Project Notes:

Project Title: Engineering a Novel Battery Using Biological Methods
Name: Seetha Raman, Abhiruph

Note Well: There are NO SHORT-cuts to reading journal articles and taking notes from them. Comprehension is paramount. You will most likely need to read it several times, so set aside enough time in your schedule.

Contents:

Knowledge Gaps:

This list provides a brief overview of the major knowledge gaps for this project, how they were resolved and where to find the information.

Knowledge Gap	Resolved By	Information is located	Date resolved
What materials are necessary for a biobattery?	Late October 2025	In existing research & in online searches	Est. around October 2025
What types of software can be used to model/simulate the battery?	Early November 2025	From online searches	Est. around November 2025
How can a physical prototype be mapped to online simulations?	Mid November 2025	From online searches & Dr. C	Est. around November 2025
How can a prototype be tested for energy output and efficiency?	Mid November 2025	From existing research & online searches	Est. around November 2025
What are the best methods for improving model longevity?	Early December 2025	From existing research	Est. December 2025
How can simulation findings be applicable to real-life results?	Early December 2025	From existing research	Est. Mid December 2025
How can simulation methodologies be applied to real-life testing?	Mid December 2025	From existing research	Est. Late December 2025

Literature Search Parameters:

These searches were performed between 07/15 and 12/18/2025.
List of keywords and databases used during this project.

Database/search engine	Keywords	Summary of search
Nature	hydropower environment	Journal Article #1: Gained a foundational understanding of current issues surrounding renewable energy generation.
IEEE	renewable energy generation	Journal Article #2: Explored power electronics and broad integration of the renewable energy (REN) generation into the power grid.
Gordon Library Search Engine	renewable energy	Journal Article #3: Did a broad search for renewable energy articles and learned about grid resilience in the context of REN generation.
Nature	biobattery	Journal Article #4: Began exploring biobatteries as a potential project path and gained a basic understanding of how they work.
Nature	microbial fuel cell	Journal Article #5: Did preliminary research into microbial fuel cells (MFCs) and learned how they work.
Nature	biobattery	Journal Article #6: Did additional research into biobatteries and potential materials/techniques needed for a project centered around them.
Chemical Reviews	Enzymatic fuel cells	Journal Article #12: Read an article that discussed the challenges and potential roadblocks in the process of engineering an EFC.

Energies	Enzymatic fuel cell	Journal Article #13: Read a paper that explained different EFC designs and how to optimize them
Journal of Power Sources	Enzymatic fuel cell	Journal Article #14: This paper discussed implications and applications of EFCs, which is something I could add to my Grant / Poster.

Tags:

Tag Name	
#energy development	#hydropower
#environmentally friendly	#electronics
#power grid	#renewable energy incorporation
#power grid stability	#bio-battery
#electricity generation	#brine-silk

Article #1 Notes: Title

Article notes should be on separate sheets

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Source Title	
Source citation (APA Format)	
Original URL	
Source type	
Keywords	
#Tags	
Summary of key points + notes (include methodology)	
Research Question/Problem/ Need	
Important Figures	
VOCAB: (w/definition)	
Cited references to follow up on	
Follow up Questions	

Article #1 Notes: A global-scale framework for hydropower development incorporating strict environmental constraints

Article notes should be on separate sheets

Source Title	A global-scale framework for hydropower development incorporating strict environmental constraints
Source citation (APA Format)	Xu, R. Zeng, Z., Pan, M., Ziegler, A.D., Holden, J., Spracklen, D.V., Brown, L.E., He, X., Chen, D., Ye, B., Xu, H., Jerez, S., Zheng, C., Liu, J., Lin, P., Yang, Y., Zou, J., Wang, D., Gu, M., … Wood, E.F., (2023, January 16). A global-scale framework for hydropower development incorporating strict environmental constraints. *Nature News*. https://www.nature.com/articles/s44221-022-00004-1
Original URL	https://www.nature.com/articles/s44221-022-00004-1
Source type	Scientific Research Journal
Keywords	Hydropower, environment, sustainable energy
#Tags	#energy development #hydropower #environmentally friendly
Summary of key points + notes (include methodology)	This paper by Xu et. al. discusses the future of hydropower plants. Since these plants have well-known drawbacks, ranging from environmental damage to the displacement of native people, this paper aims to find the potential energy output of hydropower plants under environmental constraints. They determined that the global unused profitable power could reach 5.27 petawatt-hours (PWh) per year; however, this is highly dependent on location, climate, and various other factors that determine how successful each plant is. Because these factors change over time and are difficult to predict far into the future, the electricity production potential of these plants is not fully known. The paper compares over 445,000 different plants, using their cost, measured by their levelized cost of energy (LCOE), and their environmental and societal impacts. They found that the future development of unused hydropower sites would lead to additional displacement of around 650,000 people. They concluded that the global capacity for hydropower energy production could reach 9 PWh per year through sustainable and efficient improvements to current methods. This relates to my idea because I want to try to design either an engineering device or an AI-based model to determine the optimal conditions for these plants to produce as much electricity output as possible, while minimizing societal and environmental impacts. Since this paper outlines that the total energy potential of the world is unknown and hard to predict, my model will have to source data publicly from various plants, including the type of machinery, the surrounding climate, and more. Overall, this

<table>
<tr><td></td><td>paper shows the harmful impacts associated with hydropower, but also the promising potential of the technology in the future with the right advancements.</td></tr>
<tr><td>Research Question/Problem/ Need</td><td>How can global hydropower development be approached to minimize environmental impact?</td></tr>
<tr><td>Important Figures</td><td>

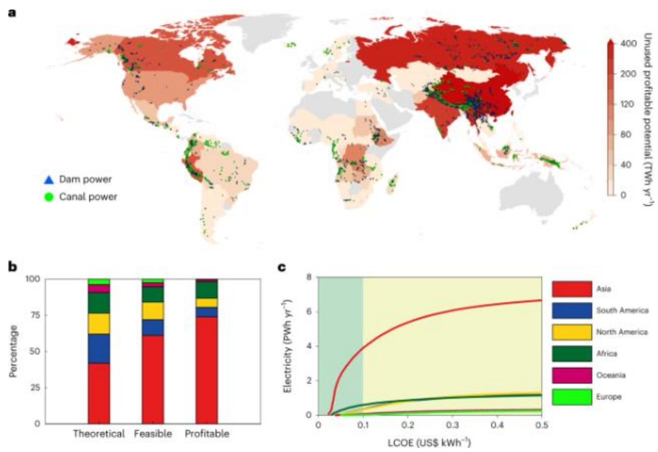

Fig. 1: Spatial distribution and cost–supply curves of unused profitable potential at the global and continental scales.

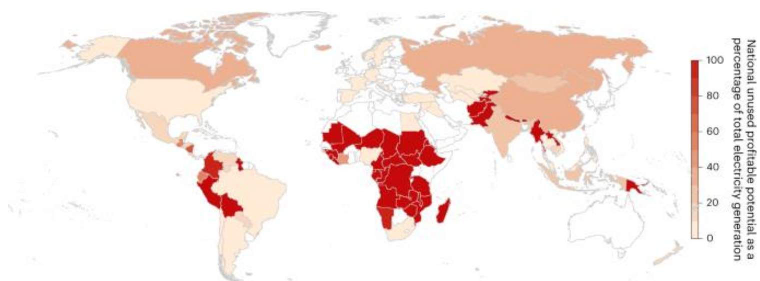

Fig. 2: National unused profitable potential as a percentage of total electricity generation.

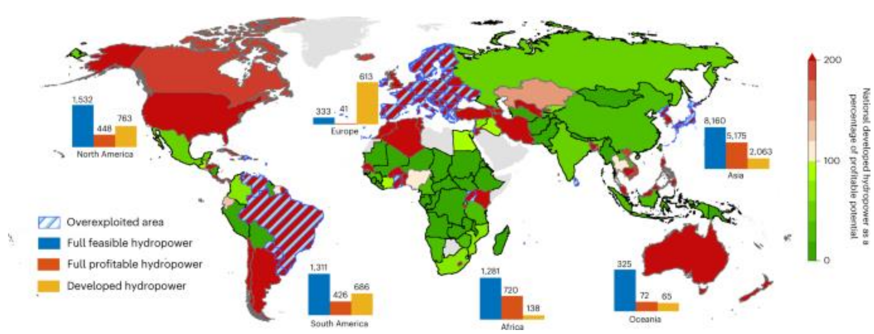

Fig. 3: Extent of hydropower development for each country and continent.</td></tr>
<tr><td>VOCAB: (w/definition)</td><td>Levelized cost of energy (LCOE): a metric used to compare the average cost of generating electricity from different sources

Altitudinal gradient: the change in environmental conditions and the distribution</td></tr>
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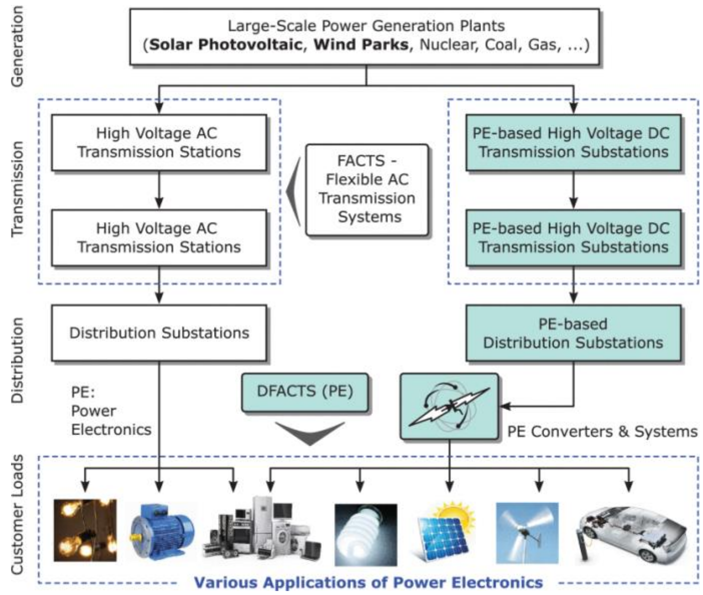
	of water throughout a range of varying elevations Dijkstra’s algorithm: a greedy algorithm used to find the shortest paths between nodes in a weighted graph
Cited references to follow up on	1. Gielen, D., Boshell, F., Saygin, D., Bazilian, M. D., Wagner, N., & Gorini, R. (2019). The Role of Renewable Energy in the Global Energy Transformation. *Energy Strategy Reviews*, *24*(24), 38–50. ScienceDirect. https://www.sciencedirect.com/science/article/pii/S2211467X19300082 2. Jacobson, M. Z., von Krauland, A.-K., Coughlin, S. J., Dukas, E., Nelson, A. J. H., Palmer, F. C., & Rasmussen, K. R. (2022). Low-cost solutions to global warming, air pollution, and energy insecurity for 145 countries. *Energy & Environmental Science, 15*(3343). https://doi.org/10.1039/d2ee00722c 3. Moran, E. F., Lopez, M. C., Moore, N., Müller, N., & Hyndman, D. W. (2018). Sustainable hydropower in the 21st century. *Proceedings of the National Academy of Sciences*, *115*(47), 11891–11898. https://doi.org/10.1073/pnas.1809426115
Follow up Questions	1. How can current methods of hydropower energy generation be improved to minimize environmental impact in environmentally sensitive areas? 2. What is inefficient about current methods that create such an environmental burden? 3. Can artificial intelligence or machine learning be employed to develop an understanding of a plausible solution for these issues?

Article #2 Notes: Power Electronics Technology for Large-Scale Renewable Energy Generation

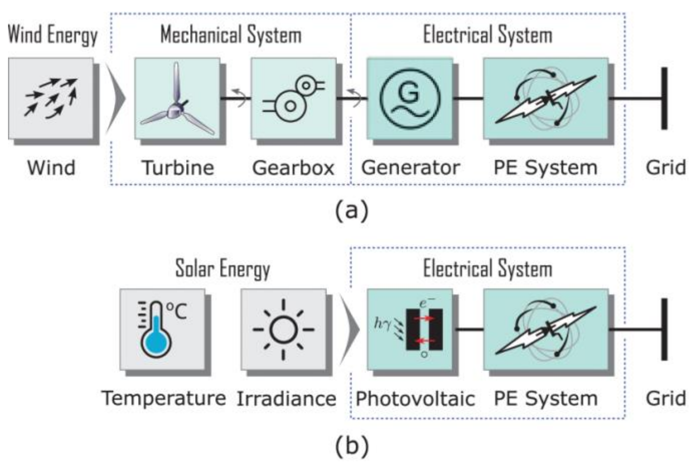
Article notes should be on separate sheets

Source Title	Power Electronics Technology for Large-Scale Renewable Energy Generation
Source citation (APA Format)	Blaabjerg, F., Yang, Y., Kim, K.A., & Rodriguez, J. (2023). Power Electronics Technology for Large-Scale Renewable Energy Generation. *Proceedings of the IEEE, 111*(4), 335–355. https://doi.org/10.1109/JPROC.2023.3253165
Original URL	https://doi.org/10.1109/JPROC.2023.3253165
Source type	Scientific Research Journal
Keywords	Power electronics, power generation, renewable energy
#Tags	#electronics #power grid
Summary of key points + notes (include methodology)	This paper discusses the infrastructure and technology required for generating large amounts of renewable energy (REN). Power electronic converters are vital to the process of generating REN. However, the use of these converters has created problems in systems that store and generate REN. REN generation is different from traditional energy generation in that it is difficult to predict, as input levels (amount of solar and wind) vary over time. Because of this variability, power electronics are used to manage the energy produced by REN resources on the same grid. However, the increased adoption of power electronics, which are inverter-based, complicates the utility grid, since traditional energy generation uses synchronous generators (SGs). This creates a need to manage the use of power electronics to optimize REN generation, without causing other problems within the utility grid. The focus of improving REN generation is on the design, control, and operation of these power electronics. Integrating large-scale energy storage can improve operation, but it poses a very high maintenance cost. AI has been tested to control power converters and has improved reliability and stability. This article connects with my research idea because I want to explore sustainable energy and make improvements to current flaws in REN generation. In this paper, the authors discuss the potential of AI to control and monitor power electronic systems, which is highly promising for my research topic. They also discuss current flaws with the hardware of power converters themselves, as they are constantly at risk of short-circuiting or thermal overload, so this is also a potential project idea. Overall, AI and engineering devices can greatly benefit the integration of power electronics into the utility grid and manage REN generation, while supplying clean energy for the future.
Research Question/Problem/ Need	How can power electronic converters be managed to optimize the generation and storage of long-term renewable energy?

Important Figures



Power electronics in modern power transmission systems and its increasing applications in future energy systems (DFACTS—distributed flexible ac transmission system), which is anticipated to be more used. Notably, power electronics are more intensively used to process electrical energy in the right five kinds of applications (appliances, LED lighting, solar PV, wind, and electric vehicles) compared to the left three.



General configuration of (a) wind power generation system (in some cases, the gearbox is optional) and (b) PV power generation system, where the PE system is the power electronics system, including power converters and the associated control. Here, the PV power generation system is based on the photovoltaic effect.

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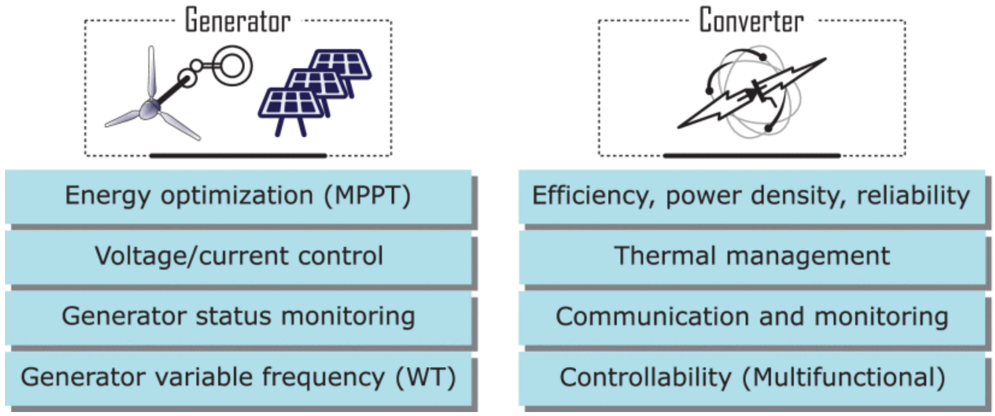
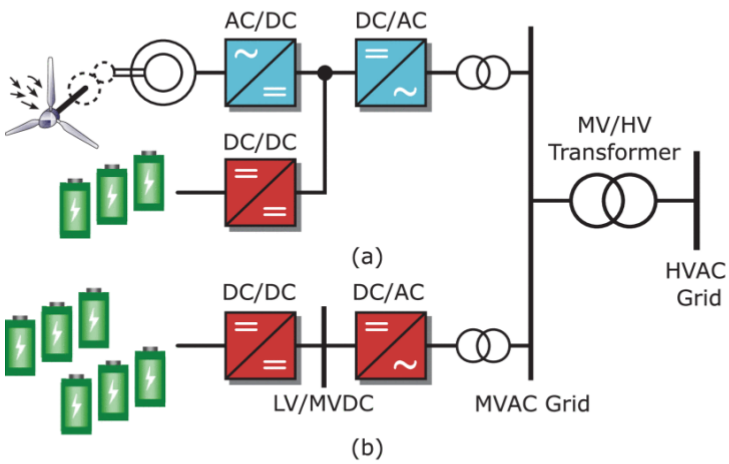


Common requirements of individual wind and solar PV power generation systems (generator and converter), where MPPT represents the maximum power point tracking and WT stands for the wind turbine.



