with breakout group prompt for resilience, ecology, and the grid.

- Nature's response to stress can be to move to an undesirable state (e.g. lakes with extensive algal growth). How does nature encourage positive feedback for desirable resilience rather than staying in the wrong state?
- Evaluate goals of the system within resources, rather than continuously grow and expect as much power as possible everywhere.
- Resilient is not the same as over-redundant. We can look for an alternative system.
- Nature balances while humans prioritize. With so many parameters and information, how can nature's way of "considering all variables" be instructive to humans?
- Negative feedback loops over longer timescales. We need to learn from the past, so we avoid the same negative consequences in future systems.
- Invasive species are incredibly innovative. They might be able to teach us something useful on being resistant to disturbance.

3.2 Sensors and Environmental Effects

Highlights from the breakout group on sensors and environmental effects:

- Of all biological creatures, the one we understand the most is a human. There may be significant lessons in the study of human anatomy and medicine.
    - Compelling biological systems include swarms and tapping into parasympathetic systems (automatic systems).
    - Fungal networks are poorly understood but promising as information processors and keen state awareness.
    - Eusocial and social insects – is there a way that these hierarchies are useful for managing complexity and relationships in grid architecture?
- Human engineering and natural systems thinking are deeply divergent around topics of hierarchy and simplicity.
- A concept in nature that may have greater value in human engineering systems is how to fail well – graceful degradation rather than catastrophic failure. Disruption is normal in nature. Can we learn more about failure and restoration in natural environments? One simple example is the wide variation in how cells manage stresses with aging. Could this be a model for "mechanical aging" of assets, for managing cumulative effects of degradation cycles or patterns?

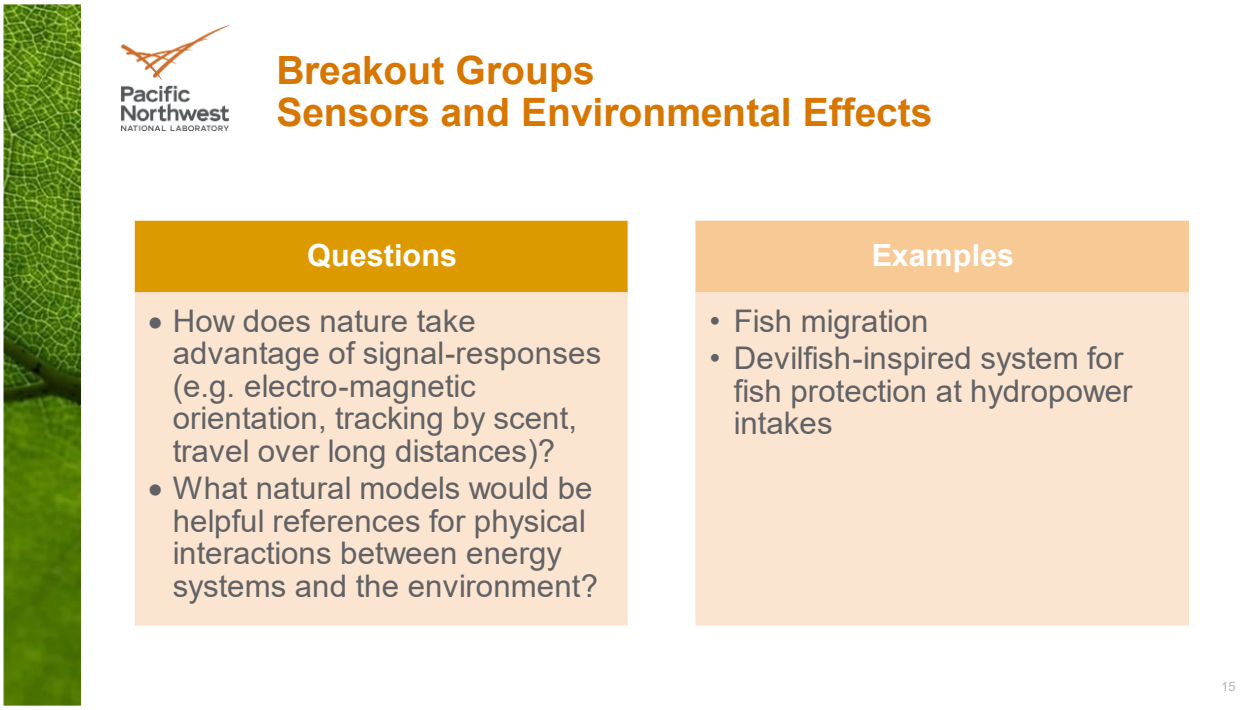

Figure 7. Slide with breakout group prompt for sensors and environmental effects.

Salient topics should be oriented a motivating question or challenge:

- It may be useful to think of environmental effects by technology type (wind, solar, hydropower) and then consider what nature does to mitigate a similar effect.

- Grid topologies, centralized hub-and-spoke, do not mirror any other recognizable colony or ecosystem.

Opportunities could also be oriented around areas of extremes, of deep uncertainty.

- Nature manages extreme information exchange.

- Looking for natural models of consumption, of economic systems (capitalistic or cooperative, everything in between). Mutualism was raised as a source of inspiration for types of efficient, sustainable coupling.

- One practice in biomimicry is to look at the edge cases, anomalies, for specialized biology.

4.0 Responsive Research Opportunities

There were three guiding topics for the brainstorm.

4.1 Technical Topics

Participants were asked for feedback on broad technical topic domains with the most applicability biomimicry.

