EnerHarv 2024

PSMA International Workshop | 26-28 June, 2024 | Perugia, Italy

COMMERCIAL SPONSORS

EnerHarv 2024 Workshop:

Harvesting Nature's Power: Plant-Microbial Fuel Cells & Adaptive Self-Scaling Energy Storage for battery-free IoT

Università di Trento
Department of Industrial Engineering

Presented By:

Doglioni Maria
PhD student
University of Trento,
Department of Industrial engineering
maria.doglioni@unitn.it

Friday, June 28, 2024

ORGANIZER
PSMA

HOST
unipg

MEDIA SPONSORS

TECHNICAL SPONSORS

OVERVIEW

- **PLANT MICROBIAL FUEL CELLS**
- **AD HOC HARVESTING AND BIOSENSING**
- **ULTRA-LOW POWER EIS SENSOR NODE**
- **DYNAMIC CAPACITANCE FOR BATTERYLESS NODES**

SUSTAINABILE WIRELESS SENSOR NETWORKS: IS IT POSSIBLE?

Renewable energy: the energy source renews naturally → **Renewable & sustainable is the future of EH** ← **Sustainable energy**: can be relied on without impacting future generations

- Established **renewable** energy sources aren't fully **sustainable:**
  - research into **renewable & sustainabl**e energy sources needed.

- Sustainability improvements for **sensor networks** operating on **ambient energy**:
  - **Battery-free, ultra low power** electronics.

HARVESTING ENERGY FROM PLANTS AND SOIL

Plant Microbial Fuel Cells (PMFCs): energy harvesting from **soil microbes** and **plants.**

- Truly **sustainable, accessible** and **circular renewable energy.**
- **Continuous** power generation (mW/dm^3, 24h/7).
- Based on **exoelectrogenic bacteria** naturally present in the soil.
- **Plant photosynthesis** yields byproducts at the roots, which sustain **bacteria.**
- Potentially generates **electricity** as long as **plant lives**.

APPLICATION SCENARIOS - PMFCs

PMFCs have a **wide application** field:

Power sources for WSNs

- Smart agriculture
- Smart cities and green roofs
- Marine and fluvial infrastructure

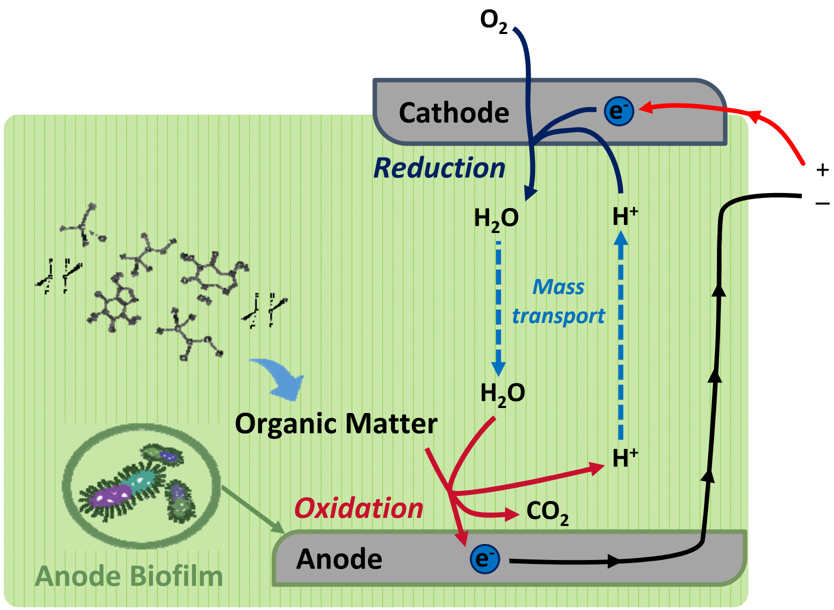
Bioremediation

- Removal of heavy metals
- Wastewater treatment
- Water desalination

Biosensing

- Water quality monitoring
- Toxicity detection
- Plant health monitoring

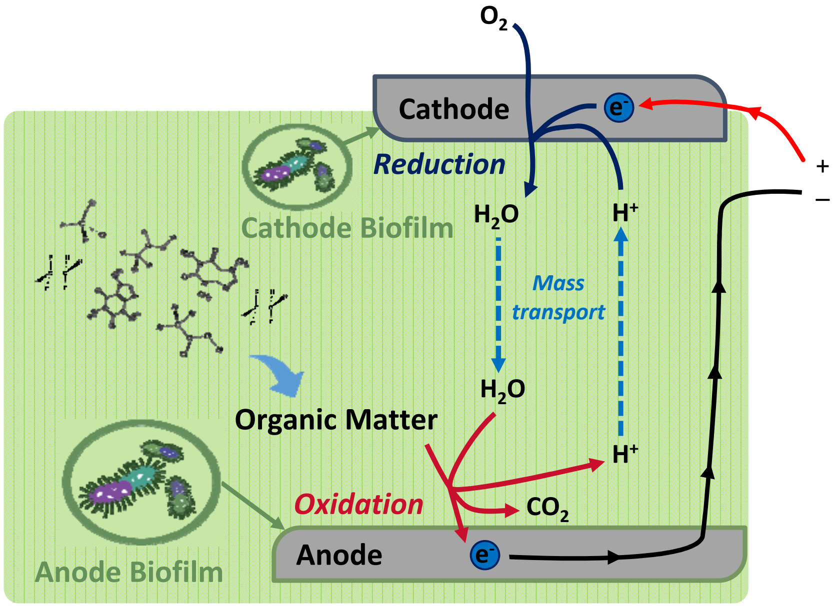
MICROBIAL FUEL CELLS: WORKING PRINCIPLE



Microbial Fuel Cells (MFCs) rely on **micro-organism mediated redox** reactions for energy production.

- **Oxidation**: microbial **metabolism** oxidates organic matter, yielding **electrons** at the anode.
- **Reduction**: half-reaction at the cathode, where electrons are consumed.
- **Potential difference** forms between the electrodes: we can **harvest** the **electron flow** through an external circuit.

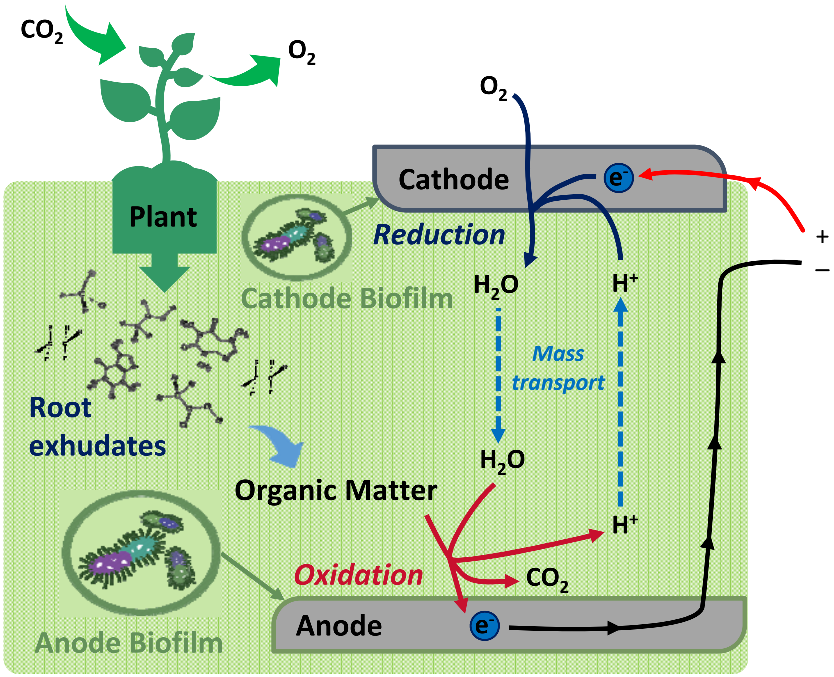
MICROBIAL FUEL CELLS: WORKING PRINCIPLE



Microorganisms have a key role in MFCs:

- **Exoelectrogenic** bacteria forms anodic, **conductive biofilm**, catalyzing **oxidation** reactions.
- **Electrotroph** bacteria can also form a cathodic biofilm, catalyzing **reduction** reactions [3]. The reduction reaction can also happen abiotically.

MICROBIAL FUEL CELLS: WORKING PRINCIPLE



The addition of **suitable plants** ensures that the microorganisms don't run out of nutrients.