ES integration architectures: (a) dc-coupling configuration as distributed solutions, exemplified on a wind power generation system and (b) ac-coupling configuration, as a centralized ES system, where dc/dc converters are optional, and multiple dc/dc converters can also be adapted to connect batteries to an MVDC grid.
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<td>VOCAB: (w/definition)</td>
<td>
Proportional-integral (PI) controller: a feedback control loop used in industrial control systems to regulate process variables, combining the functionality of proportional and integral control

Model predictive control (MPC); a control technique in which calculated control actions minimize the constraints, primarily cost, of a system

Total harmonic distortion: the measure of the distortion in a signal caused by unwanted frequencies, called harmonics
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<td>Cited references to follow up on</td>
<td>
1. Abbott, D. (2010). Keeping the Energy Debate Clean: How Do We Supply the World’s Energy Needs? Proceedings of the IEEE, 98(1), 42–66. https://doi.org/10.1109/jproc.2009.2035162
2. Kroposki, B., Johnson, B., Zhang, Y., Gevorgian, V., Denholm, P., Hodge, B.-
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	M., & Hannegan, B. (2017). Achieving a 100% Renewable Grid: Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy. *IEEE Power and Energy Magazine*, *15*(2), 61–73. https://doi.org/10.1109/mpe.2016.2637122 3. Frede Blaabjerg, Yang, Y., Ma, K., & Wang, X. (2015). Power electronics - the key technology for renewable energy system integration. *IEEE International Conference on Renewable Energy Research and Applications*. https://doi.org/10.1109/icrera.2015.7418680
Follow up Questions	1. Is a programming-based approach, rather than an engineering-oriented one, suitable for this problem? 2. What are the costs of a grid powered primarily, if not entirely, by renewable energy in the future compared to currently? 3. What are the next steps towards near-seamless integration of synchronous generators with the REN grid?

Article #3 Notes: The effect of renewable energy incorporation on power grid stability and resilience

Article notes should be on separate sheets

Source Title	The effect of renewable energy incorporation on power grid stability and resilience
Source citation (APA Format)	Smith, O., Cattell, O., Farcot, E., & Hopcraft, K.I. (2022). The effect of renewable energy incorporation on power grid stability and resilience. *Science Advances, 8*(9). https://doi.org/10.1126/sciadv.abj6734
Original URL	https://doi.org/10.1126/sciadv.abj6734
Source type	Scientific Research Journal
Keywords	Power grid, energy stability, grid resilience
#Tags	#renewable energy incorporation #power grid stability
Summary of key points + notes (include methodology)	This paper analyzes the consequences of integrating renewable energy into the traditional power grid. Currently, the use of intermittent generators to deliver energy to households risks the stability and resilience of the entire power network. Since traditional power grids are built upon a small number of high-output generators, the sudden shift toward REN generation, with a high number of low-output, intermittent generators, creates potential shocks in the grid. Traditional power grids are significantly less prone to system failure because of their innate resilience and reliability. REN grids, however, rely heavily on the availability of input resources, which vary over time, posing a system-wide risk. An increase in the distribution of these microgrids directly leads to a decrease in grid resilience and an increased power control burden. The paper concludes that changes to battery usage and the structure of the grids themselves can assist with improving their resilience and robustness. Current batteries that are used in these networks are not economically efficient, so a new design would be a good next step. These new designs, paired with energy management systems, would greatly help with future microgrids. This paper presents an interesting problem and a potential solution that I could explore further with my research project. I was focused on designing an engineering device to optimize the flow or generation of REN, and the idea of a battery control device could be a possible option. Also, the methodology included as part of the paper includes various formulas that could be very useful for my project or for additional research in the future.

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<td>Research Question/Problem/ Need</td>
<td>How can intermittent generators, used for renewable energy generation, be improved for overall future power grid stability?</td>
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<td>Important Figures</td>
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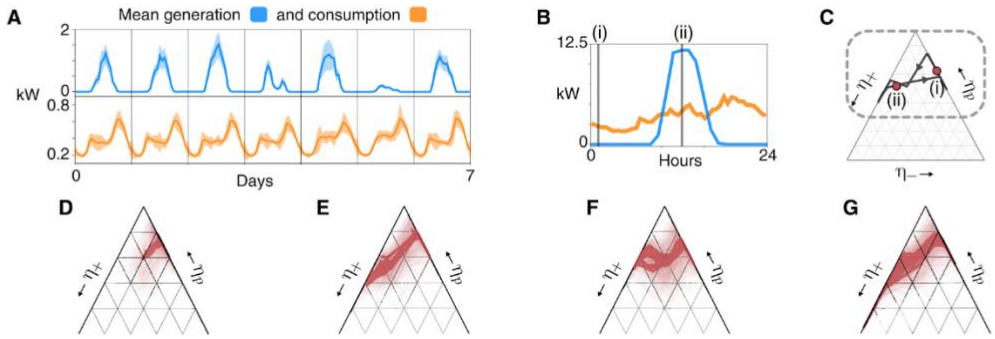

Fig. 4. Daily variations in household power demand and generation.
(A) Mean PV generation and household consumption for an example week in autumn. Shaded area shows 1 SD from the mean. (B) Total power generation (blue) and consumption (orange) in a model microgrid of *n* = 50 nodes in autumn over a day with network nodes defined by data in (A) with all nodes equipped with PV generation. (C) Trajectory in the simplex corresponding to (B), with power generation/consumption densities (*n*+, *n*−, *np*) defined by Eqs. 3 and 4. Points (i) and (ii) indicate midnight and midday, respectively. (D to G) Mean simulated weekly trajectories in the region of the simplex indicated by the dashed box in (C) for an ensemble of 50 model microgrids with generation and consumption data as in (B). All grids have *n* = 50. (D) Winter, 50% PV uptake; (E) winter, 100% PV uptake; (F) summer, 50% PV uptake; (G) summer, 100% PV uptake.

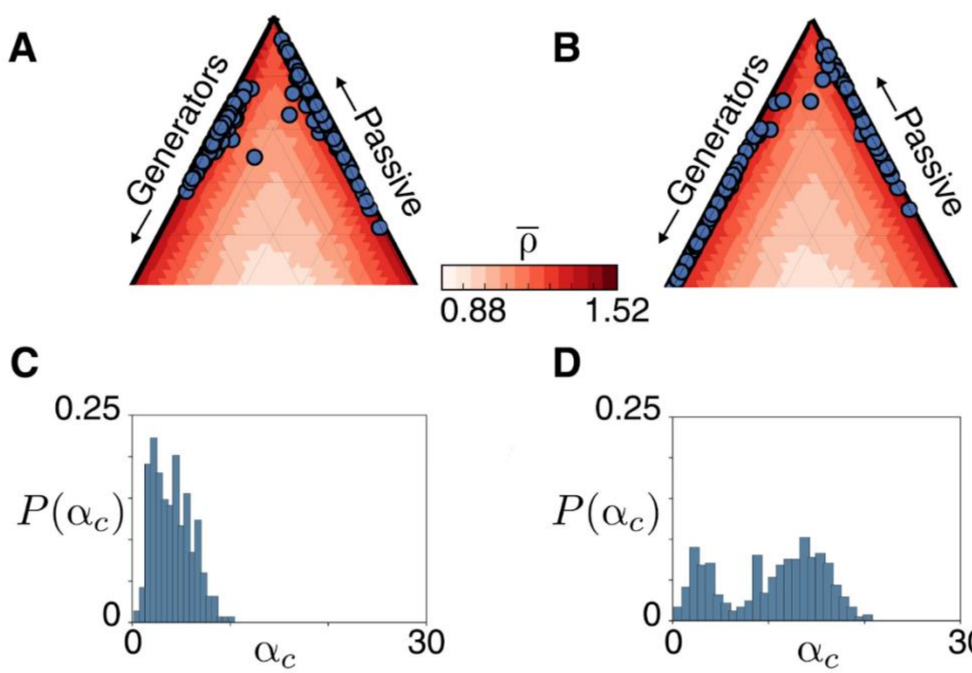

Fig. 6. Effect of PV generation on microgrid resilience.
(A and B) Points of failure for ensembles of 500 lattice microgrid realizations of size *n* = 50 and with 50% and 100% renewable uptake, respectively, during the

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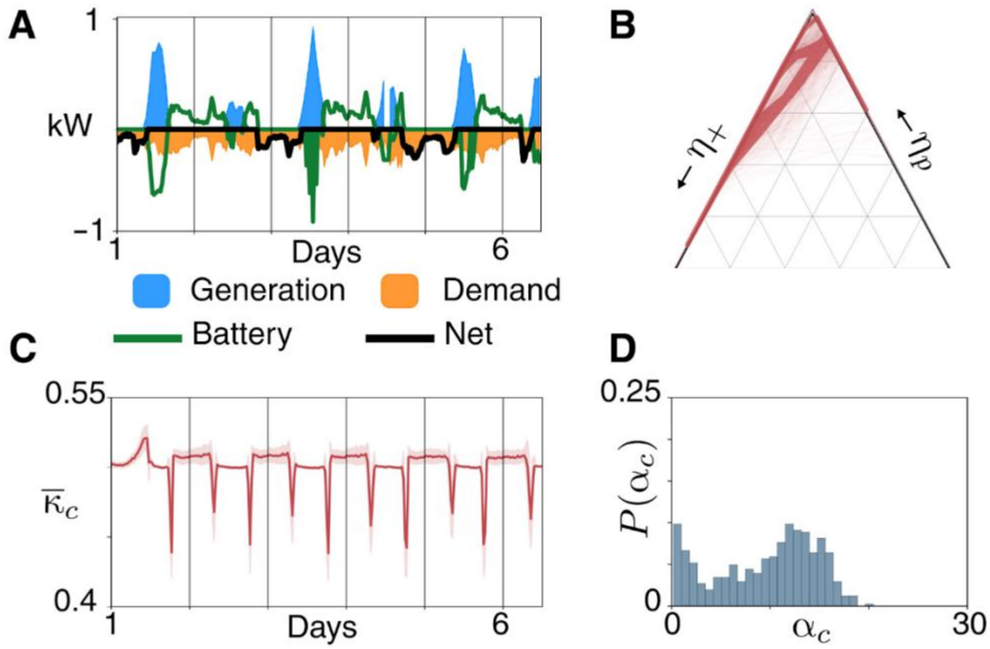
	summer. (C and D) Corresponding distributions of the critical capacity α*c* from each of these failure points.  Fig. 7. Impact of household batteries. (A) Weekly trajectory of a house equipped with PV panels and a battery during the summer. (B) Simplex trajectory of a microgrid consisting of such battery- and PV-equipped houses in the summer. (C) Corresponding values of mean critical coupling over the week. (D) Results of the resilience experiment for the ensemble in (B).
VOCAB: (w/definition)	Critical coupling capacity: a condition at which the energy loss rate of a resonator is matched to the rate at which energy is coupled into it Microgrid: a group of connected distributed energy resources within defined boundaries that act as a single entity within a broader grid Effective generators: generators that reliably and efficiently meet specified desired constraints
Cited references to follow up on	1. Scala, A., De Sanctis Lucentini, P. G., Caldarelli, G., & D'Agostino, G. (2015). Cascades in interdependent flow networks. *Physica D: Nonlinear Phenomena*, 323-324, 35–39. https://doi.org/10.1016/j.physd.2015.10.010 2. Nishikawa, T., & Motter, A. E. (2015). Comparative analysis of existing models for power-grid synchronization. *17*(1), 015012–015012. https://doi.org/10.1088/1367-2630/17/1/015012

	3. Schäfer, B., Witthaut, D., Timme, M., & Latora, V. (2018). Dynamically induced cascading failures in power grids. *Nature Communications, 9*(1), 1975. https://doi.org/10.1038/s41467-018-04287-5
Follow up Questions	1. How does the proper synchronization of REN generators and traditional power generators influence the risk of cascading power grid failure in the long term? 2. How do different types of batteries, paired with different types of generators, change grid stability? 3. Can a mathematical model be used to minimize the harmful effect of, or even prevent, cascading failures on the power grid?

Article #4 Notes: Designing water vapor fuelled brine-silk cocoon protein bio-battery for a self-lighting kettle and water-vapor panels

Article notes should be on separate sheets

Source Title	Designing water vapor fuelled brine-silk cocoon protein bio-battery for a self-lighting kettle and water-vapor panels
Source citation (APA Format)	Jangir, H., Das, M. (2022). Designing water vapor fuelled brine-silk cocoon protein bio-battery for a self-lighting kettle and water-vapor panels. *Sci Rep, 12, https://doi.org/10.1038/s41598-022-18211-x*
Original URL	https://www.nature.com/articles/s41598-022-18211-x
Source type	Scientific Journal Article
Keywords	Brine-silk cocoon bio-battery electricity
#Tags	#bio-battery #electricity generation #brine-silk
Summary of key points + notes (include methodology)	In this study, Jangir and Das explored the potential for creating a bio-battery utilizing proteins found in brine-silk cocoon mixed with a saltwater solution. This silk is produced by lepidopteran insects and exhibits many properties that make it appealing to use in such a battery. The membrane of the silk cocoon, which is a natural incubator, generates sufficient electricity to power an LED when placed between two electrodes. The aim of the study was to extend these capabilities over a longer period, while improving efficiency and overall power output. They first prepared the solution that they placed the silk cocoon in using a sodium chloride (salt) solution. Next, they took eight pieces of cocoon and connected them to form a series. Each of these series were mounted on glass slides and placed between electrodes to observe electricity generation. The results of the study show that the cocoon was able to successfully generate usable electricity, however the energy output peaks after short periods of time, which is a key area for improvement in future studies. Over a period, the energy output settled at a resting level, and the cocoon series soaked in water and salt solution showed around 50% higher levels of current and similar levels of voltage when compared to the unsoaked series. Overall, this study showed the promising potential of biomaterials, such as silk cocoon, to be utilized in ways similar to traditional biological processes to produce electricity as sustainable future options for an ever-evolving world.
Research Question/Problem/ Need	Can brine-silk cocoon proteins be used to generate sustainable electricity within a bio-battery?

Important Figures

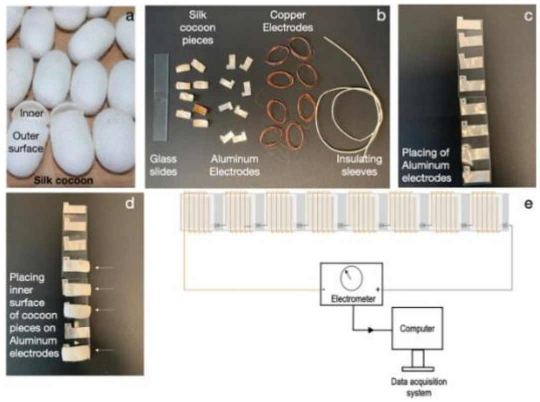


Fig. 1: The materials used in the study

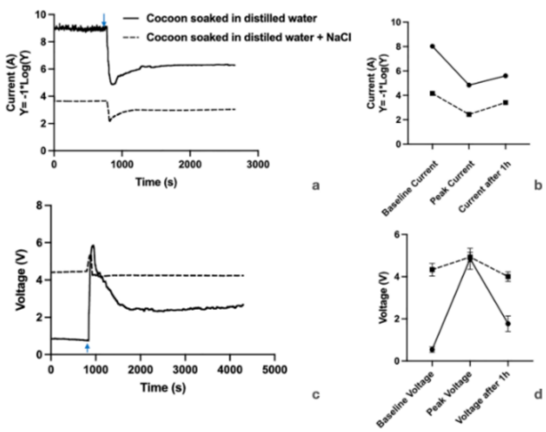


Fig. 3: The results of the study and the progression of voltage and current in both sets of cocoon series

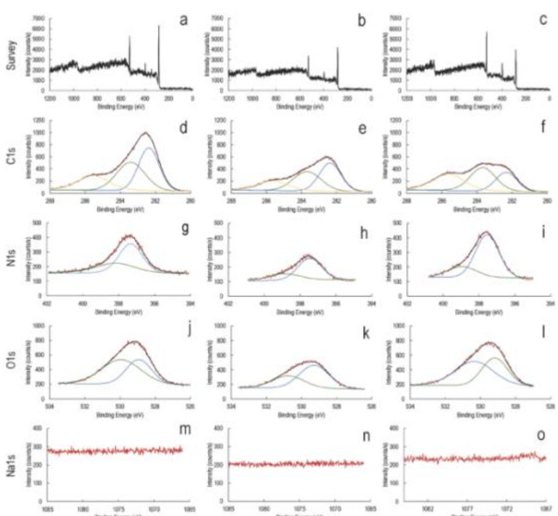


Fig. 5: Modeling the binding energy of the cocoon series

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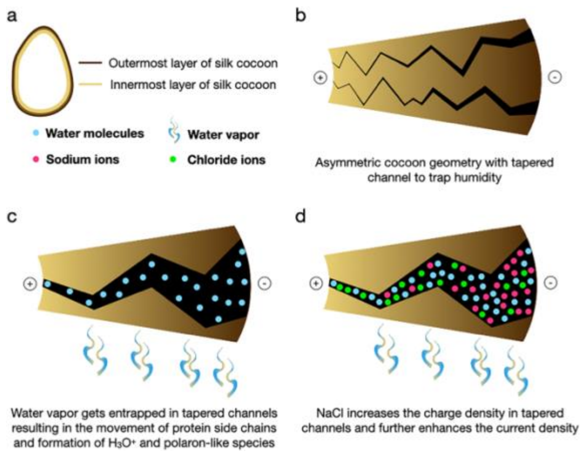

Fig. 9: Representing the system at its base level

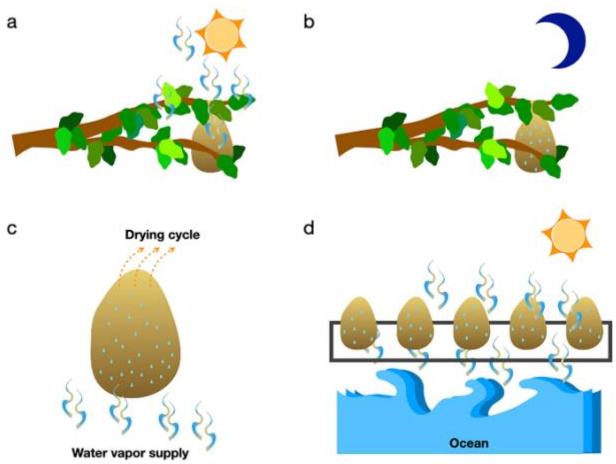

Fig. 10: Cycle of cocoon production and drying
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<td>VOCAB: (w/definition)</td>
<td>XPS (X-ray photoelectron spectroscopy) – A technique used to measure the chemical composition of atoms at a material’s surface by detecting emitted photoelectrons

Asymmetric porous architecture – A structure with varying pore sizes that influence concentration gradients and ion distribution

Percolation – The process of ions or molecules moving through a porous network (in this case, Na+ and Cl- ions)</td>
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<tr>
<td>Cited references to follow up on</td>
<td>Zhang, J., Rajkhowa, R., Li, J., Liu, X. & Wang, X. Silkworm cocoon as natural material and structure for thermal insulation. Mater. Design 49, 842–849 (2013).