- It could be helpful to select a couple key resilience challenges based on areas that clearly require complete change. We could investigate with a bias toward wholesale disruption rather than incremental shifts. What if the grid could be reimagined from the ground up today? What would be natural parallels or characteristics? Create new visions of electric grids, brittle versus malleable, alternative states.

- There are numerous examples in nature of converting chemical energy to electrical energy and energy storage that are safe, efficient, clean, and use minimal components. Conversion occurs commonly in nature but at micro-scales, which limit our intuitive connection.

- Failure or disruption is a normal process in nature that helps restore balance such as seeds that need fire to start sprouting. Searching out mitigating failure modes of electrical systems could benefit from studying self-propagating and self-correcting biological systems.

- We could have a more natural focus of balancing energy needed and production by addressing inefficient human consumption and add emergent behaviors and anomalies into models. Balancing could also include considering externalities for internal processes, a reflection of how nature and natural processes have limited to no waste.

4.2 Internal Operations

Participants discussed how biomimicry might influence how PNNL structures its research. For example, whether it could be useful to draw connections to biomimetics in PNNL research more intentionally, use the word explicitly, or apply biomimicry principles to internal processes and programs.

- How we teach engineers to solve problems in school and workforce development could include biomimicry. This might show systemic effects such as inequities that stem from not teaching this way.

- Data analysis could be done by integrating geospatial data into life cycle inventory (LCI) database structures (U.S. Life Cycle Inventory Database 2012) and link the technical LCI semantics to the ones used in the AskNature database (The Biomimicry Institute 2021). This could aid in understanding natural systems in different regions such as the great plains that have high vegetation energy uses and rethink grid hotspots in the supply chain based on how ecosystems service energy hotspots geospatially.

- Participants discussed biomimetic connections with organizational structure goals.

4.3 Partnerships

Participants considered non-traditional partnerships and mechanisms to work within this space.

- Potential strategic partners identified were indigenous and native communities that have recognized nature's intelligence and may have identified biomimicry generations before. Those partnerships could be restorative while recognizing their knowledge in this area that can help move society forward.

- Federal agencies have discussed integrating biomimetic topics into curriculum to affect engineering principles and practices.

- At the close of the workshop, the independent consulting firm bringing biomimicry solutions to companies, Biomimicry 3.8, was referenced as a resource for biomimicry descriptions in a broad sense that is accessible to a large audience (Biomimicry 3.8 2023).

4.4 Future Work

Planned next steps included the immediate workshop report and a published literature review. One area of to explore is strategic communication and engaging partners about the vision of what biomimicry work could be. It was suggested that a manifesto on what PNNL intends to accomplish with this work would be a powerful statement.

The primary outcome from this workshop was the consensus that biomimicry has potential to positively contribute to the future of clean energy research, and that PNNL is well-positioned to contribute in this area.

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Appendix A – List of Participants

Contributor	Division	Team	Role
Scott Edmundson	Coastal Sciences	Biogeochemistry	Research Botanist
Kate Buenau	Coastal Sciences	Ecosystem Sciences	Quantitative Ecologist
Molly Grear	Coastal Sciences	Ocean Energy	Environmental Engineer
Elsie Puig Santana	Communications	Project Communications	Communications Professional
Shari Matzner	Earth Systems Science	Sustainable Systems	Computer Scientist
Rebe Feraldi	Earth Systems Science	Sustainable Systems	Senior Systems Engineer
Brian Bellgraph	Earth Systems Science	Sustainable Waterpower Operations	Earth Scientist
Karma Sawyer	Electricity Infrastructure & Buildings	Division Director	Research Line Manager
Hayden Reeve	Electricity Infrastructure & Buildings	Control Design	Advisor
Vishvas Chalishazar	Electricity Infrastructure & Buildings	Grid Resilience	Electrical Engineer
Molly Rose K Kelly-Gorham	Electricity Infrastructure & Buildings	Grid Resilience	Power Systems Researcher
Rebecca O'Neil	Electricity Infrastructure & Buildings	Renewables Integration	Advisor
Pamela Jackson	Electricity Infrastructure & Buildings	Renewables Integration	Intern
Lara Aston	Electricity Infrastructure & Buildings	Renewables Integration	Research Analyst
Abhishek Somani	Electricity Infrastructure & Buildings	System Evaluation	Electrical Engineer
Bhaskar Mitra	Electricity Infrastructure & Buildings	System Evaluation	Electrical Engineer
Jennifer Yoshimura	Electricity Infrastructure & Buildings	System Planning	Advisor
Bora Akyol	Electricity Infrastructure & Buildings	Systems Engineering	Advisor
TJ Heibel	Program Development Office	Renewable Power	Manager

Appendix B – Agenda

Biomimicry for Clean Energy Workshop

Tuesday, July 25, 2023
9:00am - 12:00pm PST
Hybrid Teams & BSF Leeuwenhoek Room

Pacific Northwest NATIONAL LABORATORY

AGENDA

TIME	TOPIC
9:00 – 9:20am	**Welcome, Introductions, and The Plan for Today**
9:20 – 10:00 am	**Level set on biomimicry:** • Share biomimicry homework • Review programs at research institutions • Principles of biomimicry • Presentation on initial literature review for biomimicry and clean energy, categorization and reactions
10:00 – 11:20 am	**Breakout groups on challenges by expertise:** • Energy conversion and storage technologies • Sensors and environmental effects • Resilience, ecology and the grid
11:20– 12:00 pm	**Responsive research opportunities brainstorm:** • Technical topics and areas of future inquiry • Structural ideas (e.g. primary research "leaning into" biomimicry; applying principles to internal processes, programs) • Strategic partnerships
12:00 pm	**Wrap up**

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