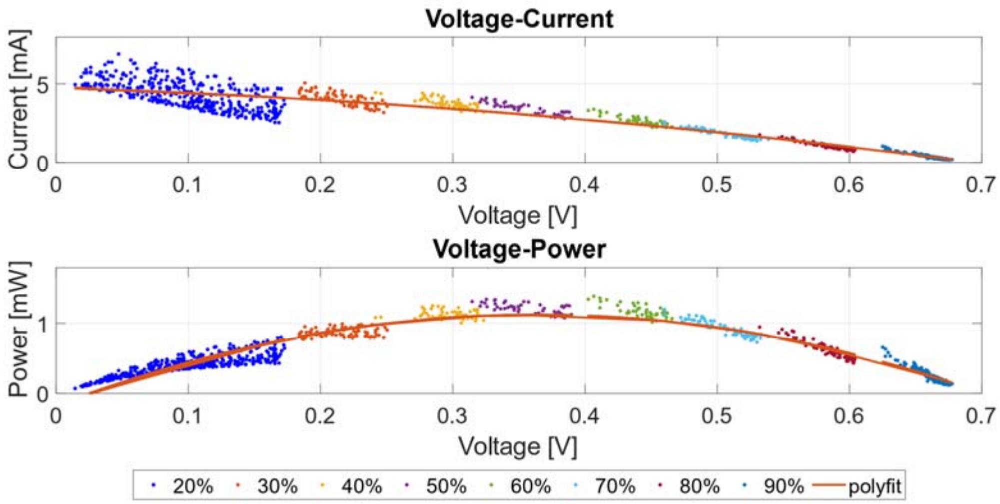
- The **symbiotic relationship** between **plant** and **micro-organism** is subject to research.

Further improvements to PMFC sustainability are possible!

- Biochar electrodes
- Biodegradable electronics

PMFC: ELECTRICAL CHARACTERISTICS

$1\ dm^3$
$PMFC\ reactor$

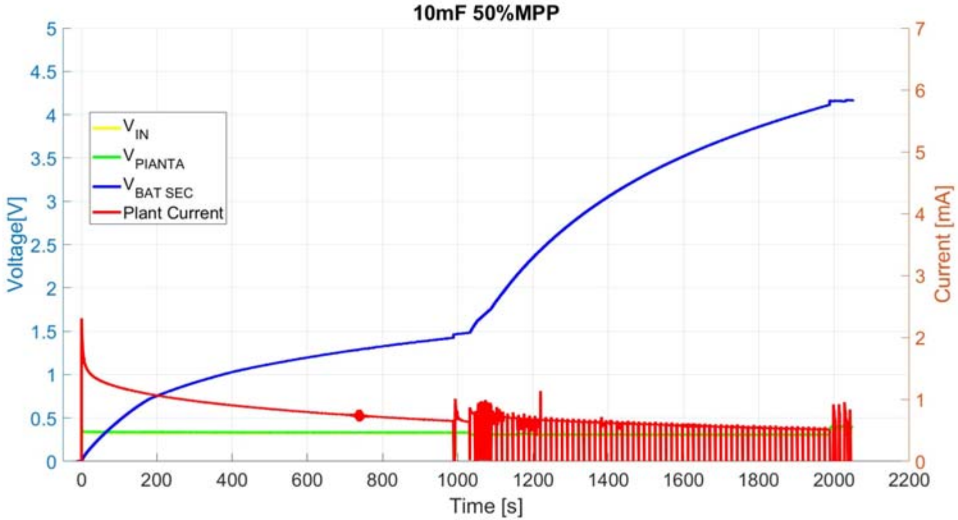


- **Typical power production density: ~ $1\frac{mW}{dm^3}$**
- **OCV reaches a maximum of 1 V.**
- **Maximum power point (MPP) at ~ 50% open circuit voltage (OCV)**
- **High source resistance: ~ 150 Ω**

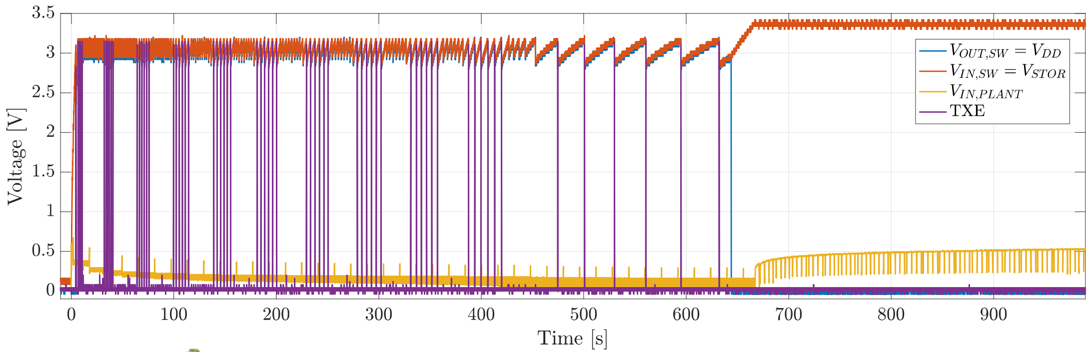
THE CHALLENGES OF HARNESSING BIOELECTRICITY

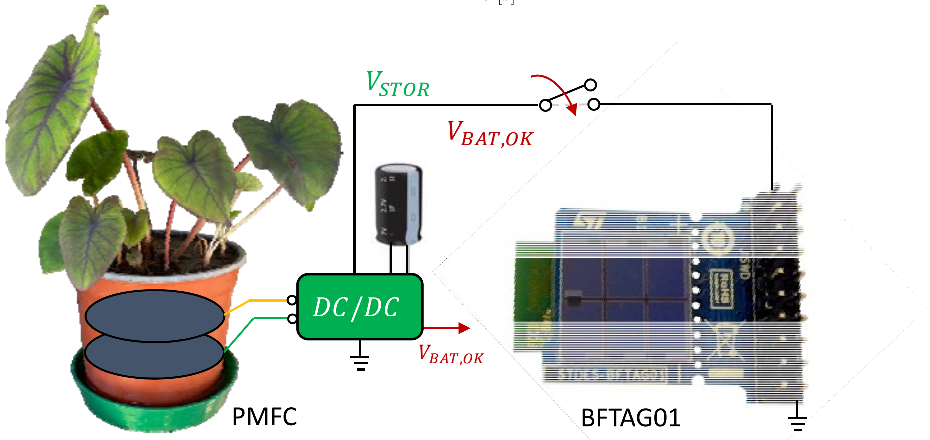
While incredibly promising, PMFCs face several **obstacles** towards **large-scale use**:

- **Low voltage, low current generation** means DC/DC boost is needed to power electronics
- **Slow dynamics** of a living-and-breathing, electrochemical system require MPPT adaptation, not featured in commercial DC/DC boosts.
- **Startup period** can be unpredictable.
- Power output decrease over time due to **biofouling/inactivation** of the electrodes.
- **Voltage reversal** phenomena can lead to non-recoverable inversion of the cell polarity.