Brindan, T. et al. Electricity from the silk cocoon membrane. Sci. Rep. 4, 5434. https://doi.org/10.1038/srep05434 (2014).

Kirshboim, S. & Ishay, J. S. Silk produced by hornets: thermophotovoltaic properties—A review. Comp. Biochem. Physiol. Part A Mol. Integr. Physiol. 127, 1–</td>
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	20 (2000).
Follow up Questions	Why does soaking the silk cocoon, on an atomic or root level, improve the efficiency of a bio-battery and what are other potential approaches to achieving the same effect? Why is the asymmetric porous structure of the silk cocoon important to the overall bio-battery design? Do other natural protein membranes show similar properties as the silk cocoon and how can these be applied to other projects?

Article #5 Notes: Compost Soil Microbial Fuel Cell to Generate Power using Urea as Fuel

Article notes should be on separate sheets

Source Title	Compost Soil Microbial Fuel Cell to Generate Power using Urea as Fuel
Source citation (APA Format)	Magotra, V.K, Kumar, S., Kang, T.W., Inamdar, A.I., Aqueel, A.T., Im, H., Ghodake, G., Shinde, S., Waghmode, D.P., & Jeon, H.C. (2020). Compost Soil Microbial Fuel Cell to Generate Power using Urea as Fuel. *Sci Rep 10*(4154). https://doi.org/10.1038/s41598-020-61038-7
Original URL	https://www.nature.com/articles/s41598-020-61038-7
Source type	Scientific Journal Article
Keywords	Microbial fuel cell compost urea
#Tags	
Summary of key points + notes (include methodology)	Eutrophication is a growing issue in natural habitats, presenting the potential for urea and other nitrogen-rich biomaterials to be used in microbial fuel cells (MFCs) to generate electricity, while reducing environmental waste. In this study, Magotra et al. studied compost soil with urea and attempted to generate sustainable energy in a MFC. To do this, they assembled a system with graphite electrodes, that are much cheaper than traditional rare metal electrodes, and the soil as the battery's separator, mediator, and ionic conductor. They measured the urea samples and conducted EIS tests to understand their electrochemical properties. They also measured the charge transfer resistance of the samples with respect to the urea concentrations to find specific correlations between the concentration of urea and the electrochemical behavior of the sample. In doing this, they were able to successfully construct the CSMFC (compost soil MFC). The cell was refueled intermittently over a 140-hour testing period and showed stable functioning throughout. When they removed the bacteria and enzymes naturally present in the CSMFC, they observed significantly lower current, indicating that these components play a crucial role in facilitating the function of the cell. The power densities of the CSMFC and the autoclave treated sample with the bacteria removed were 3.16 mW/m^2 and 0.03 mW/m^2, respectively. These data show that the bacteria were responsible for 2 orders of magnitude worth of power density difference. Overall, this study was successful for exploring and broadening knowledge of MFCs and biology-powered sustainable energy generation.
Research Question/Problem/ Need	Can urea be used to generate power in a microbial fuel cell, while reducing environmental waste and preventing eutrophication?

Important Figures

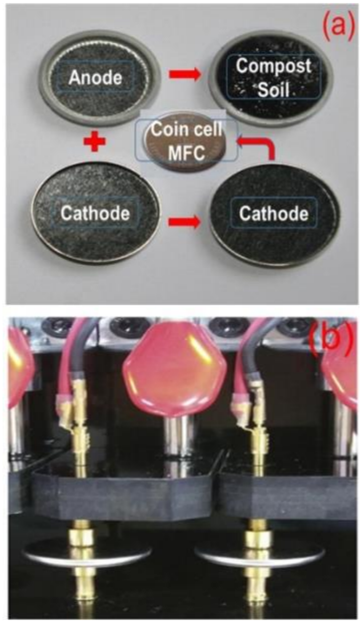


Fig. 1: An overview of the system

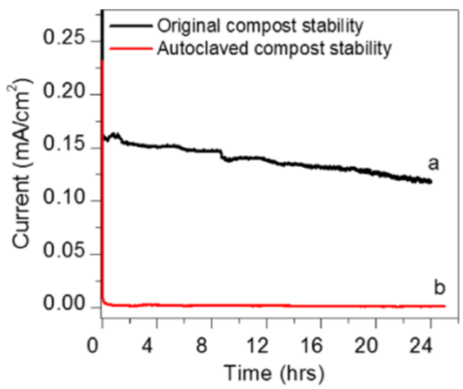


Fig. 6: The difference in current between the original and autoclaved samples

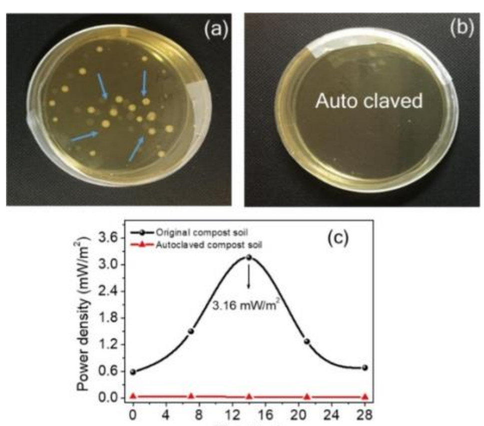


Fig. 7: The difference in power density between the original and autoclaved samples

VOCAB: (w/definition)	Cyclic voltammetry – a technique that applies varying voltages to an electrode to find how they influence the resulting current of the system Electrochemical impedance spectroscopy (EIS) – a method that applies small electrical signals to a system and measures its response to understand how it stores electrical charges Ammonification – a part of the nitrogen cycle in which microbes break down dead organisms and waste, while releasing ammonia into soil
Cited references to follow up on	Xu, W., Wu, Z., Tao, S. & Cells, U.-B. F. and Electrocatalysts for Urea Oxidation, Energy. *Technology* **4**, 1329–1337 (2016). Kumar, S. *et al*. Ahuja, Multifunctional ammonium fuel cell using compost as an oval electrocatalyst. *Journal of Power Sources* **402**, 221–228 (2018). Jiang, Y. B. *et al*. Characterization of Electricity Generated by Soil in Microbial Fuel Cells and the Isolation of Soil Source Exoelectrogenic Bacteria. *Frontiers of Microbiology* **7**, 1776 (2016).
Follow up Questions	What are other alternatives to urea and specific benefits and drawbacks of using them? What are the next steps to implementing this on a wider scale and would further improvements focus on optimizing the biological process that powers the cell or the materials involved? How does ammonification because of the biological processes present in the CSMFC affect the surrounding environment?

Article #6 Notes: Coenzyme Engineering of a Hyperthermophilic 6-Phosphogluconate Dehydrogenase from NADP+ to NAD+ with Its Application to Biobatteries

Article notes should be on separate sheets

Source Title	Coenzyme Engineering of a Hyperthermophilic 6-Phosphogluconate Dehydrogenase from NADP+ to NAD+ with Its Application to Biobatteries
Source citation (APA Format)	Chen, H., Zhu, Z., Huang, R., & Zhang, Y.H.P. (2016). Coenzyme Engineering of a Hyperthermophilic 6-Phosphogluconate Dehydrogenase from $NADP^+$ to NAD^+ with Its Application to Biobatteries. *Sci Rep* **6**, 36311. https://doi.org/10.1038/srep36311
Original URL	https://www.nature.com/articles/srep36311
Source type	Scientific Journal Article
Keywords	Coenzyme NADP NAD 6-phosphogluconate dehydrogenase
#Tags	
Summary of key points + notes (include methodology)	Coenzyme specificity engineering allows for improvements in synthetic biology. In this study, Chen et al. changed the coenzyme specificity of 6-phosphogluconate dehydrogenase (6PGDH) from its natural state of NADP+ (in the bacteria *Thermotaga maritima)* NAD+. This changes the redox cofactor in the bacteria, allowing for higher efficiency in biocatalysis. The biobattery that resulted from using the bacteria as a catalyst showed a peak power density of 1.75 mW/cm^2. In biobatteries, electrons travel via one of two methods: mediated electron transfer (MET) or electron mediators. Common alternatives to this biobattery are sugar-based batteries that, while boasting high energy density potential and safety, suffer from generally low power density, short lifetimes, and high costs. In *T. maritima*, 6PGDH converts 6-phophogluconate and NADP+ to ribulose 5-phosphate, NADPH, and CO_2, providing cellular antioxidant defense. NAD+ is much cheaper than NADH+ and NADP is more stable than NADPH for biobatteries and in general biological processes. In a variety of organisms that they surveyed, NAD^+-preferred 6PGDH was much rarer than $NADH^+$-preferred 6PGDH, meaning that converting from the former to the latter may show improvements in biobattery efficiency. In the experiment itself, they employed site-directed mutagenesis to change specific DNA sequences of enzymes to generate desirable mutants. This allowed them to generate sustainable and more efficiency in novel biobattery technology.
Research Question/Problem/ Need	Does changing the coenzyme specificity of naturally occurring NADH+ in *T. maritima* to NAD+ allow for optimized efficiency in biobatteries?

Important Figures

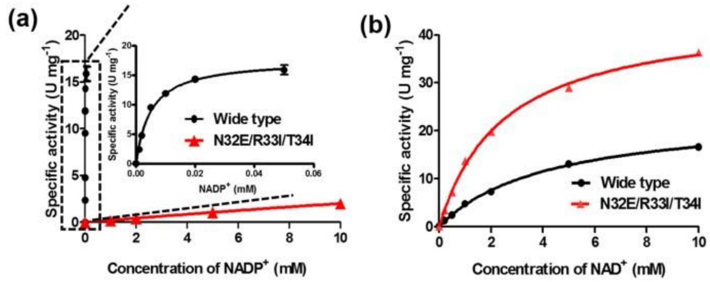


Fig. 3: The differences in concentration of NAD+ and NADP+ and their effect on enzymatic specific activity

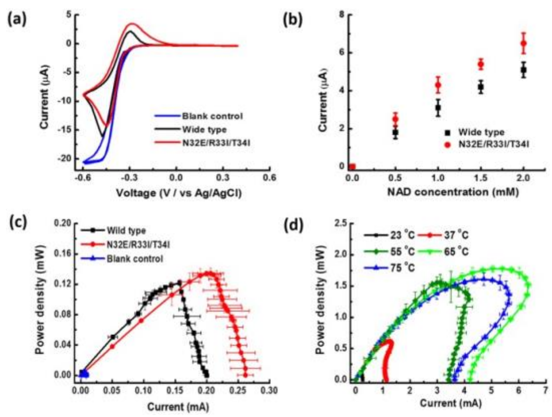


Fig. 4: Current and power density of biobattery variants utilizing NAD+ and NADP+

VOCAB: (w/definition)

Hyperthermophilic – an organism or enzyme that functions well at high temperatures

Enzyme specificity – the preference of an enzyme for one coenzyme or substrate

Rational design – an engineering approach that utilizes engineering concepts, like structure design, to create specific biological mutations

Cited references to follow up on

1. Cooney, M. J., Svoboda, V., Lau, C., Martin, G. & Minteer, S. D. Enzyme catalysed biofuel cells. Energy Environ. *Sci. 1*, 320–337 (2008).

2. Okuda-Shimazaki, J., Kakehi, N., Yamazaki, T., Tomiyama, M. & Sode, K. Biofuel cell system employing thermostable glucose dehydrogenase. *Biotechnol. Lett. 30*, 1753–1758 (2008).

3. Zhu, Z., Sun, F., Zhang, X. & Zhang, Y.-H. P. Deep oxidation of glucose in enzymatic fuel cells through a synthetic enzymatic pathway containing a cascade of two thermostable dehydrogenases. *Biosens. Bioelectron.* 36, 110–115 (2012).

Follow up Questions

1. What was the basis for deciding to switch from NADP+ to NAD+ at a conceptual level?
2. In future studies, what enhancements to the current cascading pathway

	with NAD+ can be made? 3. Can this be applied to other NAD^+-dependent enzymes?

Article #7 Notes: A high-energy-density sugar biobattery based on a synthetic enzymatic pathway

Article notes should be on separate sheets

Source Title	A high-energy-density sugar biobattery based on a synthetic enzymatic pathway
Source citation (APA Format)	Zhu, Z., Kin Tam, T., Sun, F., You, C., & Percival Zhang, Y. (2014). A high-energy-density sugar biobattery based on a synthetic enzymatic pathway. *Nature Communications*, *5*(1). https://doi.org/10.1038/ncomms4026
Original URL	https://doi.org/10.1038/ncomms4026
Source type	Scientific Research Journal
Keywords	Enzymatic fuel cell maltodextrin biobattery
#Tags	
Summary of key points + notes (include methodology)	In this study, Zhu et al. explored the potential of using maltodextrin, a polysaccharide, as fuel for an enzymatic fuel cell to generate sustainable electricity. During the study, Li-ion batteries were the most used batteries in the world, but environmental concerns from the metal extraction processes necessary for such batteries made the need for finding a sustainable alternative crucial. In this study, Zhu et al. worked to break down, or oxidize, maltodextrin into intermediary molecules, like g6p, g1p, and RU5P. These molecules would release electrons throughout the process, which were stored in the anode of the battery and converted into electricity. The theoretical limit of moles of electrons released per mole of glucose is 24 according to the oxidation equations of polysaccharides, but past studies were only able to partially oxidize glucose leading to the production of 2 moles of electrons per mole of glucose. In this study, using 13 enzymes, predominantly α-GP and G6PDH, they were able to successfully produce 22.2 moles of electrons per mole of maltodextrin, at a Faraday efficiency of 97.6 ± 3.0%. The cumulative Faraday efficiency of the battery, which considered the influence of atmospheric conditions over time, led to a resulting 92.3% efficiency. The study began by preparing the enzyme colonies, using immobilization techniques to reflect those from past studies, and measuring energy output using a Multi-Potentiostat reader. For the future, improvement in the materials involved in the experiment and the quality of the buffer and enzymes used are the most important next steps.
Research Question/Problem/ Need	Can enzymes and maltodextrin be used to emulate biological processes and release energy that can be converted to sustainable electricity?

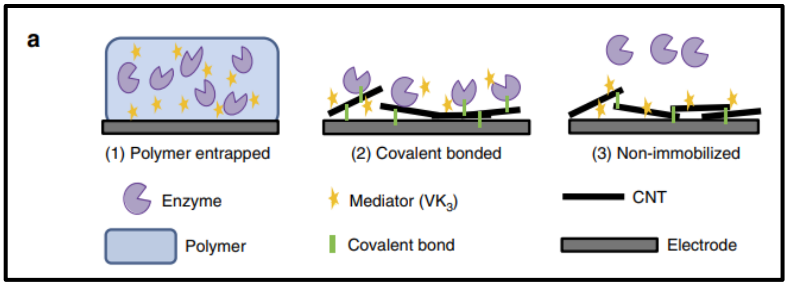
<table>
<tr><td>Important Figures</td><td>


Fig. 1: Enzyme immobilization techniques

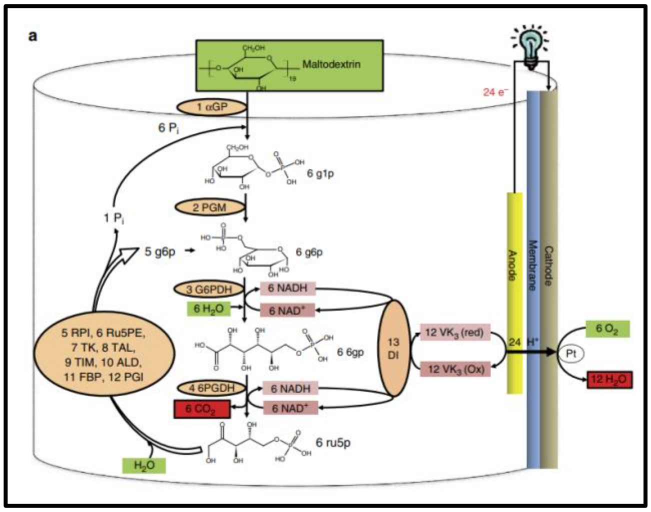


Fig. 2A: An overview of the battery and its parts

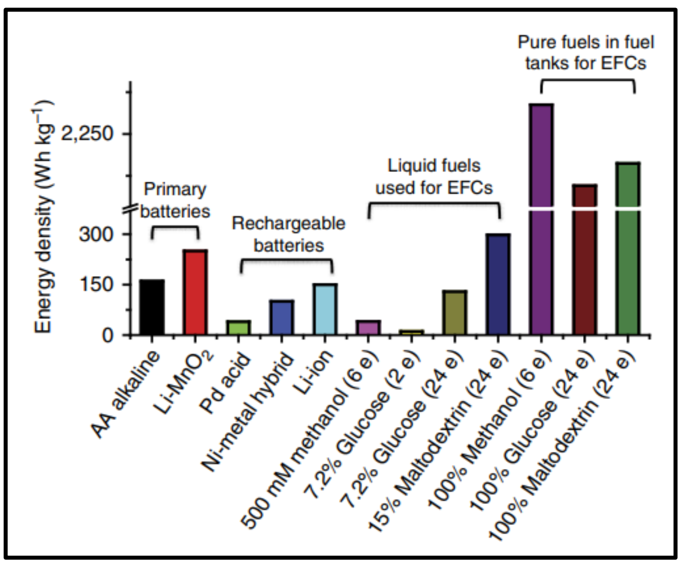


Fig. 4: A comparison in the efficiency of different types of batteries
</td><td></td></tr>
<tr><td>VOCAB: (w/definition)</td><td>Enzymatic fuel cell: A cell using enzymes to generate electricity

Microbial fuel cell: A cell using microbes to convert waste into energy</td><td></td></tr>
</table>

	Catabolic Pathway: Breaks down molecules to release energy	
Cited references to follow up on	Armand, M. & Tarascon, J. M. Building better batteries. *Nature* 451, 652–657 (2008). Chen, Z. et al. New class of nonaqueous electrolytes for long-life and safe lithium-ion batteries. *Nat. Commun. 4*, 1513 (2013). Moehlenbrock, M. & Minteer, S. Extended lifetime biofuel cells. *Chem. Soc. Rev*. 37, 1188–1196 (2008).	
Follow up Questions	1. How well do other polysaccharides fare in the oxidation process? 2. What biological processes does the battery aim to emulate and how can further efficiency be encouraged through them? 3. What specific materials can be used to replicate a system like this that focuses on common materials and accessible technology?	