THE CHALLENGES OF HARNESSING BIOELECTRICITY

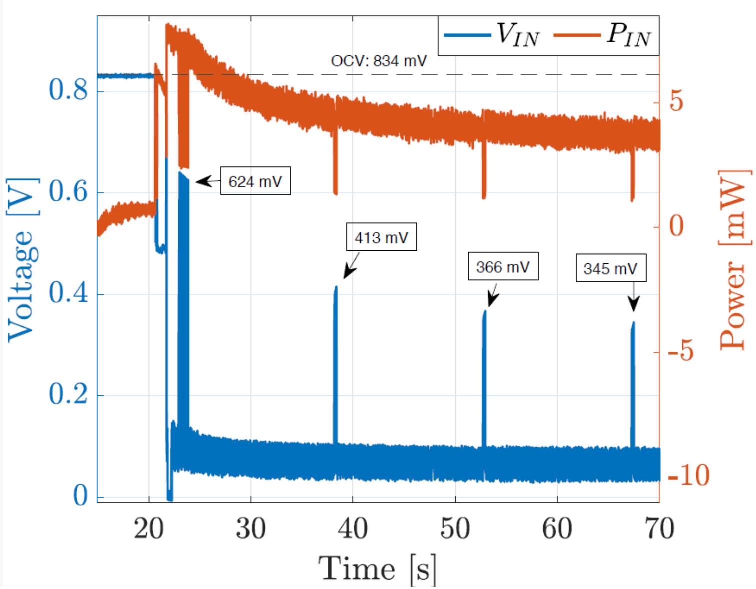


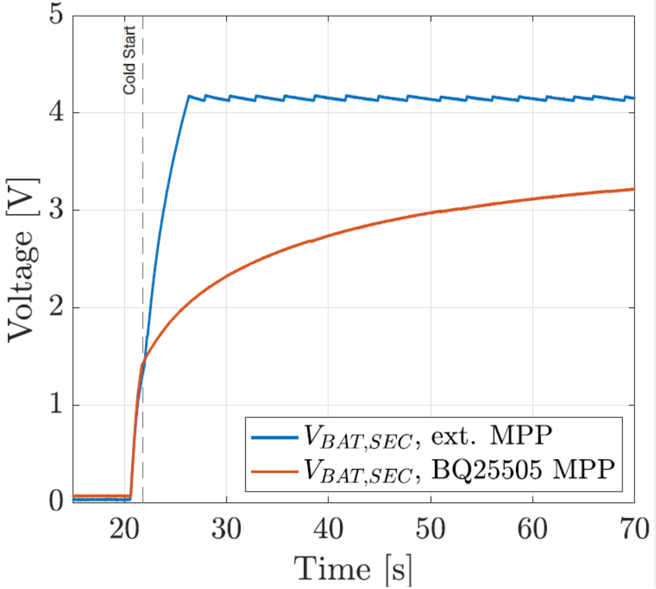


BLE tag (STM's BFTAG01) supplied by a PMFC.

- Classic FOCV applied by commercial DC/DC.
- Beacons space out due to sampled MPP != actual MPP.
- Continuous load could also «tire» PMFC.
- OCV recovers to initial value after around 10 mins.

PLANT MICROBIAL FUEL CELLS – AD HOC HARVESTING TECHNIQUE

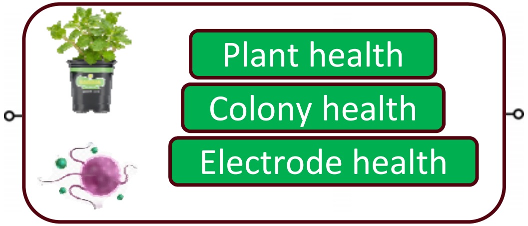




The harvesting **technique** needs to be **fit** to the energy harvesting **source**:

- **Slow dynamics** impose long settling times: this is important if we want to measure OCV correctly!
- The **cells require rest**: allow recovery of the bacteria colony inbetween harvesting cycles.
- Also: measure the cell's impedance to execute efficient MPPT.

PMFC ELECTROCHEMICAL STATE MEASUREMENT



How do we access this information?

Can we do it in a self-powered context?

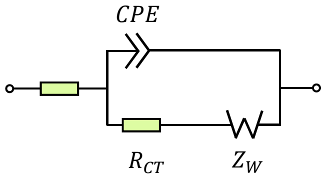
Need for **non-destructive measurement** to understand more about the **electrochemical state** of the PMFC:

- **OCV** and **power output** can be indirectly linked to plant health, but don’t provide much information as to «why».
- PMFC **impedance spectra** can be a key element in understanding underlying **electrobiochemical phenomena** within PMFCs.

ELECTROCHEMICAL IMPEDANCE SPECTROSCOPY ON PMFCS

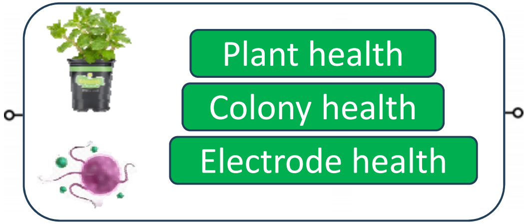
EIS: electrochemical impedance spectroscopy

- **Impedance** measurement at **varying frequencies**: $Z(\omega) = \frac{V(\omega)}{I(\omega)}$
- **Non-destructive, online** measurement.



Equivalent, physical based cell model

EIS data fitting

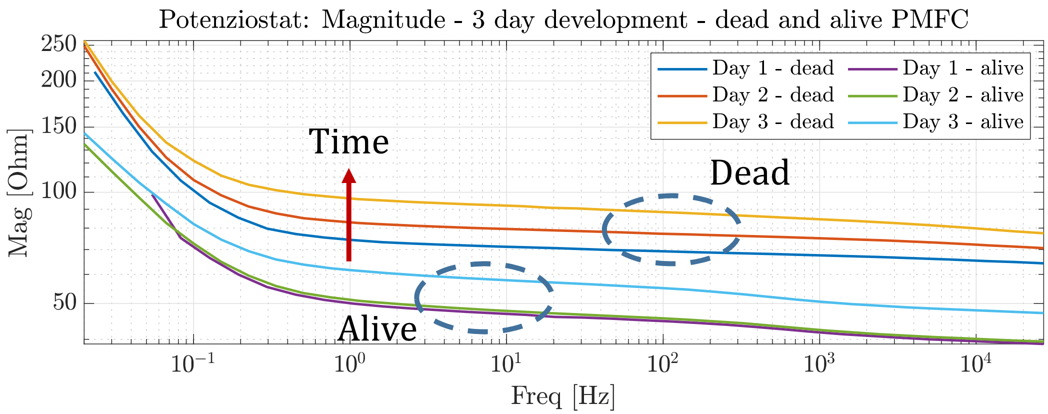


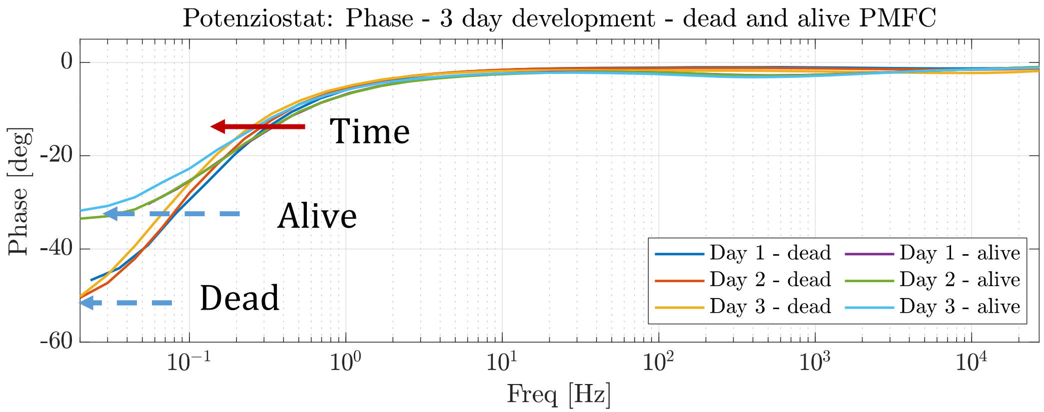
Through EIS, we believe it is possible to:

- Use the cell as a **plant health biosensor** by developing models which include both plant ad microbial contributions.
- **Execute MPPT** which also considers the cell's **biochemical dynamics**.

Ultimately, it could prove useful for timely detection and contrast of **aging** and **voltage reversal** phenomena, as well as aiding the improvement of **cell startup**.

PLANT MICROBIAL FUEL CELLS – EIS BIOSENSING



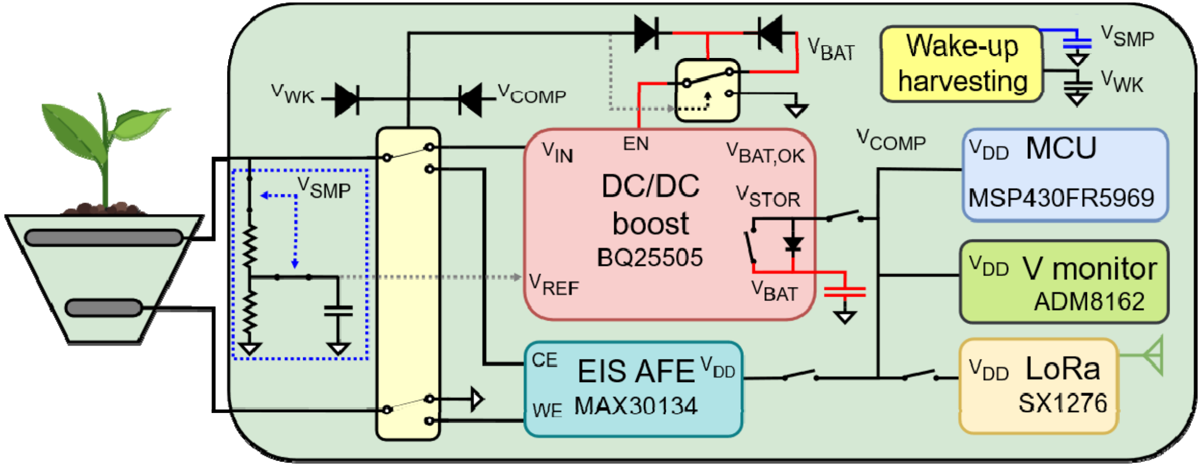


Comparison between **healthy** and **struggling** plant across three days:

- Impedance magnitude is always greater in struggling plant and increases over time
- Impedance phase is also different, with struggling plant having higher phase at lower frequencies.

Difference across plant health and time seems significant and promising - **worth exploring!**

ULTRA LOW POWER ARCHITECTURE FOR SELF-POWERED BIOSENSING

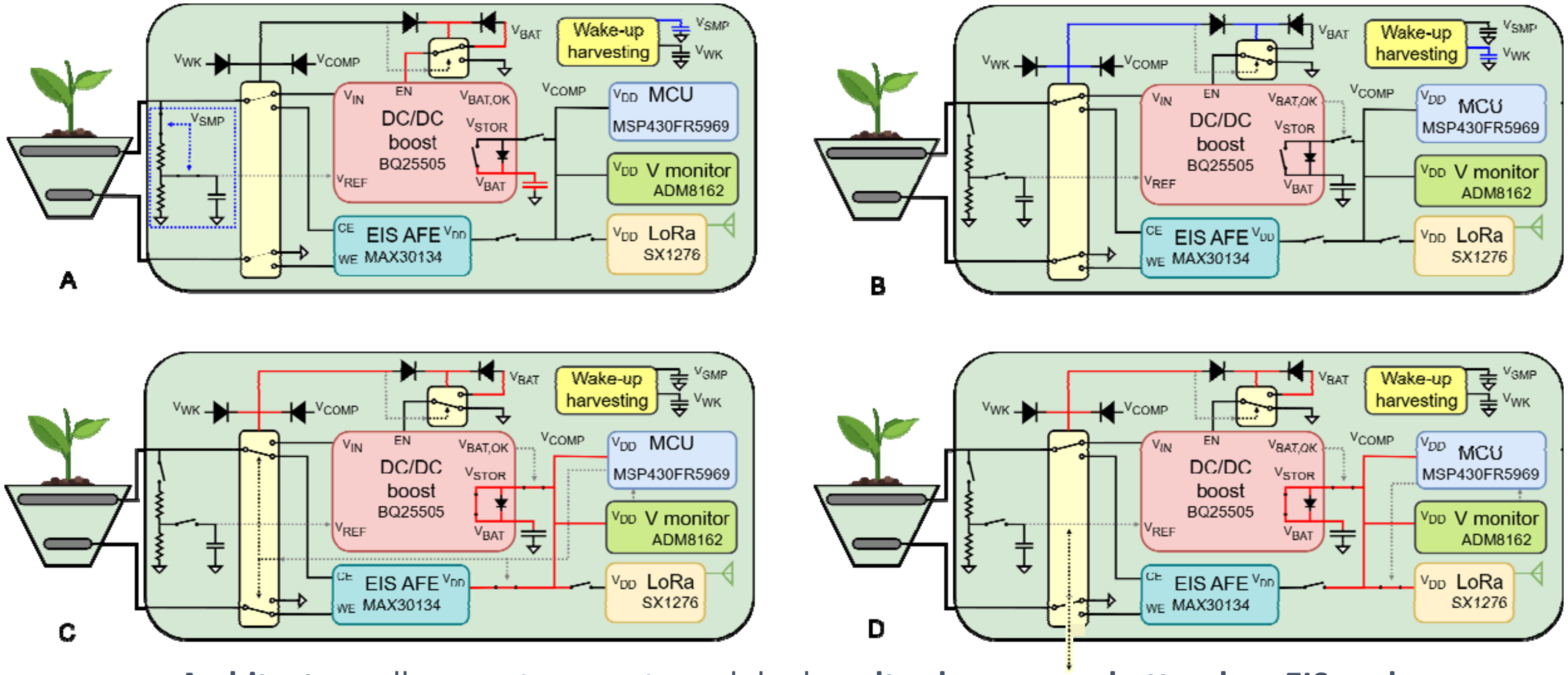


Self-measuring, self-powered plant microbial fuel cell system:

- Harvest energy from a PMFC
- Store it in a capacitor
- Execute an energy-intensive impedance spectroscopy (EIS) measurement on the PMFC.

- This measurement is interesting for PMFC monitoring within PMFC-powered WSNs as long as it can be **self-powered**.
- We designed an **ultra-low power EIS sensor node** to prove that it is possible to execute **EIS on a very tight budget**.
- This architecture features EIS and harvesting on the **same electrodes**.

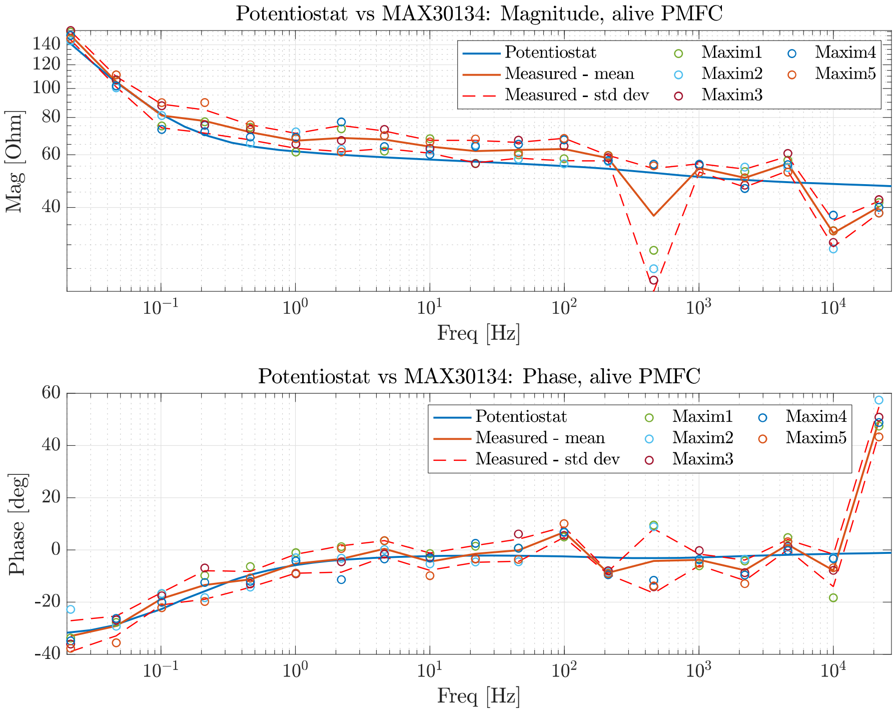
ULTRA LOW POWER ARCHITECTURE FOR SELF-POWERED BIOSENSING

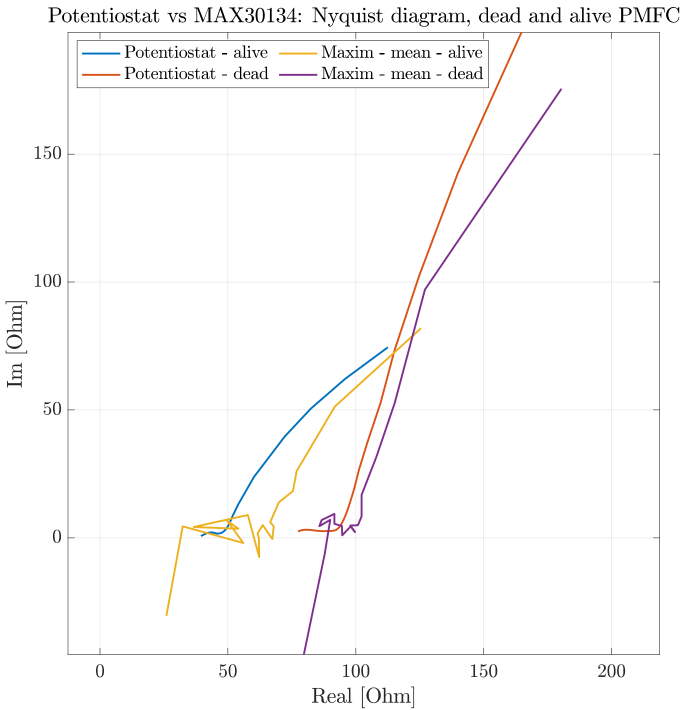


Architecture allows us to execute and deploy **ultra-low power batteryless EIS nodes**

- ✓ EIS sweep with **proposed architecture** only requires **3.64 J** of energy.
- This can be sourced by a 1 F capacitor in the [1.8 3.6] V range.