Article #8 Notes: *In vitro* metabolic engineering of bioelectricity generation by the complete oxidation of glucose

Article notes should be on separate sheets

Source Title	*In vitro* metabolic engineering of bioelectricity generation by the complete oxidation of glucose
Source citation (APA Format)	Zhu, Z., & Zhang, Y.H.P. (2016). *In vitro* metabolic engineering of bioelectricity generation by the complete oxidation of glucose. *Metabolic Engineering 39.* 110-116. https://doi.org/10.1016/j.ymben.2016.11.002
Original URL	https://doi.org/10.1016/j.ymben.2016.11.002
Source type	Scientific Research Journal
Keywords	Glucose bioelectricity oxidation
#Tags	
Summary of key points + notes (include methodology)	In this study, Zhu and Zhang conducted experiments to identify methods for oxidizing glucose as a means of generating sustainable electricity. They began with glucose, and utilized *in vitro* metabolic engineering, a process that constructs cell-free synthetic enzymatic pathways. If they successfully extracted all the potential electrons per mole of glucose (24 moles), the resulting biobattery would display a power density almost 20 times that of Li-ion batteries that dominate the battery market. Thus, they decided to use a pathway of 12 enzymes to catalyze the reactions and to optimize the flow of the battery overall. The primary enzyme used in the process was G6PDH. By dividing the battery system into 3 modules: including a sugar phosphorylation module, an oxidoreduction module for electron generation, and a carbon compound recycling module. In doing so, they streamlined the oxidation, or break down, of glucose, resulting in a Faraday efficiency of 98.8%. This shows extremely efficient breakdown of glucose molecules and consistent release of electrons to the anode of the battery, showing the potential for biobatteries to reach efficiencies even higher than those dominating current markets. Next steps for this project include investigating long term energy production and enzyme optimization and improving the system to mediate enzyme interactions and electron transfer.
Research Question/Problem/ Need	Can glucose be used as a fuel for generating electricity within an enzymatic fuel cell utilizing *in vitro* metabolic engineering?

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<td>Important Figures</td>
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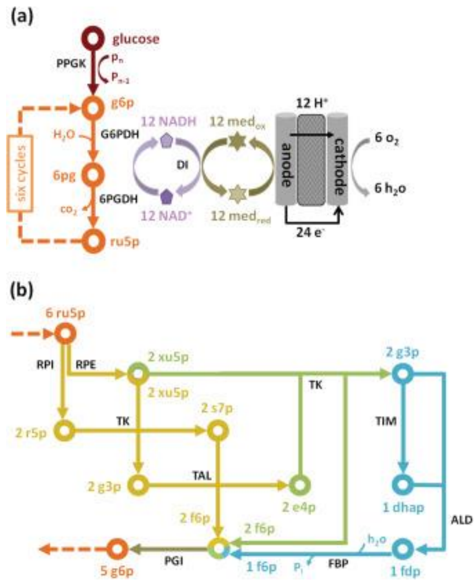
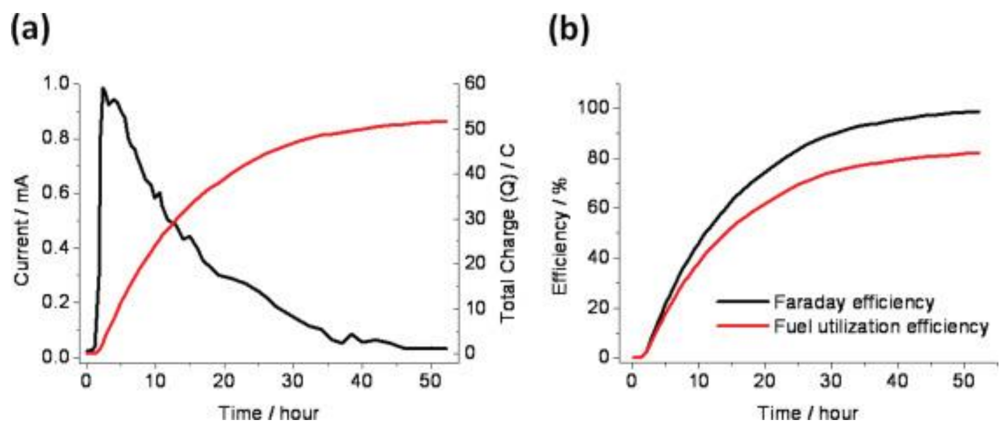


Figs. 1A and 1B: An overview of the parts of the enzymatic oxidation system



Figs. 3A and 3B: Graphs of the current, Faraday efficiency, and fuel utilization efficiency over time
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<tr>
<td>VOCAB: (w/definition)</td>
<td>Open circuit potential: the potential of a working electrode in relation to a reference electrode when no external current is applied.

Oxidoreductase: an enzyme that catalyzes the transfer of electrons from one molecule to another through redox reactions

Enzyme promiscuity: the ability of enzymes to catalyze a variety of different reactions</td>
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<tr>
<td>Cited references to follow up on</td>
<td>Armand, M., Tarascon, J.M., 2008. Building better batteries. Nature 451, 652–657.
Bauer, H.P., Srihari, T., Jochims, J.C., Hofer, H.W., 1983. 6-Phosphogluconolactonase – purification, properties and activities in various tissues. Eur. J. Biochem. 133, 163–168.

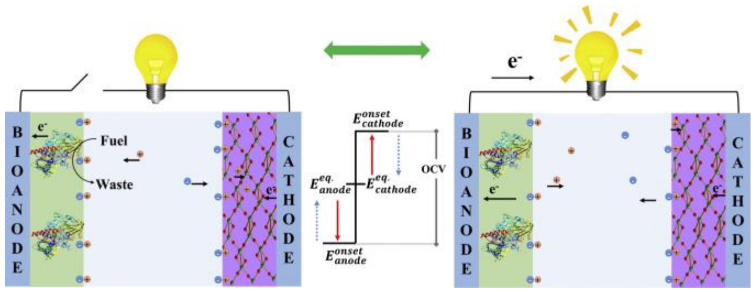
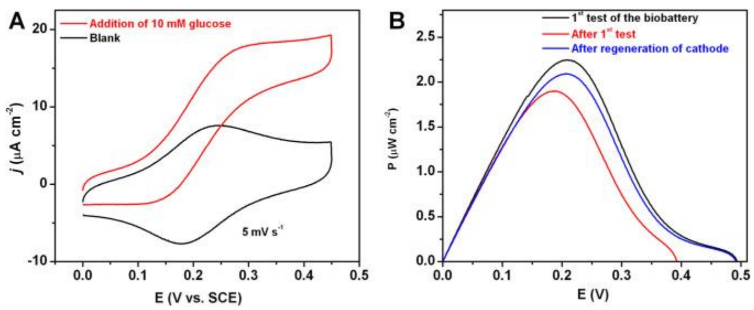
Bogorad, I.W., Chen, C.-T., Theisen, M.K., Wu, T.-Y., Schlenz, A.R., Lam, A.T., Liao,</td>
</tr>
</table>

	J.C., 2014. Building carbon–carbon bonds using a biocatalytic methanol condensation cycle. *Proc. Natl. Acad. Sci. USA 111*, 15928–15933. Calabrese Barton, S., Gallaway, J., Atanassov, P., 2004. Enzymatic biofuel bells for implantable and microscale devices. *Chem. Rev. 104*, 4867–4886.
Follow up Questions	1. How will scaling up the battery's electrode surface area or reactor volume affect overall performance over time? 2. How can buffer and enzyme ratios be adjusted to increase the lifetime of the battery? 3. What types of sugars, electron mediators, and separators lend themselves to improving the lifetime of the battery?

Article #9 Notes: An oxygen-independent and membrane-less glucose biobattery/supercapacitor hybrid device

Article notes should be on separate sheets

Source Title	An oxygen-independent and membrane-less glucose biobattery/ supercapacitor hybrid device
Source citation (APA Format)	Xiao, X., Conghaile, P., Leech, D., Ludwig, R., Magner, E. (2017). An oxygen-independent and membrane-less glucose biobattery/supercapacitor hybrid device. *Biosensors and Bioelectronics 98*. 421-427. https://doi.org/10.1016/j.bios.2017.07.023
Original URL	https://doi.org/10.1016/j.bios.2017.07.023
Source type	Scientific Research Journal
Keywords	Enzymatic biofuel cells glucose
#Tags	
Summary of key points + notes (include methodology)	In this study, Xiao et al. explored the potential for designing a biobattery hybrid device capable of operating without oxygen or a membrane. They placed the battery within a solution of glucose and successfully registered a maximum power density of 2.3 µW/cm^2. This, when paired with a supercapacitor device, registered a maximum power density of 676 µW/cm^2, showing that the hybrid device was responsible for an increase in the efficiency of the battery by more than 2 orders of magnitude. Utilizing redox potentials of known oxidation reactions, Xiao et al. were able to determine a feasible range of energy output given their materials. In this design, they used a cathode composed of MnO_2 that was immobilized on nanoporous gold (NPG). Since the electrodes in this design were solid electrodes, no membrane was necessary within the design, which is a major difference from prior studies. This allowed the device to act as both a battery and supercapacitor, meaning that it can both store energy and release it in bursts of power. This enhances the potential of the device for industrial applications, since it exhibits potential for energy storage, but also power generation. The supercapacitor was able to discharge at current densities up to 2 mA/cm^2. Over a 25-hour period, the device was able to do 50 charge-discharge cycles, which means that it was able to keep replenishing internal substrates that allowed continuous energy production. While the findings for this study show immense promise for future work, some next steps for improving the design include improving the power density function when the device operates in battery mode, as 2.3 µW/cm^2 is still quite low for functional application. Also, since the device was only tested for 25 hours, doing testing over longer periods of time allows for a more holistic understanding of

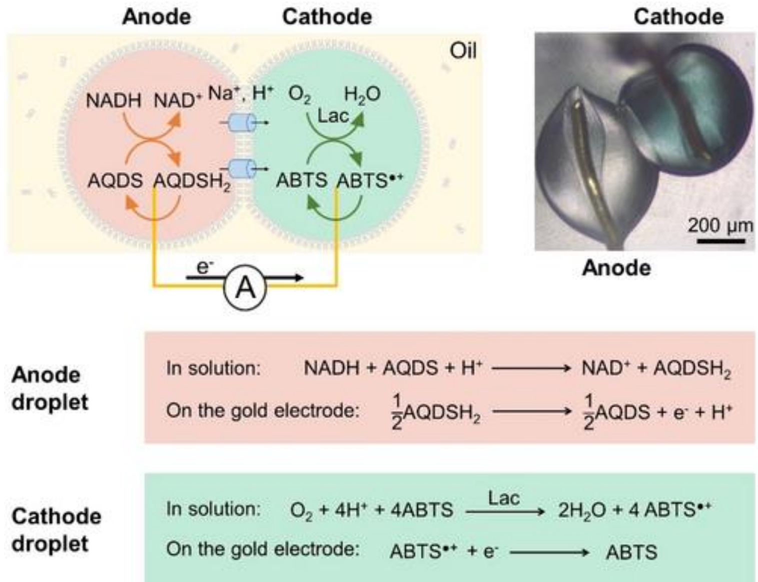
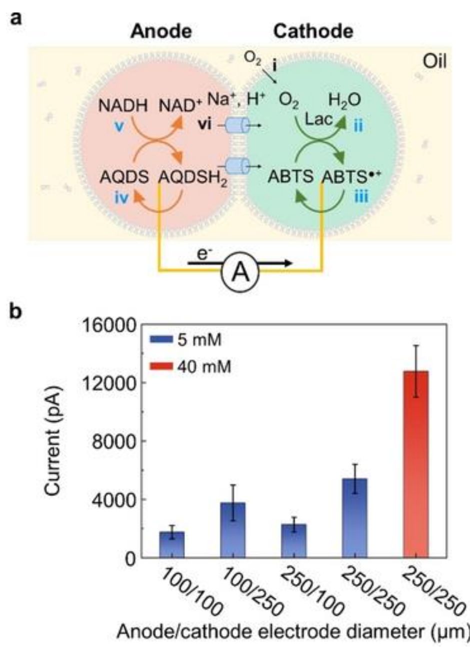
	strengths and weaknesses of the design.
Research Question/Problem/ Need	Can a biobattery be designed without a membrane or oxygen dependency, while still maintaining functional sustainable electricity output?
Important Figures	 Fig. 1: The design of the biobattery/supercapacitor with electron transfer and energy production  Figs. 2A and 2B: The power and current densities of the designs after regeneration of the internal substrates
VOCAB: (w/definition)	Asymmetric supercapacitor: a hybrid supercapacitor with 2 different electrodes Ohmic resistance: the resistance encountered during the transportation of electrons within a cell Electrodeposition: the field of science that studies the deposition of chemical materials onto a surface by applying an electric field
Cited references to follow up on	Addo, P., Arechederra, R., Minteer, S. (2010). Towards a rechargeable alcohol biobattery. *Journal of Power Sources*. https://doi.org/10.1016/j.jpowsour.2010.06.032 Kizling, M., Draminska, S., Stolarczyk, K., Tammela, P., Wang, Z., Nyholm, L., Bilewicz, R. (2015). Biosupercapacitors for powering oxygen sensing devices. *Bioelectrochemistry*. https://doi.org/10.1016/j.bioelechem.2015.04.012 Leech, D., Kavanagh, P., Schuhmann, W. (2012). Enzymatic fuel cells: Recent progress. *Electrochimica Acta*. https://doi.org/10.1016/j.electacta.2012.02.087

Follow up Questions	1. Since the battery was only tested for 25 hours, is there a point at which substrate regeneration is not possible? 2. How does time and atmospheric conditions over a longer period influence power regeneration and production overall? 3. How would this battery work in a variety of atmospheres, and what adaptations can be made to the design or to the materials used to enhance performance across different environments?

Article #10 Notes: Enzyme-Enabled Droplet Biobattery for Powering Synthetic Tissues

Article notes should be on separate sheets

Source Title	Enzyme-Enabled Droplet Biobattery for Powering Synthetic Tissues
Source citation (APA Format)	Liu, J., Qing, Y., Zhou, L., Chen, S., Li, X., Zhang, Y., & Bayley, H. (2024). Enzyme-Enabled Droplet Biobattery for Powering Synthetic Tissues. *Angewandte Chemie*. https://doi.org/10.1002/anie.202408665
Original URL	https://doi.org/10.1002/anie.202408665
Source type	Scientific Research Journal
Keywords	Biobattery synthetic tissue
#Tags	
Summary of key points + notes (include methodology)	In this study, Liu et al. engineered a biobattery that could produce a stable output current of around 13,000 pA over a 24-hour period, which is a 600x increase over previously researched light-based processes of energy generation. The droplet biobattery was built from nanoliter droplets that were fueled by enzyme-catalyzed oxidation of reduced NAD. NAD is an electron carrier in many biological processes and is used in biobatteries to streamline electron transfer between the anode and the cathode. The droplets within the battery design were separated by droplet-interface bilayers, or DIBs. Within the cathode, laccase catalyzes the oxidation of the electron mediator, ABTS, into $ABTS^{+}$. This allows for incremental energy output. The combination of NADH and NAD+ allows for the generation of energy throughout the process. The movement of ions into gA, or gramicidin A, resulted in current output of around 2000 ± 300 pA over a period of 30 minutes. The peak power output was 2.5 pW, meaning that the overall battery design was very efficient. After 12 hours, though, current production dipped to 670 pA, showing the need for development and refining of materials used to enhance long-term efficiency. However, one strength of the design was that it allowed for the movement of larger, charged molecules across droplet networks, such as cationic pyronin Y and anionic fluorescein. Next steps include stabilizing the gA channels within the design, optimizing DIB compositions, and operating within different environments to test how atmospheric conditions affect electron flow.
Research Question/Problem/ Need	How can a biobattery powered by nanoliter droplets be used to power synthetic tissues?