MAX30134 EIS CHIP – preliminary results





Max30134 ultra low power EIS chip vs PGSTAT302N, reference EIS workstation

- Measurement results follow reference instrument well, except at higher frequencies.

EnerHarv 2024 PSMA

UNIVERSITÀ DI TRENTO

PMFC-POWERED SENSOR NODES

The commercial use of PMFCs is currently being researched.

- **Plant-e: PMFC research since 2009**
  - Innovative architecture for easy deployment & cathode insufflation: the PowerStick.
  - Difficulty of soil deployment led Plant-e to develop solutions for fully waterlogged environments (fluvial/marshgrass/hydroponics)
- **Jen and Yaliff [5] developed a practical guide for MFC design testing in less water-dense environments.**
  - Throughout multiple design iterations, they compiled a list of do’s and don’ts when it comes to building and deploying PMFCs

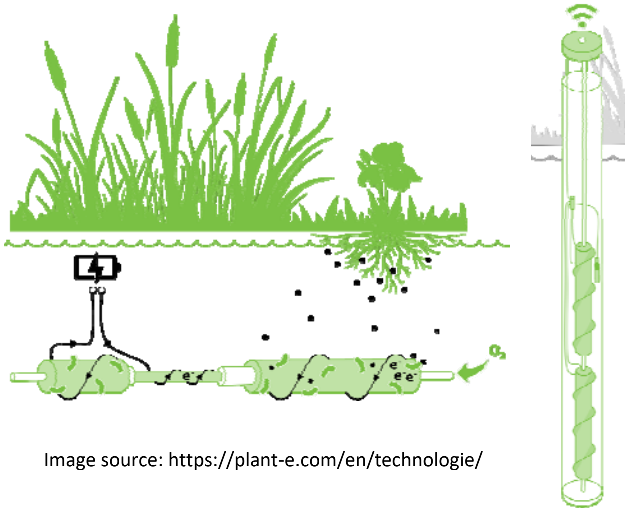


Image source: https://plant-e.com/en/technologie/

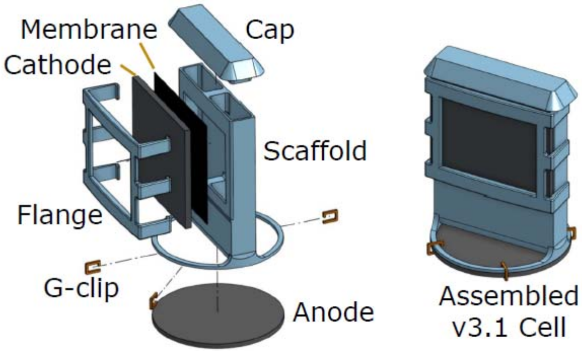
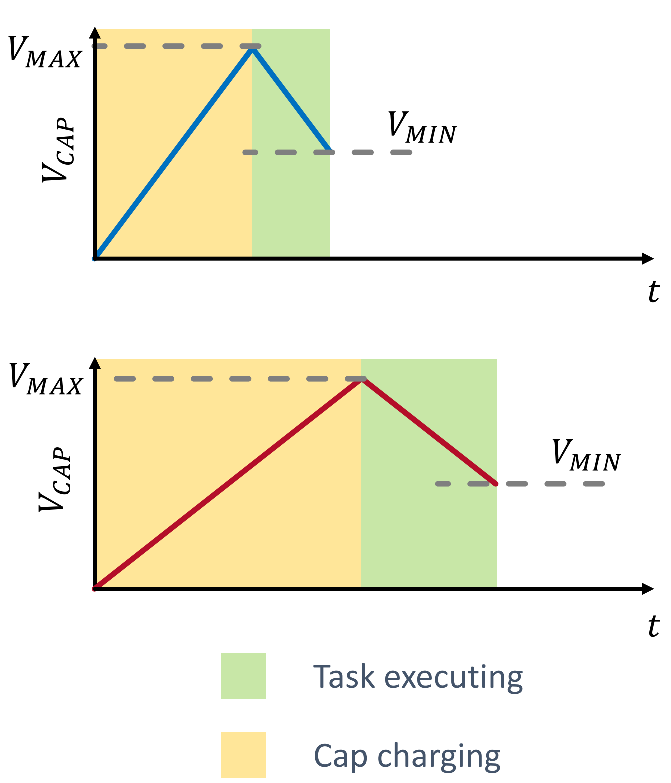
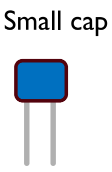


Image source: [5]

THE NEED FOR DYNAMIC CAPACITANCE





Small storage cap:

- Charges fast → fast startup
- Drains fast
- Little leftover energy

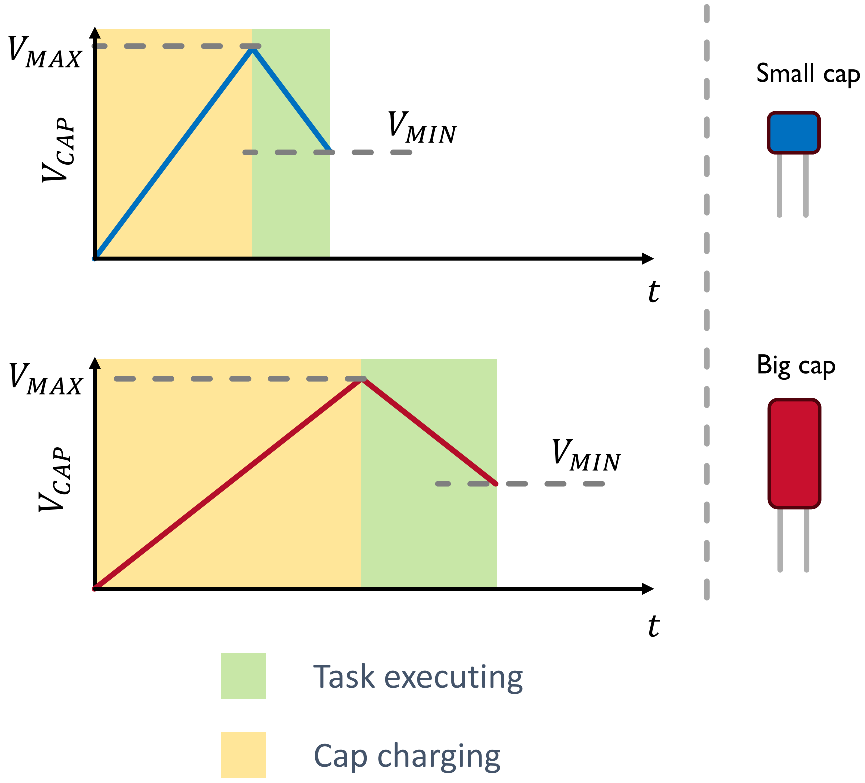
What if we adapted the capacitor size to the task we want to execute?

What if we could minimize leftover energy?

Large storage cap:

- Charges slow
- Drains slow → extended operation
- Large leftover energy

THE NEED FOR DYNAMIC CAPACITANCE



Usually: **fixed buffer**

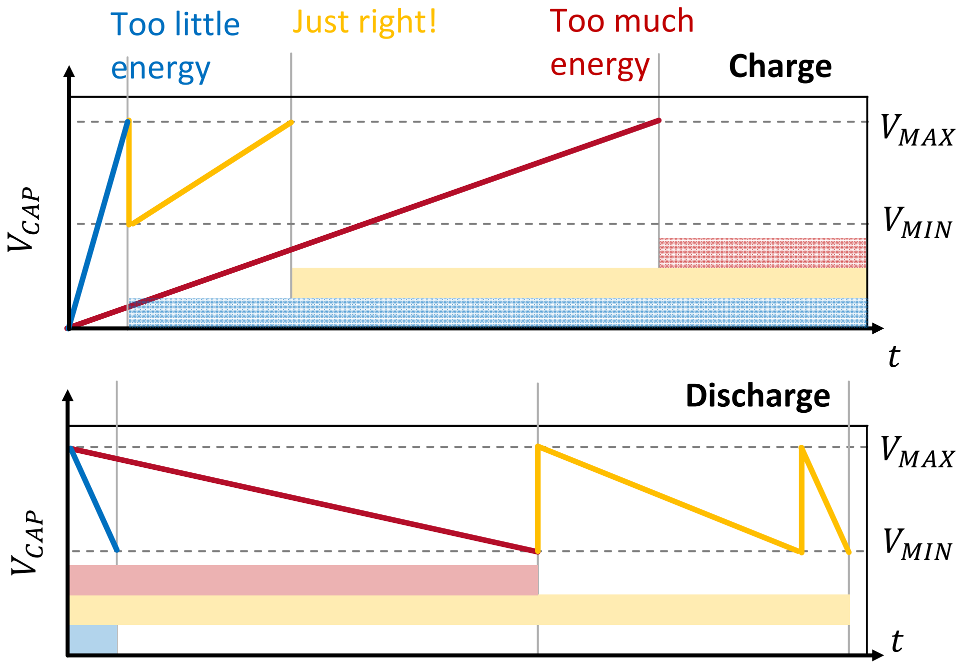
- Largest task in application sets cap size.
- A voltage monitor trimmed to a certain voltage notifies when cap is sufficiently charged for a given task.