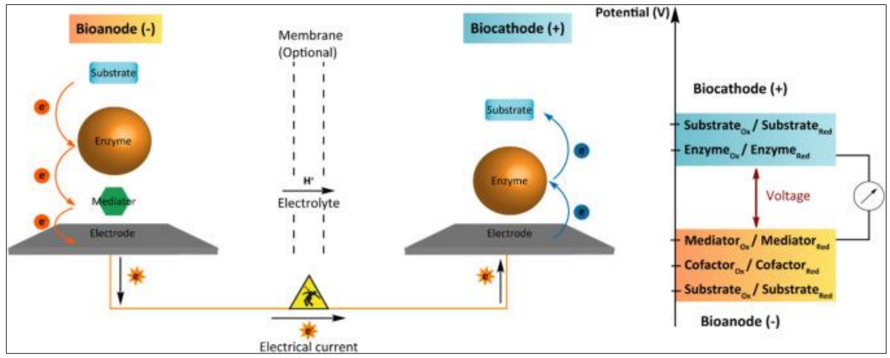
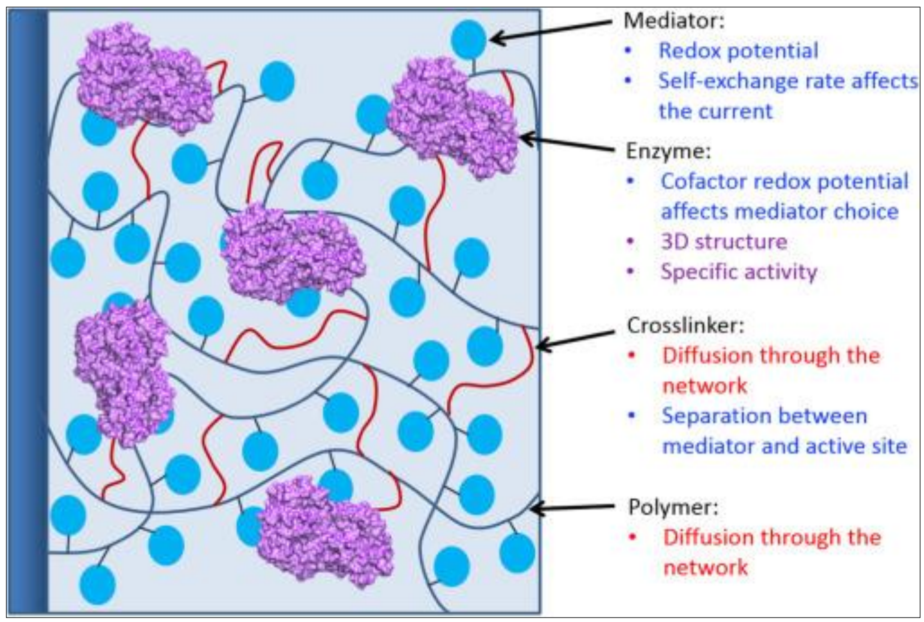
Important Figures	 Graphical Abstract: the anode and cathode droplets, along with the chemical equations that show the flow of electrons and changes between ABTS and $ABTS^+$  Figs. 2A and 2B: Current output and anode/cathode electrode diameter for both battery designs (5mM and 40mM)
VOCAB: (w/definition)	Pyronin Y: a fluorescent dye used as a tracer molecule ABTS radical cation: a molecule used in redox reactions that is visible due to its color change Droplet interface bilayer: a lipid bilayer formed between 2 aqueous droplets in an oil that mimics the function of biological membranes

Cited references to follow up on	Stolarczyk, K., Rogalski, J., Bilewicz, R. (2020). NAD(P)-dependent glucose dehydrogenase: Applications for biosensors, bioelectrodes, and biofuel cells. *Bioelectrochemistry*. https://doi.org/10.1016/j.bioelechem.2020.107574 Jiang, Y., & Tian, B. (2018). Inorganic semiconductor biointerfaces. *Nature Reviews*. https://doi.org/10.1038/s41578-018-0062-3 Mano, N., de Poulpiquet, A. (2018). O_2 Reduction in Enzymatic Biofuel Cells. *ACS Publications*. https://doi.org/10.1038/s41578-018-0062-3
Follow up Questions	1. What contributes to the degradation of the gA channels over time, and how can this be mitigated in the design? 2. How can the battery be scaled/improved to increase the maximum power density over a longer period? 3. What channel proteins can be explored in further research, and what materials can be added to the design?

Article #11 Notes: Enzymatic biofuel cells: 30 years of critical advancements

Article notes should be on separate sheets

Source Title	Enzymatic biofuel cells: 30 years of critical advancements
Source citation (APA Format)	Rasmussen, M., Abdellaoui, S., & Minteer, S. D. (2015). Enzymatic biofuel cells: 30 years of critical advancements. *Biosensors and Bioelectronics*, 63, 10–18. https://doi.org/10.1016/j.bios.2015.06.029
Original URL	https://doi.org/10.1016/j.bios.2015.06.029
Source type	Scientific Research Journal
Keywords	Biofuel cells, bioelectrocatalysis, bioanodes, biocathodes, biobattery
#Tags	
Summary of key points + notes (include methodology)	This paper explains the recent advancements in the field of enzymatic biofuel cells. Fundamentally, enzymatic biofuel cells are fuel cells that utilize oxidoreductase enzymes to convert chemical potential energy into electrical energy. Oxidoreductase enzymes are enzymes that oxidize a fuel source, commonly glucose or another polysaccharide, to produce energy. In nature, these enzymes are mainly used for reactions like glycolysis, but they can be used across different reaction types, whether they are catabolic or anabolic. One of the most common cofactors for oxidoreductase enzymes is $NAD(P)^+$, which is a diffusional mediator. A diffusion mediator is one that allows for altered rates of diffusion, in this case the diffusion of electrons to and from the electrode. After the fuel source is oxidized, $NAD(P)^+$ becomes NAD(P)H, and must be regenerated at the electrode. The class of oxidoreductase enzymes that include $NAD(P)^+$ is known as dehydrogenases. Dehydrogenase enzymes are also common in natural processes and their distinction from traditional oxidoreductase enzymes is that they transfer hydride ions between the molecules in the oxidation-reduction reaction. However, complex mediator processes became a secondary focus within biobattery research when a membrane less biofuel cell was first engineered and proposed. Additionally, the focus on enzyme immobilization for enhanced stability and longer-term performance has greatly improved fuel cell efficiency. These improvements have led to advances in aqueous solution-based biofuel cells, along with growth in the use of computational modeling. The main challenges with biofuel cells currently are their lower power density compared to traditional batteries, which limit their use and applications in daily life.
Research Question/Problem/ Need	How have enzymatic biofuel cells changed over the past 30 years and what do these improvements mean for the future of biofuel cell technology?

Important Figures	 Fig. 1: A diagram showing the flow of energy within an enzymatic biofuel cell  Fig. 3: An analysis of the different properties within an enzymatic biofuel cell that affect potential (blue), current density (red), and both (purple)
VOCAB: (w/definition)	Oxidoreductase enzyme: an enzyme that catalyzes oxidation-reduction reactions Nanoparticle: a particle extremely small (1-100 nm in diameter) Open circuit potential: the voltage measured between two electrodes of an electrochemical system when no current is flowing (the circuit is open)
Cited references to follow up on	Agnes, C., Holzinger, M., Le Goff, A., Reuillard, B., Elouarzaki, K., Tingry, S., & Cosnier, S. (2014). Supercapacitor/biofuel cell hybrids based on wired enzymes on carbon nanotube matrices: Autonomous reloading after high power pulses in neutral buffered glucose solutions. *Energy & Environmental Science, 7*(6), 1884–1888. https://doi.org/10.1039/C4EE00677G Akers, N. L., Moore, C. M., & Minteer, S. D. (2005). Development of alcohol/O2 biofuel cells using salt-extracted tetrabutylammonium bromide/Nafion membranes to immobilize dehydrogenase enzymes. *Electrochimica Acta,*

	50(12), 2521–2525. https://doi.org/10.1016/j.electacta.2004.11.010 Amir, L., Tam, T. K., Pita, M., Meijler, M. M., Alfonta, L., & Katz, E. (2009). Biofuel cell controlled by enzyme logic systems. *Journal of the American Chemical Society, 131*, 826–832. https://doi.org/10.1021/ja808086d
Follow up Questions	1. Why, on a biological level, are open circuit potentials significantly lower in EFCs and how can biological engineering improve current performance? 2. What trade-offs exist between enzyme performance and battery stability that comes with enzyme immobilization? 3. What is the primary need for improvement for enzymatic biofuel cells prior to widespread use in everyday life?

Article #12 Notes: Tackling the Challenges of Enzymatic (Bio)Fuel Cells

Article notes should be on separate sheets

Source Title	Tackling the Challenges of Enzymatic (Bio)Fuel Cells
Source citation (APA Format)	Xiao, X., Xia, H.-Q., Wu, R., Bai, L., Yan, L., Magner, E., Cosnier, S., Lojou, E., Zhu, Z., & Liu, A. (2019). Tackling the challenges of enzymatic (bio)fuel cells. *Chemical Reviews*, *119*(16), 9509–9558.
Original URL	https://doi.org/10.1021/acs.chemrev.9b00115
Source type	Scientific Research Journal
Keywords	Electrodes, fuel cells, fuels, peptides and proteins, power
#Tags	
Summary of key points + notes (include methodology)	As global energy demand has grown, research into sustainable alternatives, particularly those involving biological approaches, has increased. One of these approaches is enzymatic catalysis of oxidation reactions occurring within an engineered enzymatic (bio)fuel cell (EFC). EFCs have a plethora of advantages over traditional batteries from the perspective of sustainability, but this paper aims to address the challenges with EFC development and future steps to continue research in the field. This paper discusses the major improvements in the technology, such as the use of enzymes to increase power density and efficiency, for example. One of the main focuses on direct application of EFCs has been implantable devices. These devices work in a similar way to standalone, independent EFCs but use human-released energy as the main substrate for electricity generation. However, some challenges that have hindered EFC development and pushed off large-scale applications include the inability to fully oxidize the substrate at hand and low power densities. These are crucial to address before EFCs become widely used, because high-level performance is important to ensure that the cells are being sustainably produced and fueled. The main cause of these performance issues surrounds the enzyme being used in the cell. The active site of the enzyme being used is often buried inside of a large insulating protein moiety. This prevents optimal function, reducing the maximum attainable power for the EFC. Enzyme cascading/enzyme pathways are potential solutions to this as the complete oxidation of high-energy-density fuels is a viable approach to high-power-density EFCs. Including bioanodes and biocathodes with proper enzyme implementation is also a proposed solution. Overall, EFCs are a bright and quickly growing technology and with the proper implementations of the identified potential solutions, could become a part of daily life very soon.
Research Question/Problem/	How has the development and research on EFCs changed over time, and what are

<table>
<tr><td>Need</td><td>the implications of current findings on future research in the field?</td></tr>
<tr><td>Important Figures</td><td>
Fig. 1: A diagram of the general system-level design of EFCs

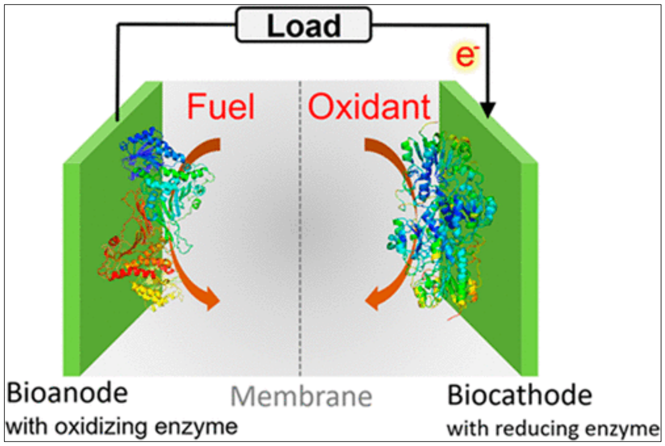
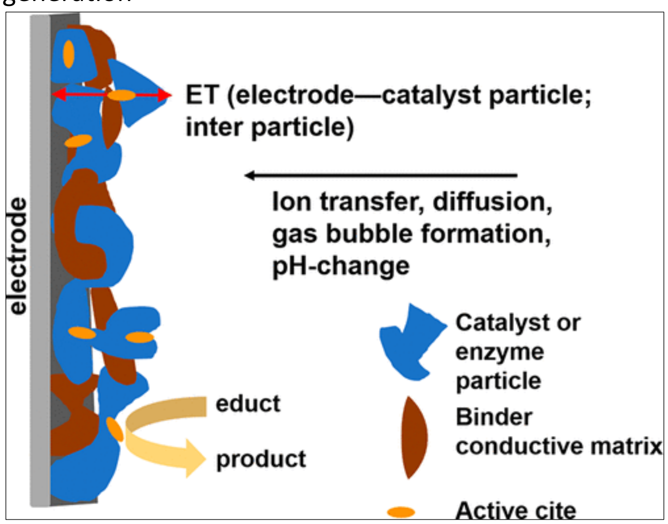


Fig. 5: A diagram of the enzyme-substrate interactions that lead to electricity generation



</td></tr>
<tr><td>VOCAB: (w/definition)</td><td>
Protein moiety: the significant part or half of a larger molecule or protein

Michaelis constant: a measure of an enzyme’s affinity for its substrate, resulting in the substrate concentration where the reaction rate is half of its maximum speed

Michaelis-Menten equation: an equation that describes the rate of an enzyme-catalyzed reaction as a function of substrate concentration
</td></tr>
<tr><td>Cited references to follow up on</td><td>
Carrette, L., Friedrich, K. A., & Stimming, U. (2001). Fuel cells: Fundamentals and applications. *Fuel Cells, 1*(1), 5–39. https://doi.org/10.1002/1615-6854(200105)1:1<5::AID-FUCE5>3.0.CO;2-Gopen_in_newISSN

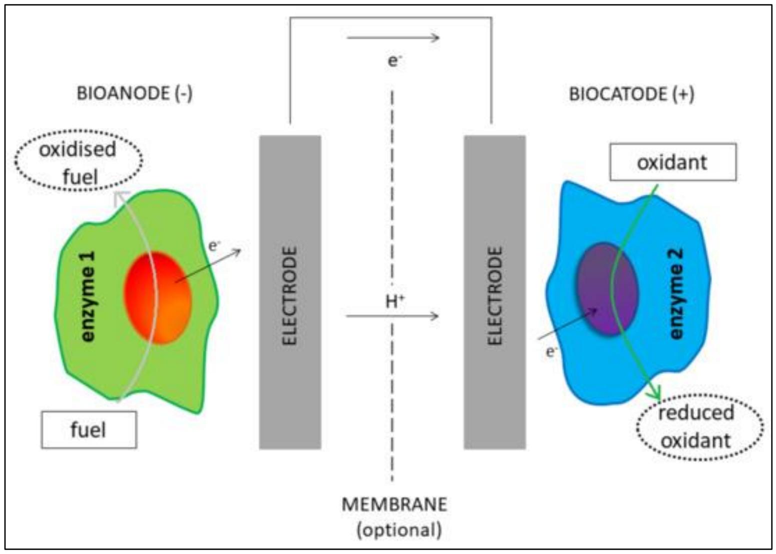
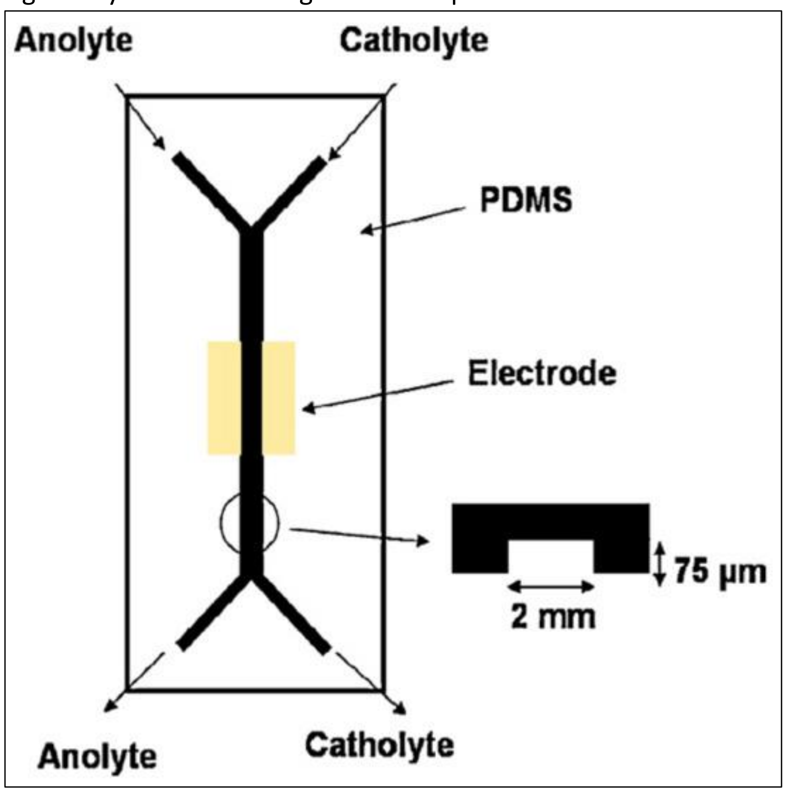
Windmiller, J. R., & Wang, J. (2013). Wearable electrochemical sensors and biosensors: A review. *Electroanalysis, 25*(1), 29–46.
</td></tr>
</table>

	https://doi.org/10.1002/elan.201200349 Katz, E., & MacVittie, K. (2013). Implanted biofuel cells operating *in vivo*: Methods, applications and perspectives. *Energy & Environmental Science, 6*(10), 2791–2803. https://doi.org/10.1039/c3ee42126k
Follow up Questions	1. What are the main limitations with crosslinking and how do they affect power density and total output? 2. What properties allow for high-level catalysis by extremophile enzymes at high temperatures and can this improve EFC efficiency at a low-cost level? 3. What molecular characteristics create the distinction between reversible and irreversible inhibition between different laccases?

Article #13 Notes: Enzymatic Biofuel Cells: A Review on Flow Designs

Article notes should be on separate sheets

Source Title	Enzymatic Biofuel Cells: A Review on Flow Designs
Source citation (APA Format)	Barelli, L., Bidini, G., Pelosi, D., & Sisini, E. (2021). Enzymatic Biofuel Cells: A Review on Flow Designs. *Energies*, *14*(4), 910. https://doi.org/10.3390/en14040910
Original URL	https://doi.org/10.3390/en14040910
Source type	Scientific Research Journal
Keywords	Enzymatic biofuel cell, electron transfer, flow design, microfluidic cell
#Tags	
Summary of key points + notes (include methodology)	One of the most promising sustainable energy storage technologies is fuel cells. The most researched types of fuel cells are enzymatic fuel cells, or EFCs. EFCs are enzyme-catalyzed biological cells that work by oxidizing fuel at the anode and reducing an oxidant at the cathode. The electron transfer that occurs through these processes results in electricity generation. Fuel cells are much less environmentally harmful than traditional energy storage strategies, such as lithium-ion batteries. In some cases, they are a net positive to the environment because they use otherwise biological waste for a sustainable purpose. The theoretical performance of these cells is quantified through their formal redox potential. This is a metric that evaluates the enzymes' ability to catalyze reactions that lead to more products through the chemical reactions that occur. The selectivity of enzymes to their substrates, or their tendency to move towards them to catalyze reactions, is crucial to the total energy output of EFCs, and directly contributes to their power density. Power density is a metric that quantifies the amount of power, or the rate of change of energy with respect to time, which is a good indicator of the effectiveness of the internal chemical reactions that occur to facilitate electron transfer. Xurography is a technique that has been researched to fabricate microfluidic devices by using a cutting plotter to cut layers of materials. This streamlines the production process, making it possible for wide-spread adoption of microfluidic EFCs. This provides immense potential in making future energy storage methods sustainable and efficient, while minimizing environmental harm that may arise from these technologies.
Research Question/Problem/ Need	What are the main developments that have been made in EFC research and how do these influence future research paths?
Important Figures	Fig 1: A diagram of the general system-level design of an EFC

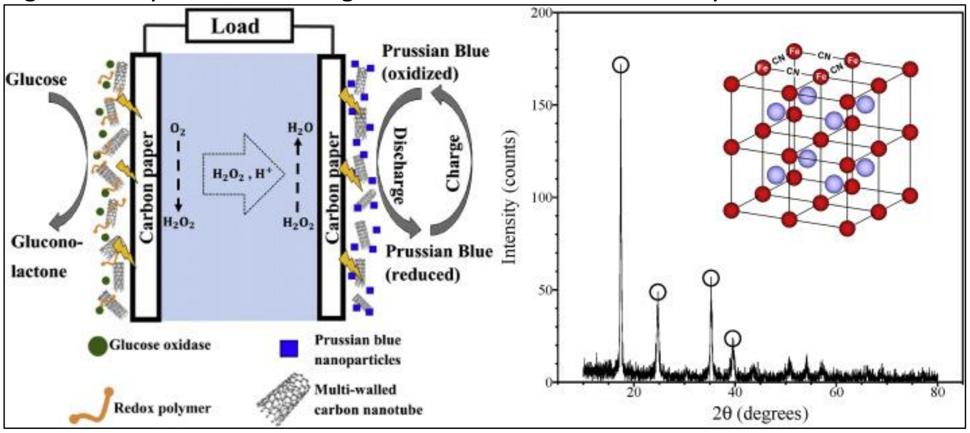
	 Fig 7: A system-level design of a Y-shaped microfluidic EFC 
VOCAB: (w/definition)	Microfluidic cell: a cell that is altered using microfluidic devices (chips with tiny channels to precisely control small volumes of fluids) Mass transport effect: the movement of matter from an area of high concentration to an area of low concentration, mainly through diffusion and convection

	Selectively permeable layers: membranes that selectively allow certain molecules/ions to pass through, but not others
Cited references to follow up on	Leech, D., Kavanagh, P., & Schuhmann, W. (2012). Enzymatic fuel cells: Recent progress. *Electrochimica Acta*, 84, 223–234. https://doi.org/10.1016/j.electacta.2012.03.162 Nasar, A., & Perveen, R. (2019). Applications of enzymatic biofuel cells in bioelectronic devices—A review. *International Journal of Hydrogen Energy, 44*(29), 15287–15312. https://doi.org/10.1016/j.ijhydene.2019.04.093 Cooney, M. J., Svoboda, V., Lau, C., Martin, G., & Minteer, S. D. (2008). Enzyme catalysed biofuel cells. *Energy & Environmental Science, 1*(3), 320–337. https://doi.org/10.1039/B810548K
Follow up Questions	1. How do flow-based EFC designs improve overall battery stability compared to traditional models? 2. Why is glucose oxidase a preferred enzyme that is used in the bioanode of EFCs? 3. Should future research prioritize enzyme engineering and optimization, or the design of efficient systems through prototyping and modeling?

Article #14 Notes: Rechargeable membraneless glucose biobattery: Towards solid-state cathodes for implantable enzymatic devices

Article notes should be on separate sheets

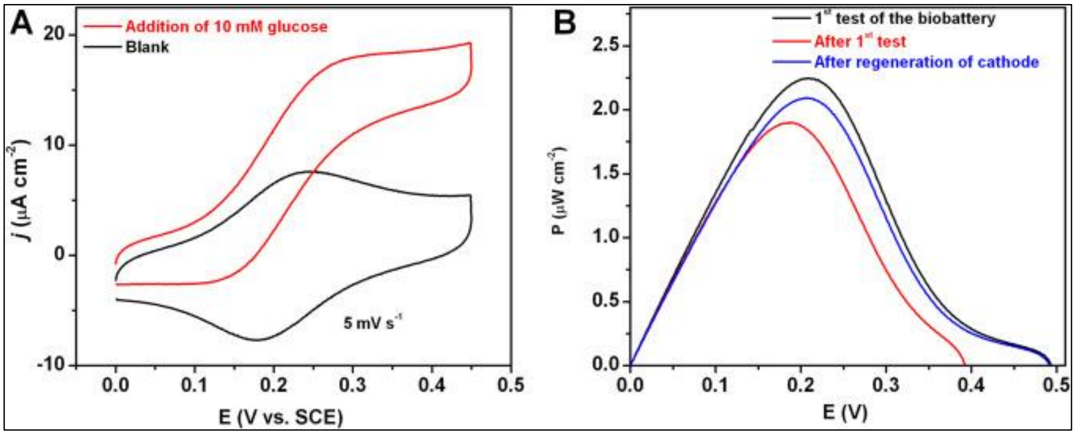
Source Title	Rechargeable membraneless glucose biobattery: Towards solid-state cathodes for implantable enzymatic devices
Source citation (APA Format)	Yazdi, A. A., Preite, R., Milton, R. D., et al. (2017). Rechargeable membraneless glucose biobattery: Towards solid-state cathodes for implantable enzymatic devices. *Journal of Power Sources*, 343, 103–108. https://doi.org/10.1016/j.jpowsour.2017.01.057
Original URL	https://www.sciencedirect.com/science/article/abs/pii/S0378775317300320
Source type	Scientific Research Journal
Keywords	Rechargeable, membraneless, glucose, implantable
#Tags	
Summary of key points + notes (include methodology)	In this paper, Yazdi et al. discuss the potential for implantable enzymatic devices to be used to generate sustainable energy within the bodies of humans. Essentially, these devices work by breaking down the readily available energy present in human physiological fluids to create a sustainable energy stream. This allows for *in vivo* power generation, or the ability for a device to generate power while implanted in a living organism. The design itself works by coupling a glucose oxidase anode with a solid-state Prussian Blue thin film cathode. The design also operates without a membrane, increasing the scope of the design, as strict environmental conditions and material constraints do not have to be met for high-level energy and power output. This design falls within the broad subfield of fuel cells known as biofuel cells, or cells that generate sustainable forms of energy or electricity using biological approaches. As a result of their design, these models possess substantially less environmental impact than other batteries widely used today. Furthermore, the biocatalysts present within these cells (generally enzymes) function optimally at physiological temperatures and pH, making these designs especially effective for medical and real-world applications. This paper presents concluded by engineering a biobattery with a maximum power density of 44 µW cm^{-2} and a maximum current density of 0.9 mA cm^{-2}. These metrics are 37% and 180% higher than an enzymatic fuel cell with a bilirubin oxidase cathode, respectively, showing the potential for the model to be applied in situations outside of a controlled lab environment.

Research Question/Problem/ Need	How can enzyme-catalyzed devices be used for *in vivo* power generation within a membraneless design?
Important Figures	Figure 1: A system-level design of the membraneless battery 
VOCAB: (w/definition)	Bilirubin oxidase – an enzyme used to catalyze oxidation-reduction reactions Overpotential – voltage required beyond the theoretical total to drive a reaction Parasitic reaction – an unwanted side reaction that reduces efficiency of the model
Cited references to follow up on	Bertaglia, T., Costa, C. M., Lanceros-Méndez, S., & Crespilho, F. N. (2024). Eco-friendly, sustainable, and safe energy storage: A nature-inspired materials paradigm shift. *Materials Advances*, 5, 7534–7547. https://doi.org/10.1039/D4MA00363B Wang, C., Shim, E., Chang, H.-K., Lee, N., Kim, H. R., & Park, J. (2020). Sustainable and high-power wearable glucose biofuel cell using long-term and high-speed flow in sportswear fabrics. *Biosensors and Bioelectronics*, 169, 112652. https://doi.org/10.1016/j.bios.2020.112652 Ho, D. P., Pinyou, P., Kim, J., & Minteer, S. D. (2019). Applications of enzymatic biofuel cells in bioelectronic devices – A review. *International Journal of Hydrogen Energy*, *44*(29), 15287–15312. https://doi.org/10.1016/j.ijhydene.2019.04.182
Follow up Questions	1. What are the main advantages of a design using solid-state cathodes opposed to oxygen-based cathodes? 2. What role does glucose oxidase play in allowing for optimal function within the biobattery? 3. What improvements to this design can improve performance for implantable devices?

Article #15 Notes: An oxygen-independent and membrane-less glucose biobattery/supercapacitor hybrid device

Article notes should be on separate sheets

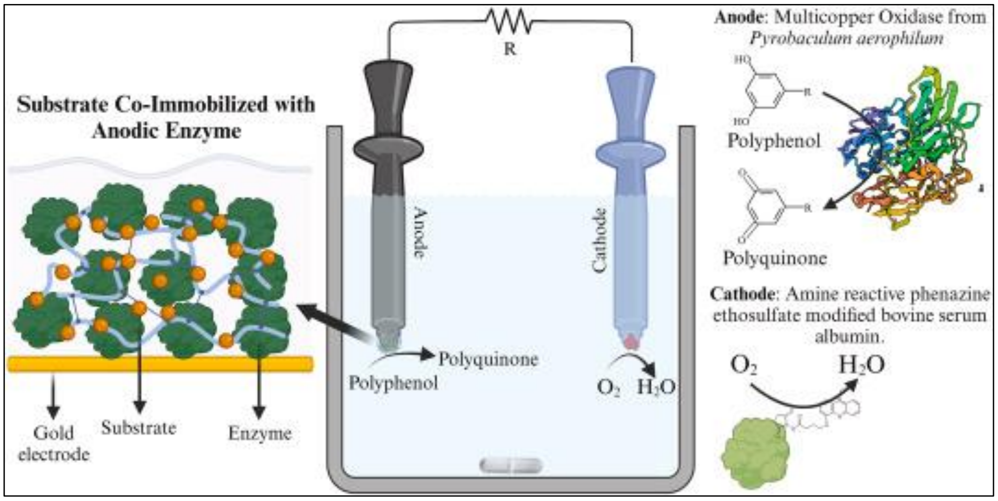
Source Title	An oxygen-independent and membrane-less glucose biobattery/supercapacitor hybrid device
Source citation (APA Format)	Xiao, X., Ó Conghaile, P., Leech, D., Ludwig, R., & Magner, E. (2017). An oxygen-independent and membrane-less glucose biobattery/supercapacitor hybrid device. *Biosensors and Bioelectronics*, 98, 421–427. https://doi.org/10.1016/j.bios.2017.07.023
Original URL	https://www.sciencedirect.com/science/article/abs/pii/S0956566317304712?via%3Dihub
Source type	Scientific Research Journal
Keywords	Oxygen-independent, membrane-less, supercapacitor, hybrid
#Tags	
Summary of key points + notes (include methodology)	In this paper, Xiao et al. analyzed the potential for *in vivo* applications of hybrid supercapacitor-biobattery devices that can generate sustainable energy from the readily available energy present in physiological fluids. These devices bridge the gap between traditional batteries and capacitors, allowing for high-level energy output without additional material constraints. *In vivo* application of these devices involves careful design constraints as traditional fuel sources differ heavily from the concentration of substrates present in physiological fluids. In traditional designs, oxygen is critical to the energy generation process; however, this paper proposes an alternate design that does not involve oxygen by developing an air-breathing biocathode. A hybrid device consisting of a biobattery and a supercapacitor has the potential for higher energy output than both designs individually, but also the capability for higher stability and more use-cases across different applications. In this paper, the engineered hybrid device generated 294 times higher power pulses than the biobattery alone, showing the capability for supercapacitors to drastically improve the reaction rate and power production of these models.
Research Question/Problem / Need	Can a supercapacitor-biobattery hybrid device deliver high power and energy densities, with *in vivo* power generation applications?
Important Figures	Figure 1: A comparison of voltage and the saturated calomel electrode (SCE) and their relationship to power and current densities

	
VOCAB: (w/definition)	MnO_2 cathode – A manganese dioxide solid-state cathode used for charge storage and discharge Pseudo-capacitance – charge storage through fast, reversible redox reactions rather than only electrostatic charge Intercalation – the reversible insertion or removal of ions into or from a solid electrode material
Cited references to follow up on	Addo, P. K., Arechederra, R. L., & Minteer, S. D. (2011). Towards a rechargeable alcohol biobattery. *Journal of Power Sources*, *196*(7), 3448–3451. https://doi.org/10.1016/j.jpowsour.2010.11.055 Ardizzone, S., Fregonara, G., & Trasatti, S. (1990). “Inner” and “outer” active surface of RuO_2 electrodes. *Electrochimica Acta*, *35*(1), 263–267. https://doi.org/10.1016/0013-4686(90)85068-X Jenkins, P. A., Tuurala, S., Vaari, A., Valkiainen, M., Smolander, M., & Leech, D. (2011). A comparison of glucose oxidase and aldose dehydrogenase as mediated anodes in printed glucose/oxygen enzymatic fuel cells. *Bioelectrochemistry*, 87, 172–177. https://doi.org/10.1016/j.bioelechem.2011.11.011
Follow up Questions	1. What role does the spontaneous recovery of MnO_2 within the cathode play in allowing for the design to show supercapacitor-like behavior? 2. Why is glucose dehydrogenase preferred over glucose oxidase? 3. How does the power density of the hybrid device compare to a traditional EFC?

Article #16 Notes: Development of the BioBattery: A novel enzyme fuel cell using a multicopper oxidase as an anodic enzyme

Article notes should be on separate sheets

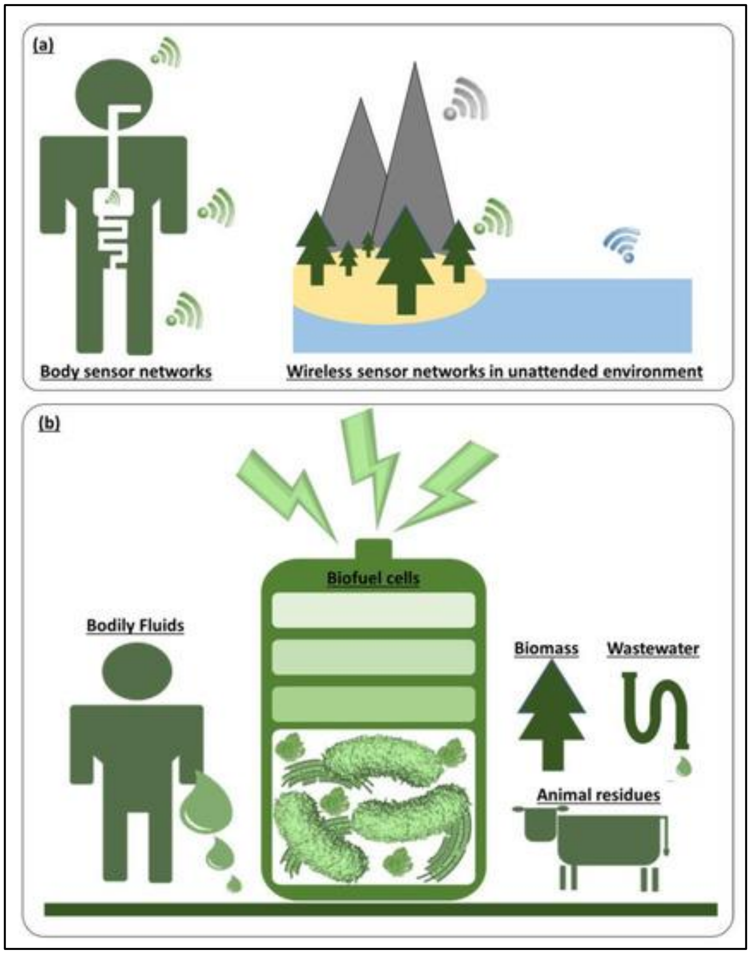
Source Title	Development of the BioBattery: A novel enzyme fuel cell using a multicopper oxidase as an anodic enzyme
Source citation (APA Format)	
Original URL	https://www.sciencedirect.com/science/article/abs/pii/S0956566324000952?via%3Dihub
Source type	Scientific Research Journal
Keywords	Biobattery, multicopper, anodic enzyme
#Tags	
Summary of key points + notes (include methodology)	In this paper, Batchu et al. engineered a novel enzymatic fuel cell with a wide range of applications including wearable sensors, textiles, and environmental setups. However, the direct application of the device proposed in this paper is *in vivo* power generation, or the ability of a device to generate power while implanted in a living organism, specifically within humans. The design of the battery itself is very similar to traditional batteries, involving electrodes (the anode and the cathode) and an electrolyte solution. Multicopper oxidases are a class of enzymes that are used to catalyze oxidation-reduction reactions and for this paper, were used as the anodic enzyme, or the enzyme present at the anode. This allows for enhanced electron transfer processes, increasing the power production capabilities of the cell. The design also involves the oxidation of polyphenols, which are naturally occurring compounds, into polyquinones, which are organic polymers. This conversion process allows for increased capacitance, or the ability for a certain material to store electric charge, increasing the power generation and productive capabilities of the cell. The design involved enzyme mixes to catalyze the oxidation processes, for which McoP (multicopper oxidase from *Pyrobaculum aerophilum*) produced the highest power and current densities at 0.45 ± 0.02 mW cm^{-2} and 0.56 ± 0.08 A m^{-2}. This shows the potential for the design principles to apply for future technologies in the field of biobatteries utilizing anodic enzymes.
Research Question/Problem / Need	Can multicopper oxidases function as efficient anodic enzymes within a biobattery design?
Important Figures	Figure 1: A diagram of the system-level design of the biobattery

	
VOCAB: (w/definition)	Multicopper oxidase – a class of enzymes that contain multiple copper ions, which are mainly used to catalyze oxidation-reduction reactions Diffusion limitation – a restriction in power output caused by slow transport of substrates (diffusion) Series/parallel stacking – electrical configurations used to increase voltage/current
Cited references to follow up on	Gough, D. A., Leypoldt, J. K., & Armour, J. C. (1982). Progress toward a potentially implantable, enzyme-based glucose sensor. *Diabetes Care*, *5*(3), 190–196. https://doi.org/10.2337/diacare.5.3.190 Hanashi, T., Yamazaki, T., Tsugawa, W., Ikebukuro, K., & Sode, K. (2011). BioRadioTransmitter: A self-powered wireless glucose-sensing system. *Journal of Diabetes Science and Technology*, *5*(4), 1030–1035. https://doi.org/10.1177/193229681100500502 Hanashi, T., Yamazaki, T., Tanaka, H., Ikebukuro, K., Tsugawa, W., & Sode, K. (2014). The development of an autonomous self-powered bio-sensing actuator. *Sensors and Actuators B: Chemical*, 196, 429–433. https://doi.org/10.1016/j.snb.2014.01.117
Follow up Questions	1. How does co-immobilizing the substrate with the anodic enzyme change power limitations? 2. How does integrating the battery with a capacitor expand its use cases? 3. What role does glutaraldehyde play in immobilizing the enzyme and acting as a fuel source?