Change of paradigm: **dynamic buffer**

- Fit capacitor size to **next task**, to minimize charging times but also bring task to completion.
- As task executes, revert back to small cap to "squeeze out" all the stored energy.
- Trigger task at V_{MAX}:

  no need for a per-task voltage monitor!

THE NEED FOR DYNAMIC CAPACITANCE



Fixed, small capacitor - active

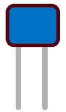
Fixed, large capacitor - active

Variable capacitor - active

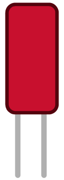
- Improve **reactivity/charge time** for "smaller" tasks by setting backup size to match exactly desired task.

- Improve **end-to-end efficiency** by limiting leftover charge.

Small cap



Big cap

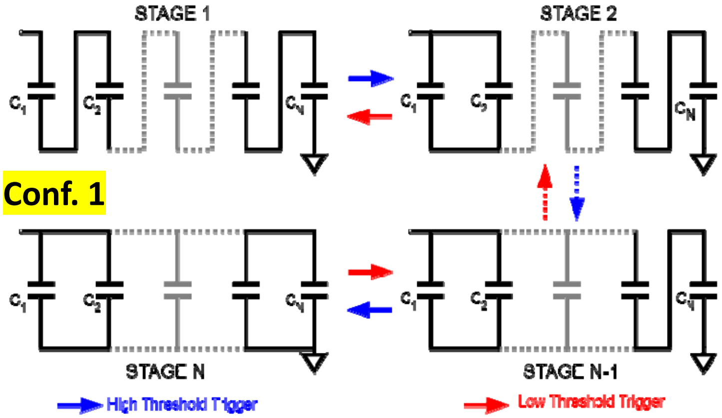


DYNAMIC CAPACITOR BANKS

- **How can we achieve dynamic capacitance?**

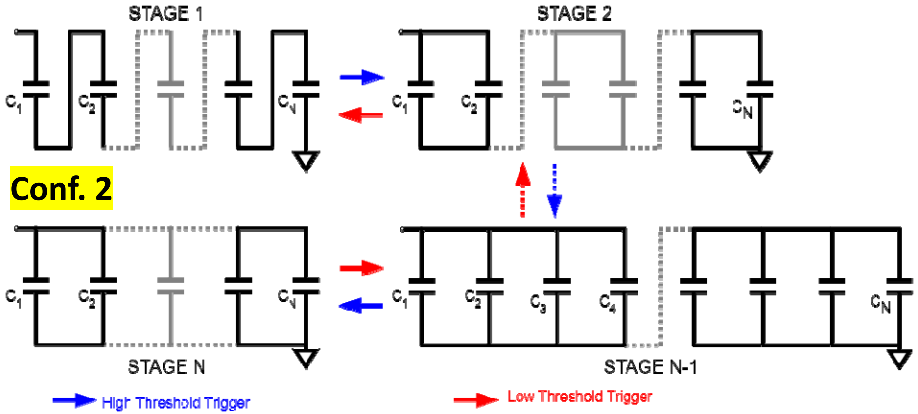
Multiple solutions exist, each optimizing different aspects of the capacitor bank:

Conf. 1



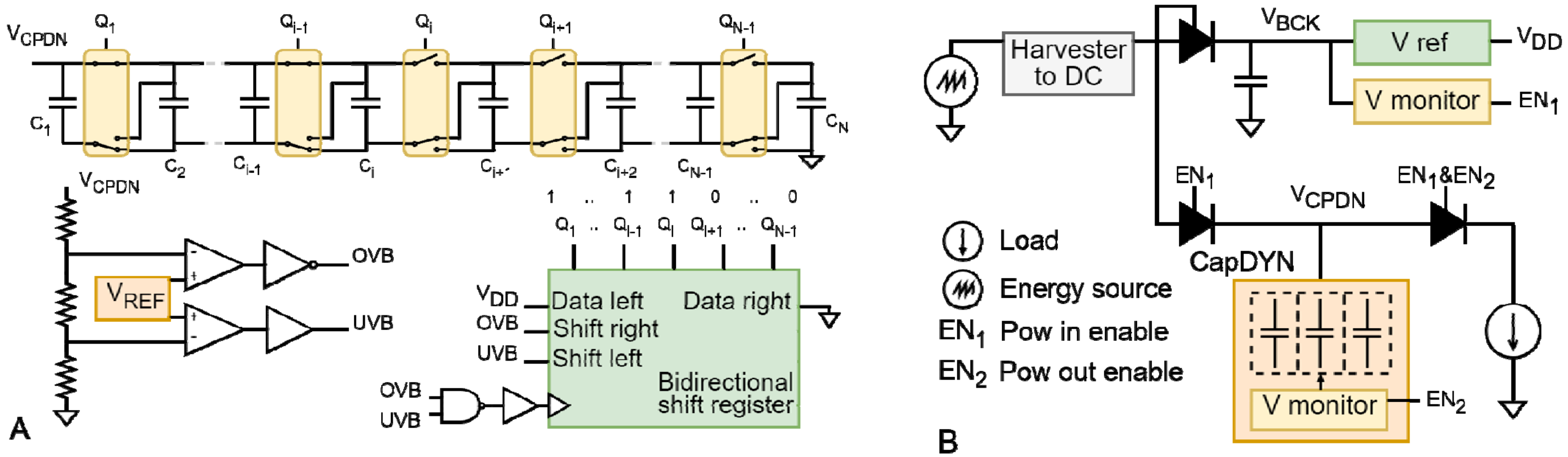
- Good capacitance ratio vs component n°.
- Linear increase of components with +1 stage.
- Slightly reduced efficiency due to some sub-ideal switching effects.

Conf. 2



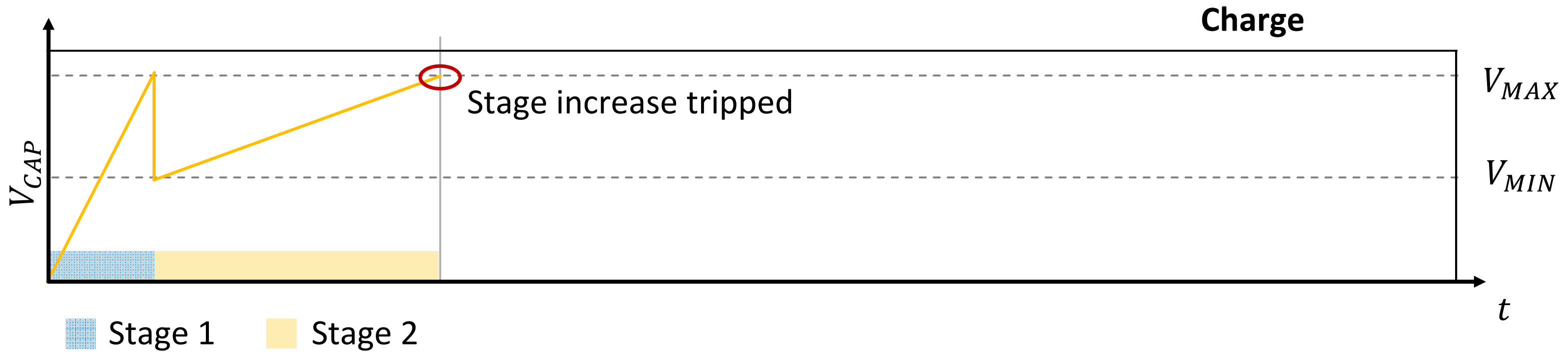
- Efficient switching strategy.
- Quadratic increase in components for each additional stage.

CAPDYN – FULLY AUTONOMOUS DYNAMIC CAPACITOR



- Capacitor bank control: fully **autonomous**!
- Can be used with different capacitor bank designs.
- Input/output control of both capacitor bank and backup capacitor.