Article #17 Notes: Biofuel cells and biobatteries: Misconceptions, opportunities, and challenges

Article notes should be on separate sheets

Source Title	Biofuel cells and biobatteries: Misconceptions, opportunities, and challenges
Source citation (APA Format)	Choi, S. (2023). Biofuel cells and biobatteries: Misconceptions, opportunities, and challenges. *Batteries*, *9*(2), 119. https://doi.org/10.3390/batteries9020119
Original URL	https://doi.org/10.3390/batteries9020119
Source type	Scientific Research Journal
Keywords	Enzymatic fuel cells, microbial fuel cells, biobatteries, biofuel cells, bioelectronics
#Tags	
Summary of key points + notes (include methodology)	Biofuel cells have extraordinary potential for being sustainable energy storage/energy generation alternatives to current methods, especially when it comes to *in vivo* power generation. As technology improves, electronics are becoming more portable and flexible, allowing for a wider range of applications, making research and development into currently under-researched fields such as biofuel cells critical. Biofuel cells can be categorized into MFCs and EFCs. MFCs, or microbial fuel cells, are cells that are capable of fully breaking down a fuel source and extracting as much energy as possible, but they require a high amount of maintenance and up-keep, making them less applicable for industrial and technological applications. EFCs, or enzymatic fuel cells, on the other hand, are much more efficient in terms of their independence, but they are unable to fully oxidize/break down the fuel sources that drive their power generation. This leads to trade-offs between their use cases, making development into EFC/MFC important for allowing for improved performance across applications. The majority of current MFC development focuses on the application of MFCs for wastewater treatment but has not shown any commercial success. EFC development has also been heavily lab-based and theoretical with few models making it to real-life applications. Wearable devices are an area of promising research that heavily relies on EFC/MFC development, as the potential for using human physiological energy as the fuel source for these cells means minimal environmental impact, if any. However, one of the most important things to focus on for future research is the longevity and shelf-life of these fuel cells, as biological compounds, regardless of intended use, often experience heavy fluctuations due to atmospheric/external conditions.
Research Question/Problem/ Need	How has biofuel research in the past contributed to models today and what are the optimal paths for future development in the field?

<table>
<tr><td>Important Figures</td><td>Figure 1: A diagram showing the potential for implantable/wearable EFC and MFC devices to be used within the human body and in unattended environments

</td></tr>
<tr><td>VOCAB: (w/definition)</td><td>Exoelectrogens – microorganisms capable of transferring electrons outside of their cell to generate electricity

Biotic-abiotic interface – the interface between living and nonliving components in biofuel cells

Organelle-based fuel cell – biofuel cells using cellular organelles to improve efficiency</td></tr>
<tr><td>Cited references to follow up on</td><td>Bueno, P. R., & Davis, J. J. (2020). Charge transport and energy storage at the molecular scale: From nanoelectronics to electrochemical sensing. Chemical Society Reviews, 49(21), 7505–7515. https://doi.org/10.1039/D0CS00241D

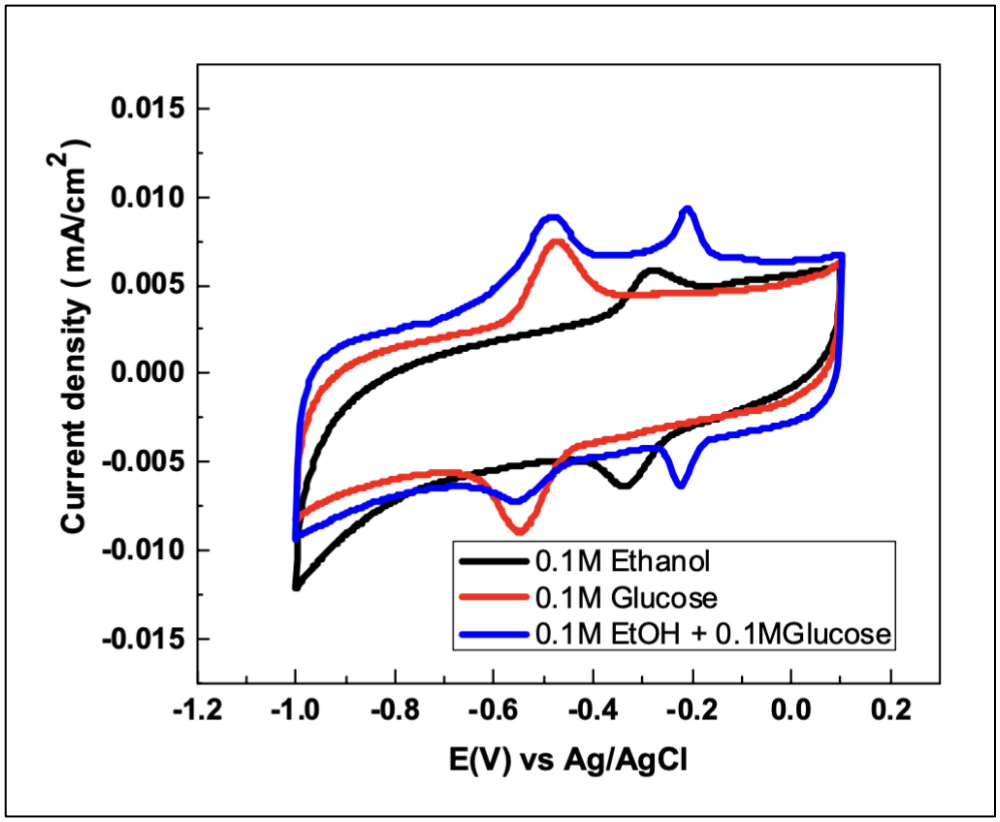
Wang, P., Hu, M., Wang, H., Chen, Z., Feng, Y., Wang, J., Ling, W., & Huang, Y. (2020). The evolution of flexible electronics: From nature, beyond nature,</td></tr>
</table>

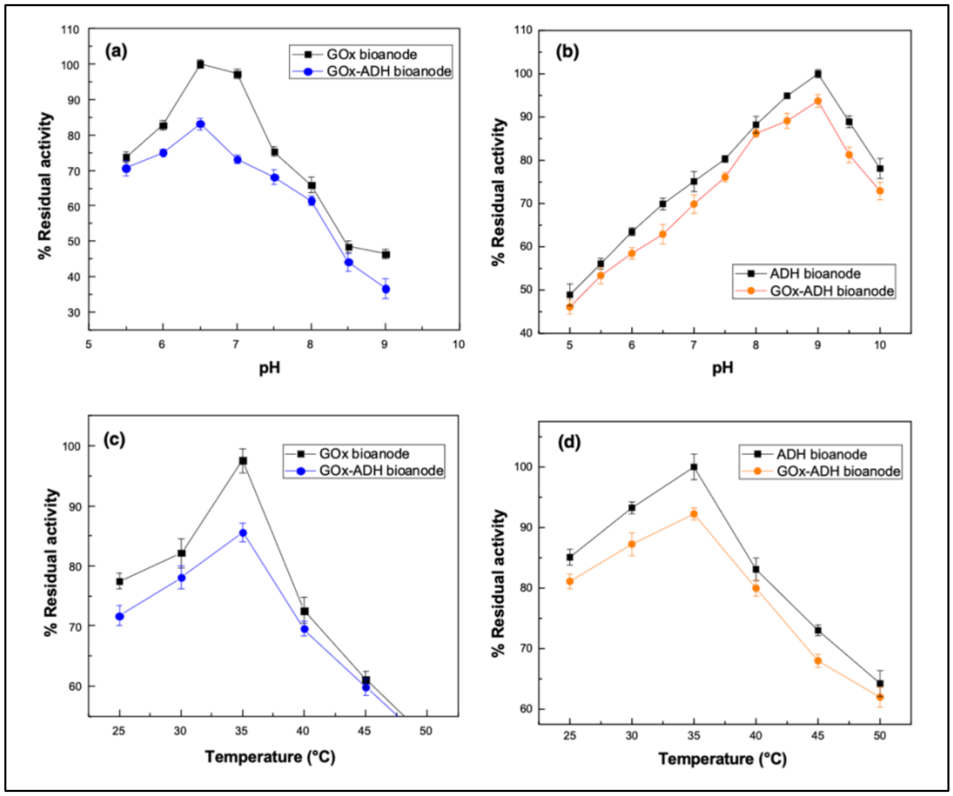
	and to nature. *Advanced Science, 7*(20), 2001116. https://doi.org/10.1002/advs.202001116 Yao, S., Ren, P., Song, R., Liu, Y., Huang, Q., Dong, J., O'Connor, B. T., & Zhu, Y. (2020). Nanomaterial-enabled flexible and stretchable sensing systems: Processing, integration, and applications. *Advanced Materials, 32*(19), 1902343. https://doi.org/10.1002/adma.201902343
Follow up Questions	1. How do MFCs differ structurally from EFCs and how do these differences contribute to performance? 2. How can supercapacitative electrodes enhance biofuel cell power output? 3. What are the best strategies for improving EFC/MFC longevity?

Article #18 Notes: Development of bioanode for versatile applications: microfuel cell system in the presence of alcohol and glucose

Article notes should be on separate sheets

Source Title	Development of bioanode for versatile applications: microfuel cell system in the presence of alcohol and glucose
Source citation (APA Format)	Ledesma-García, J., Gurrola, M.P., Trejo-Arroyo, D.L., Rodríguez-Morales, J.A., Gutiérrez, A., Escalona-Villalpando, R.A., & Arriaga, L.G. (2022). Development of bioanode for versatile applications: microfuel cell system in the presence of alcohol and glucose. *Materials for Renewable and Sustainable Energy*. https://doi.org/10.1007/s40243-022-00207-2
Original URL	https://doi.org/10.1007/s40243-022-00207-2
Source type	Scientific Research Journal
Keywords	Bioanode, microfuel, alcohol, glucose
#Tags	
Summary of key points + notes (include methodology)	This paper aims to engineer a bioanode that can function using glucose oxidase and alcohol dehydrogenase, which are enzymes capable of oxidizing glucose and alcohols present in beverages. Oxidation using multiple enzymes has a lot of potential for biological and technological applications, as the ability of enzymes to catalyze large amounts of substrates given little input energy makes them very efficient. This increases the amount of fuel used and increases current density. Enzymes also have high selectivity, meaning that minimal energy is lost from bonds between enzymes and non-substrates, which also contributes to high efficiency levels. However, despite the potential for multi-enzyme models, there are a variety of issues that inhibit optimal enzyme function, which include interactions between glucose oxidase and the site of the anode. Three bioanodes were designed in this project: a strictly glucose oxidase-catalyzed anode, an alcohol dehydrogenase-catalyzed anode, and a combination of both. The activity of glucose oxidase was determined by the amount of hydrogen peroxide produced when 3,30,5,50 TMB was introduced as a co-substrate. All groups contained enzymes immobilized using the same methods. The glucose oxidase-only anode produced the best energy output, with a higher OCV (0.93 V compared to 0.9 V), density (8.06 mA cm^{-2} compared to 7.71 mA cm^{-2}), and power density (3.87 mW cm^{-2} compared to 2.71 mW cm^{-2}). When a second enzyme was added, there was likely a reduced current density because of increased non-conductive protein mass present in the design, which would inhibit enzyme performance over time. This

	paper successfully designed a microfluidic cell capable of oxidizing both glucose and ethanol, recording a maximum power density of 5071 µW cm^{-2}, marking the first time a fuel cell could successfully do both.
Research Question/Problem/ Need	Can a glucose-oxidase-catalyzed bioanode function successfully within an efficient and sustainable biobattery design?
Important Figures	Figure 2: Cycling voltammograms of the redox FAD^+ and NAD^+ of the bioanode with both enzymes  Figure 4: Comparison of the effect of varying pH levels on bioanode performance



VOCAB: (w/definition)

$FADH_2$ – a redox cofactor used in reactions involving glucose oxidase catalysis

Laminar flow – smooth, non-turbulent fluid flow in traditional microfluidic cell systems

Lab-on-a-chip – mini devices containing multiple lab functions on a microchip

Cited references to follow up on

Sakuta, R., Takeda, K., Ishida, T., Igarashi, K., Samejima, M., Nakamura, N., & Ohno, H. (2015). Multi-enzyme anode composed of FAD-dependent and NAD-dependent enzymes with a single ruthenium polymer mediator for biofuel cells. *Electrochemistry Communications, 56*, 75–78. https://doi.org/10.1016/j.elecom.2015.04.013

Shao, M., Nadeem, M., Sygmund, C., Guschin, D. A., Ludwig, R., Peterbauer, C. K., Schuhmann, W., & Gorton, L. (2013). Mutual enhancement of the current density and the coulombic efficiency for a bioanode by entrapping bi-enzymes with Os-complex modified electrodeposition paints. *Biosensors and Bioelectronics, 40*, 308–314. https://doi.org/10.1016/j.bios.2012.07.069

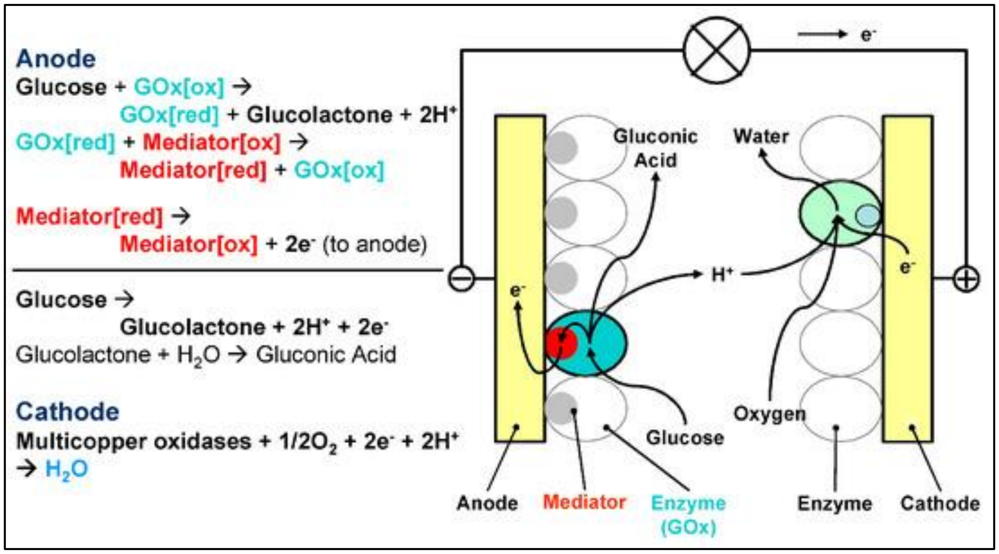
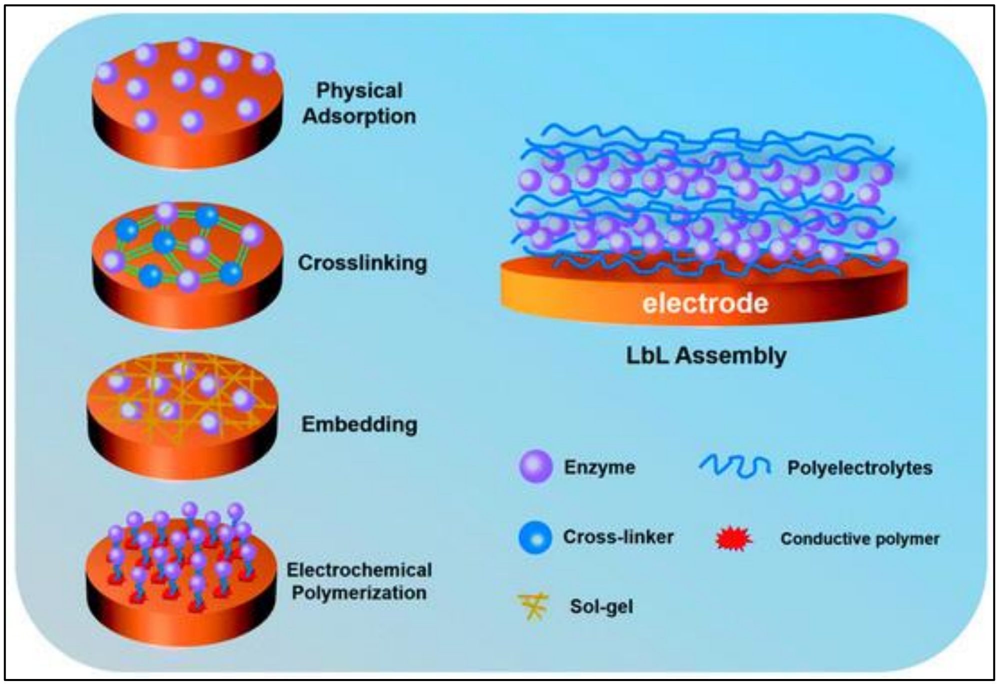
Nguyen, H. H., Lee, S. H., Lee, U. J., Fermin, C. D., & Kim, M. (2019). Immobilized enzymes in biosensor applications. *Materials, 12*(1), 121. https://doi.org/10.3390/ma12010121

Follow up Questions	1. What role do functionalized CNFs play in enzyme stability? 2. Since GOx and ADH operate optimally at different pH levels, how should a model containing both be designed? 3. What are the main next steps for scaling this design for real-life applications?