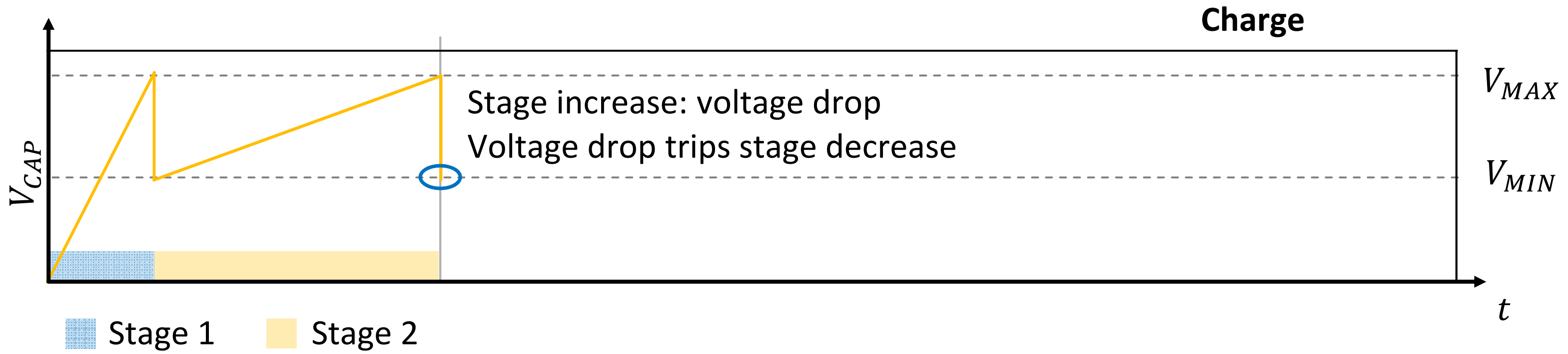
CAPACITOR BANK DIMENSIONING – config 1



The **“loop” problem**:

- Bank **switching** gives way to **voltage spikes/drops**.
- These changes must not activate “**stage reversion**” with the selected voltage thresholds.

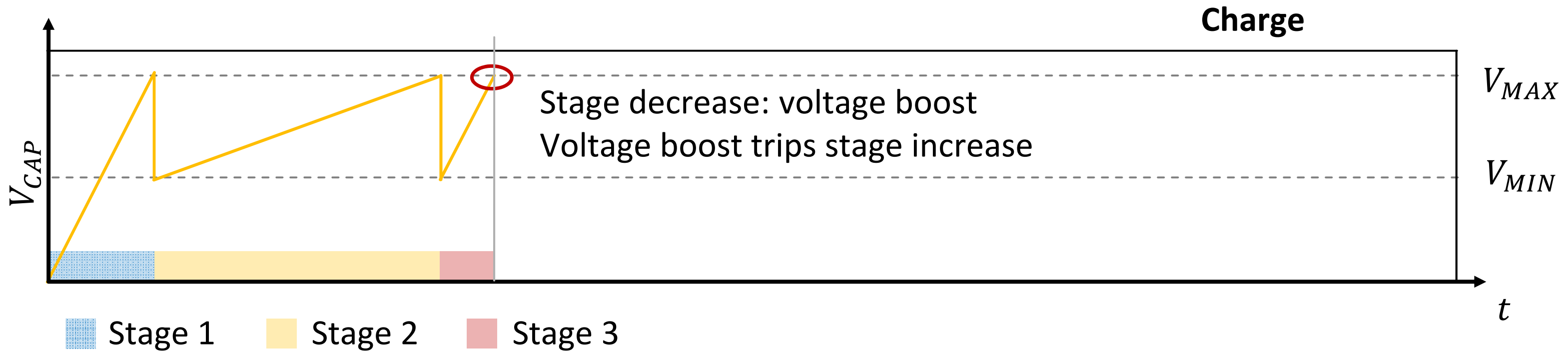
CAPACITOR BANK DIMENSIONING – config 1



The **“loop” problem**:

- Bank **switching** gives way to **voltage spikes/drops**.
- These changes must not activate “**stage reversion**” with the selected voltage thresholds.

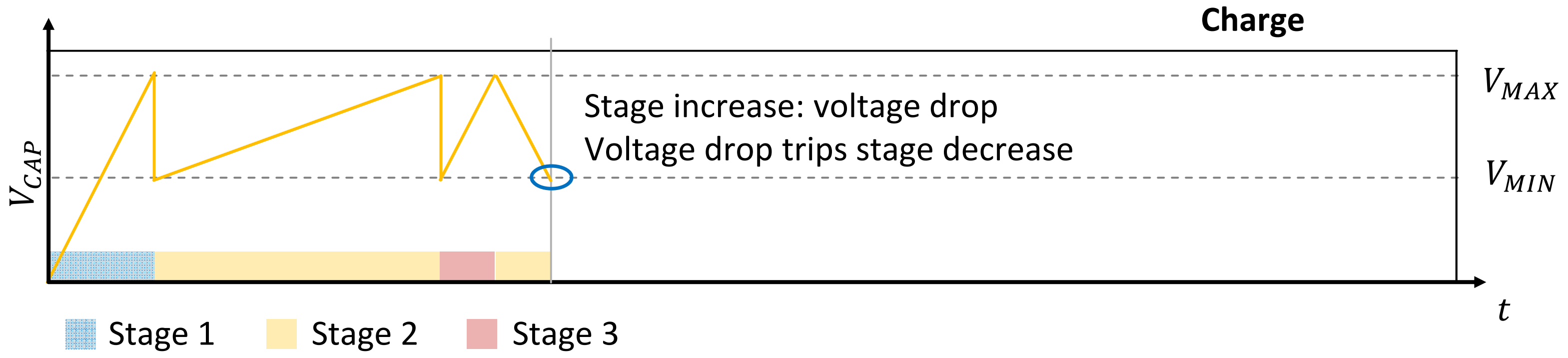
CAPACITOR BANK DIMENSIONING – config 1



The **"loop" problem**:

- Bank **switching** gives way to **voltage spikes/drops**.
- These changes must not activate "**stage reversion**" with the selected voltage thresholds.

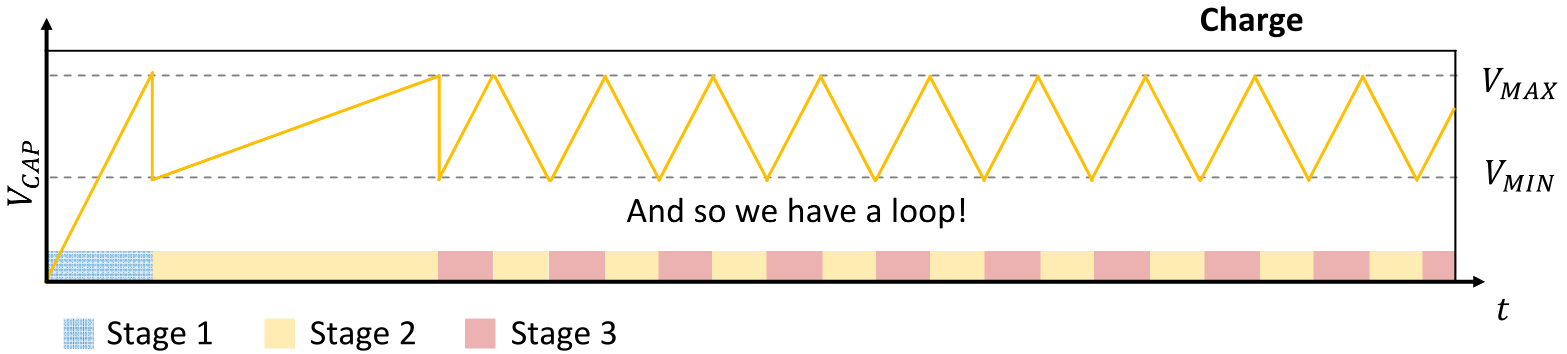
CAPACITOR BANK DIMENSIONING – config 1



The **“loop” problem**:

- Bank **switching** gives way to **voltage spikes/drops**.
- These changes must not activate “**stage reversion**” with the selected voltage thresholds.