Article #19 Notes: Research Progress in Enzyme Biofuel Cells Modified Using Nanomaterials and Their Implementation as Self-Powered Sensors

Article notes should be on separate sheets

Source Title	Research Progress in Enzyme Biofuel Cells Modified Using Nanomaterials and Their Implementation as Self-Powered Sensors
Source citation (APA Format)	Cao, L., Chen, J., Pang, J., Qu, H., Liu, J., & Gao, J. (2024). Research Progress in Enzyme Biofuel Cells Modified Using Nanomaterials and Their Implementation as Self-Powered Sensors. *Molecules*, *29*(1), 257. https://doi.org/10.3390/molecules29010257
Original URL	https://doi.org/10.3390/molecules29010257
Source type	Scientific Research Journal
Keywords	Biofuel cells, nanomaterials, self-powered
#Tags	
Summary of key points + notes (include methodology)	Enzymatic biofuel cells are an extremely promising alternative to current energy storage systems for their durability and efficiency. At their core, they work by utilizing enzyme catalysis to oxidize fuel sources, eventually converting them into usable electricity. One of the main enzymes used in these cells is glucose oxidase, an enzyme capable of converting standard glucose into gluconolactone and hydrogen ions, along with electrons being released to the anode as energy. Glucose oxidase has extreme catalytic abilities because of its durability and efficiency. While enzymes like glucose oxidase are useful in enzymatic biofuel cells, it often helps to immobilize, or stabilize, enzymes before use in lab environments. This stems from the natural tendency of enzymes to sway heavily with atmospheric factors, meaning that physical and chemical immobilization techniques are used throughout EBFC research. However, another promising alternative to immobilization is the use of nanomaterials, which are also used to enhance stability in EBFC designs. While they may have some negative impacts on enzyme activity, nanomaterials are generally an extreme positive to enzyme efficiency and productivity in EBFC designs. One of the main reasons for their benefits is that they are naturally conductive materials. A key application of EBFCs is for human-based, or *in vivo*, power generation, which utilize naturally available physiological energy for conversation to usable electricity. However, an important challenge to address before EBFC-SPS devices are implemented at a large-scale is to improve their stability and longevity for prolonged and high-level performance.
Research Question/Problem/	How can enzyme biofuel cells be used as self-powered sensors?

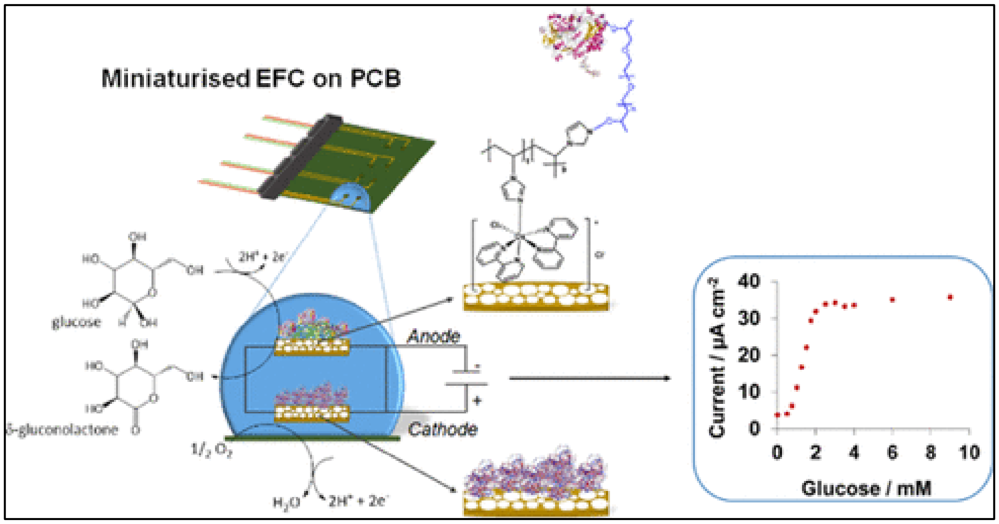
Need	
Important Figures	Figure 1: A diagram of the energy flow within an EBFC  Figure 2: Enzyme immobilization strategies to improve cell performance 
VOCAB: (w/definition)	Mediated electron transfer – electron transfer between an electrode and the electrolyte that involves the assistance of redox mediators

	Hybrid conductive materials – composites combining carbon nanomaterials and metal nanoparticles Aptasensor – a sensor that uses aptamers for recognition
Cited references to follow up on	Huang, J., Zhao, P., Jin, X., Wang, Y., Yuan, H., & Zhu, X. (2020). Enzymatic biofuel cells based on protein engineering: Recent advances and future prospects. *Biomaterials Science, 8*(18), 5230–5240. https://doi.org/10.1039/D0BM00941A Huang, J., Zhang, Y., Deng, X., Li, J., Huang, S., Jin, X., & Zhu, X. (2022). Self-encapsulated enzyme through in situ growth of polypyrrole for high-performance enzymatic biofuel cells. *Chemical Engineering Journal, 429*, 132148. https://doi.org/10.1016/j.cej.2021.132148 Qin, H., Wang, Z., Yu, Q., Xu, Q., & Hu, X.-Y. (2022). Flexible dibutyl phthalate aptasensor based on self-powered CNTs–rGO enzymatic biofuel cells. *Sensors and Actuators B: Chemical, 371*, 132468. https://doi.org/10.1016/j.snb.2022.132468
Follow up Questions	1. What makes hybrid materials more efficient/applicable for EBFC designs? 2. Within MET-based EFCs, what inhibits maximum open circuit voltage? 3. What factors influence the sensitivity of aptasensors?

Article #20 Notes: Self-Powered Detection of Glucose by Enzymatic Glucose/Oxygen Fuel Cells on Printed Circuit Boards

Article notes should be on separate sheets

Source Title	Self-Powered Detection of Glucose by Enzymatic Glucose/Oxygen Fuel Cells on Printed Circuit Boards
Source citation (APA Format)	Gonzalez-Solino, C., Bernalte, E., Bayona Royo, C., Bennett, R., Leech, D., Di Lorenzo, M. (2021). Self-Powered Detection of Glucose by Enzymatic Glucose/Oxygen Fuel Cells on Printed Circuit Boards. *ACS Applied Materials & Interfaces*, *13*(23), 26704-26711. https://doi.org/10.1021/acsami.1c02747
Original URL	https://doi.org/10.1021/acsami.1c02747
Source type	Scientific Research Journal
Keywords	Detection, printed circuit boards, enzymatic, glucose
#Tags	
Summary of key points + notes (include methodology)	Glucose is a crucial compound in the context of biology. However, excess glucose in any organism can create health risks and complications, making glucose monitoring crucial. An under-researched technology for this need is EFCs, or enzymatic fuel cells. Enzymatic fuel cells use fuel sources, often polysaccharides like glucose, to generate usable electricity. Not only does this prove useful for glucose monitoring and regulation but also allows to produce sustainable and efficient renewable energy. This paper proposes the use of EFCs on printed circuit boards (PCBs) for glucose monitoring, providing sustainable and efficient care. The main methods used in the study involved enzyme immobilization only electrodes placed onto PCBs and bioelectrode categorization. The main enzyme used in the design was glucose oxidase, which required the use of a redox mediator. The performance of the EFC was measured in a buffer within a controlled lab environment. The EFC was tested for a variety of electrochemical metrics, such as current density and power. The design utilizing GDH, NADH, and Vitamin K3 as electron mediators was the most successful of the groups tested, providing a detection sensitivity of only 0.004 μW cm^{-2} mM^{-1}. Therefore, this study was able to successfully conclude that glucose/oxygen fuel cells catalyzed by glucose oxidase and a variety of electron mediators was able to detect glucose and provide an efficient glucose monitor.
Research Question/Problem/ Need	Can enzymatic fuel cells be used as safe and efficient glucose monitors?

Important Figures	Figure 1: The proposed design for an EFC on a PCB, along with the chemical reactions that the cell participates in *in vivo* 
VOCAB: (w/definition)	Osmium redox polymer – a polymeric mediator used to electrically connect glucose oxidase to the electrode Highly porous gold – a gold film with high electrochemical surface area Linear sweep voltammetry – a technique used to find catalytic activity at the anode of an EFC
Cited references to follow up on	Zhou, M. (2015). Recent progress on the development of biofuel cells for self-powered electrochemical biosensing and logic biosensing: A review. *Electroanalysis, 27*(8), 1786–1810. https://doi.org/10.1002/elan.201500173 Bartlett, P. N., & Al-Lolage, F. A. (2018). There is no evidence to support literature claims of direct electron transfer (DET) for native glucose oxidase (GOx) at carbon nanotubes or graphene. *Journal of Electroanalytical Chemistry, 819*, 26–37. https://doi.org/10.1016/j.jelechem.2017.06.021 Ruff, A. (2017). Redox polymers in bioelectrochemistry: Common playgrounds and novel concepts. *Current Opinion in Electrochemistry, 5*, 66–73. https://doi.org/10.1016/j.coelec.2017.06.007
Follow up Questions	1. Why does enzyme adsorption lead to lower long-term stability? 2. How does enzyme denaturation or leaching in a lab environment affect stability for real-life applications? 3. Why is porous gold more effective than planar gold for implantable EFCs?

Patent #1 Notes: Biological battery and biological cathode

Article notes should be on separate sheets

Source Title	Biological battery and biological cathode
Source citation (APA Format)	Zhang, P. (2020). *Biological battery and biological cathode* (U.S. Patent No. 10,658,692 B1). United States Patent and Trademark Office. https://patents.google.com/patent/US10658692B1
Original URL	https://patents.google.com/patent/US10658692B1/en
Source type	Patent
Keywords	Electrode, biobattery, fuel cells
#Tags	
Summary of key points + notes (include methodology)	Batteries are the primary form of energy storage used worldwide. At the time of this patent's publications, battery sales comprised nearly $48 billion yearly. However, the premier models used in technological and industrial applications feature metal-based designs for efficient and high-power energy generation. This is an issue because the environmental harm derived from the mining processes of these metals severely diminishes their potential utility and benefits. Metal-air models, such as Zinc-air batteries, have been proposed as sustainable alternatives. These designs involve the use of atmospheric oxygen at the cathode, allowing for external energy and compounds to interact with the otherwise independent battery system. Manganese catalyzed cathodes provide the best specific current capacity, at 3137 mA·H/g, more than 20% higher than cobalt catalyzed cathodes showing extreme potential for real-world applications. However, biological alternatives to battery concerns involve the use of bioderived compounds that interact in a way that emulates the electrode-electrolyte interactions present in traditional batteries. There are 2 main alternatives under the umbrella of biological solutions: MFCs and EFCs. MFCs, or microbial fuel cells, involve the use of microbes to catalyze reactions that produce external energy, stored within the anode as electricity. By contrast, EFCs, or enzymatic fuel cells, implement a similar process, but instead use enzymes as biological catalysts to speed up oxidation reactions to break down fuel sources, generally polysaccharides, into their intermediate parts. This patent proposes a biological cathode design that utilizes a variant of *Geobacter sulfurreducens*, known as KN400. In the design, KN400 functions as a catalyst at the cathode, allowing for faster oxidation reactions to occur. This is beneficial in 2 ways. Firstly, this allows for a higher energy creation potential. Additionally, it allows for increased power, or the ability to produce a high amount of energy in a short period of time, proving this design's capability to enhance existing biobattery designs and potentially even define a novel system-

level design for improved biobattery function.

Research Question/Problem/ Need

How can a biological cathode and biobattery improve upon existing metal-based designs for reduced environmental impact and greater performance capabilities?

Important Figures

Fig. 1: A comparison of enzymatic fuel cell (EFC) models and their performances over varying testing times

Fig. 4

Author and year	Current density (A/m2)	Duration during testing (day)	Cathode material	Polarization method	Culture	Lowest Polarization potential vs. SHE(V)
Bergel et al, 2005	0.46 no control	12	Stainless steel	Constant Polarization	Mix culture	-0.156
Erable B., Bergel et al. 2010	0.6 no control	NA	Graphite felt (no collector)	Constant Polarization	Mix culture	-0.001
Rabaey et al. 2008	0.37 vs. control	Not indicated	Stainless steel	Polarization curve (1mV/s)	Pure culture	-0.32
Vandecandelaere et al. 2008	0.50 no control	Not indicated	Stainless steel	Polarization curve	Pure culture	-0.001
Pei Zhang et al, 2011(manuscript)	0.92 vs. control	>11	Graphite rod	Constant Polarization	Pure culture	-0.351
Pei Zhang et al, 2012	7.5 vs. control	>11	Carbon material	Constant Polarization	Pure culture	-0.351
Pei Zhang et al	Expect > 7.5 vs. control	>11	Compatible material	Constant Polarization	Pure culture	-0.351

VOCAB: (w/definition)

Biofilm – a set of microorganisms arranged and attached to a surface
Renewable feedstock – raw materials that can be replenished naturally
Ion exchange membrane – a membrane that allows ions to pass while separating the anode and cathode

Cited references to follow up on

Sotomura, T. (2003). *Composite electrode for reducing oxygen* (U.S. Pub. No. US 2003/0091889 A1). U.S. Patent and Trademark Office. https://patents.google.com/patent/US6576370B1/zh

Nealson, K. H., Pirbazari, M., & Hsu, L. (2013). *Microbial fuel cells* (U.S. Patent No. 8,415,037 B2). United States Patent and Trademark Office. https://patents.google.com/patent/US8415037B2/en

Greenman, J., & Ieropoulos, A. I. (2014). *Microbial fuel cell* (U.S. Patent Application No. US20140057136A1). United States Patent and Trademark Office. https://patents.google.com/patent/US20140057136A1/en

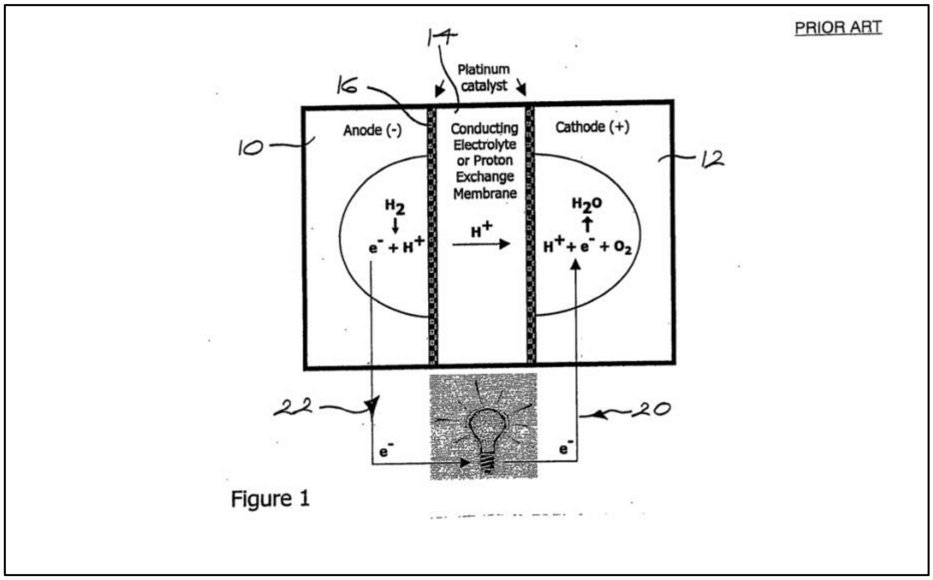
Follow up Questions

1. How does the biological cathode add to current designs?
2. Are there any challenges with implementing these designs alongside existing ones?
3. What about the system itself causes lower overpotentials?

Patent #2 Notes: Enzymatic fuel cell

Article notes should be on separate sheets

Source Title	Enzymatic fuel cell
Source citation (APA Format)	Du Plessis, C. A. (Inventor), & BHP Billiton SA Limited (Applicant). (2006). *Enzymatic fuel cell* (International Publication No. WO 2006/015392 A2). World Intellectual Property Organization. https://patents.google.com/patent/WO2006015392A2/en
Original URL	https://patents.google.com/patent/WO2006015392A2/en
Source type	Patent
Keywords	Bacteria, thermophilic, archaea, fuel cell
#Tags	
Summary of key points + notes (include methodology)	Fuel cells are a promising alternative to batteries. Batteries are widely used across different industries and at varying scales but are crucial to all technology. However, the material sourcing process for many batteries, generally surrounding metal mining, make them sub-optimal for global applications. Fuel cells are biological cells that utilize a variety of bioderived compounds to catalyze internal reactions that produce energy. Generally, the reaction at the anode of the fuel cell releases electrons, which are then used at the cathode for a secondary reaction that produces a final production, which then goes through the reaction pathway once again. This process of energy conversion breaks down the initial fuel source/compound into its intermediate parts, with the electrons released becoming usable electricity. Specifically, enzymatic fuel cells are a subset of fuel cells that use enzymes as biological catalysts to speed up these reactions in the pursuit of higher energy output. This design proposes the use of thermophilic enzymes, along with phospholipids, to improve the efficiency of these reactions to create more efficient systems overall. Thermophilic enzymes are those that are stable at high temperatures, meaning that they are much more stable than traditional enzymes that would otherwise denature under sub-optimal atmospheric temperature and pH. This allows for a wider range of uses for these enzymes, along with improved performance. Phospholipids are compounds that are lipids that contain both a hydrophilic and hydrophobic component, allowing them to be used across different environments and designs. This patent proposes using these compounds to improve the flow of energy throughout the design, which would lead to improved Faradaic efficiency, along with higher energy density and potential output.
Research Question/Problem/ Need	How can a pathway of phospholipids and thermophilic enzymes contribute to improved energy production in biobatteries?

Important Figures	Fig. 1: A diagram showing the flow of energy within the proposed design, along with the chemical equations that define the reactions 
VOCAB: (w/definition)	Ether-linked lipids – lipids in which hydrocarbon chains are linked to a glycerol backbone S-layer proteins – surface-layer proteins forming a crystalline layer outside of the cell membrane for support and stability Biomimetic applications – technologies that mimic natural biological structures
Cited references to follow up on	Le Goff, A., & Holzinger, M. (2018). *Molecular engineering of the bio/nano-interface for enzymatic electrocatalysis in fuel cells*. *Sustainable Energy & Fuels, 2*(9), 2555–2566. https://doi.org/10.1039/C8SE00374B Ivanov, I., Vidaković-Koch, T., & Sundmacher, K. (2010). *Recent advances in enzymatic fuel cells: Experiments and modeling*. *Energies, 3*(4), 803–846. https://doi.org/10.3390/en3040803 Ghassemi, Z., & Slaughter, G. (2017). *Biological fuel cells and membranes*. *Membranes, 7*(1), 3. https://doi.org/10.3390/membranes7010003
Follow up Questions	1. How do the ether-linked lipids from thermophilic archaea contribute to the stability of the overall model? 2. How does the active proton-pumping approach in this EFC differ from diffusion? 3. How does the use of thermophilic enzymes change the model's overall performance and efficiency?