CAPACITOR BANK DIMENSIONING – config 1

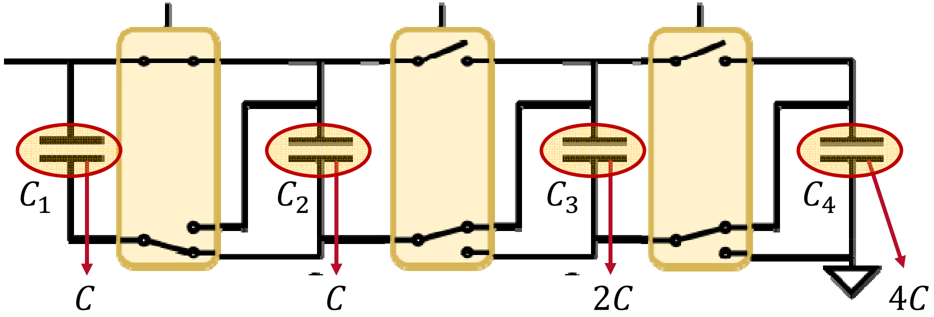


The **“loop” problem**:

- Bank **switching** gives way to **voltage spikes/drops**.
- These changes must not activate “**stage reversion**” with the selected voltage thresholds.

CAPDYN – FULLY AUTONOMOUS DYNAMIC CAPACITOR

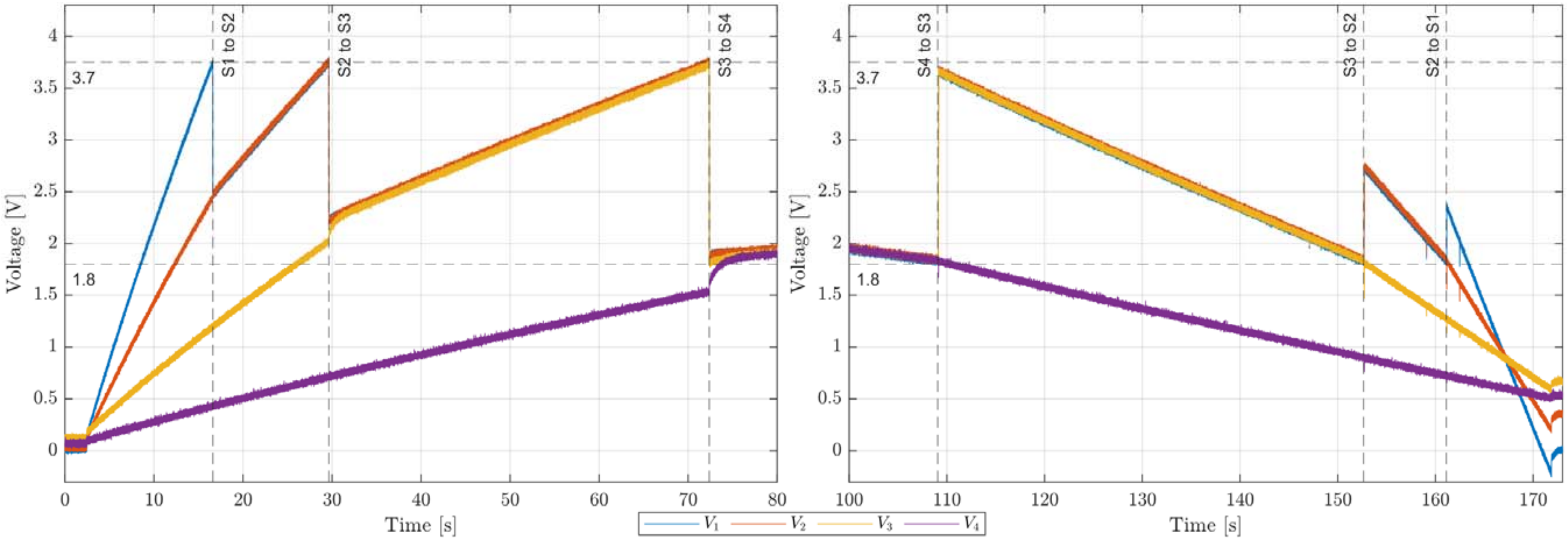
- Capacitor dimensioning solution: config 1, ***«power of two»***



Single capacitor sizing	Bank equivalent capacitance
$C_2 = C_1 = C$	$C_{MIN} = \frac{2^N}{3 \cdot 2^N - 2^2} C$
$C_i = 2^{i-2} C \quad i = [3, N]$	$C_{MAX} = 2^{N-1} C$

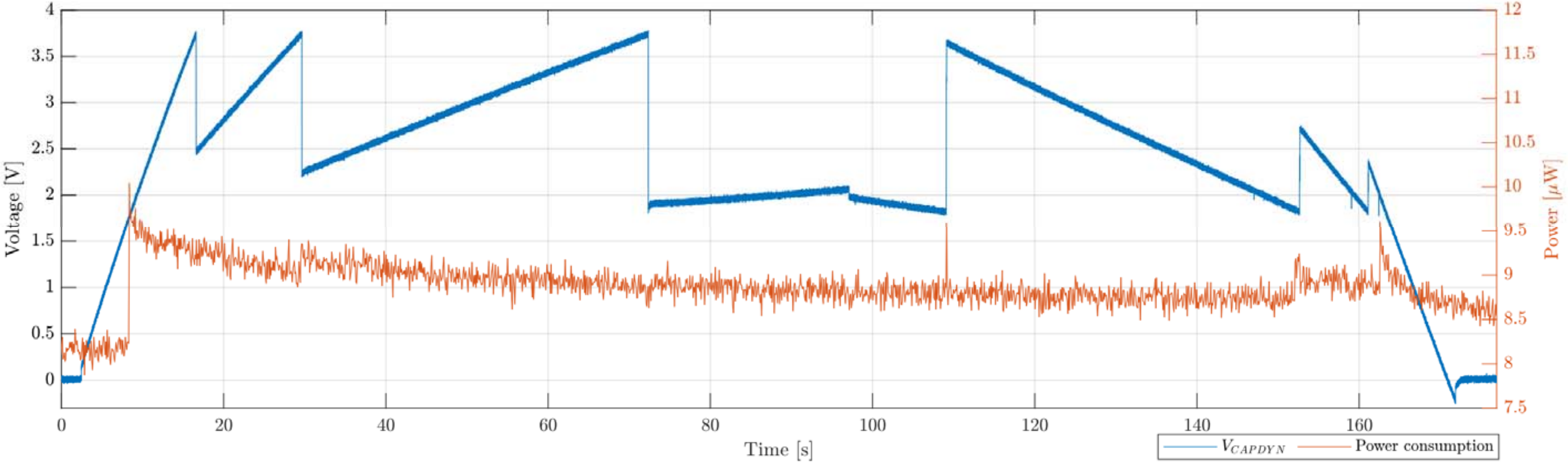
- Bank control can be used with **different capacitor bank designs.**
  - With config – 1: we developed a capacitor dimensioning solution to **avoid the loop problem**, under the $V_{\mathrm{MAX}} = 2V_{MIN}$ assumption.

CAPDYN – PROTOTYPE RESULTS – CAPACITANCE SWITCHING



- First prototype: 4-stage capacitor bank, 1-config.
- Simulation results are confirmed!

CAPDYN – FULLY AUTONOMOUS DYNAMIC CAPACITOR



- Constant power consumption throughout switching.
- **Ultra low power** at just 9 μW.

CAPDYN AND THE EIS NODE: A PERFECT MATCH

EIS sensor node: characteristics

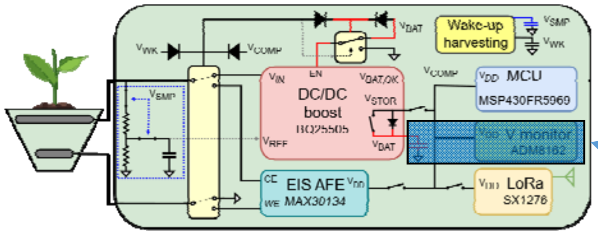
- PMFC power input: **low input power.**
- DC/DC boost harvests more efficiently (from 5% to 90%) with storage above 1.5 V: **overcome cold start.**

- Task set with **varied energy requirements**:
  1. Execute an energy-intensive impedance spectroscopy (EIS) measurement on the PMFC: **large task.**
  2. Transmit results back for analysis: **medium task.**
  3. Monitor other environmental parameters: **small task.**

CapDYN can help!

- Initial storage capacitance is small, to **improve reactivity** and to **overcome cold start** even with **low input power**.

- By adapting storage size to each task, we **minimize charge time** and **the leftover charge** through CapDYN's autonomous reconfiguration.



CapDYN's dynamic storage can optimize:

1. **Reactivity**
2. **End-to-end efficiency**

Of the EIS sensor node.

EnerHarv 2024 PSMA

UNIVERSITÀ DI TRENTO

Conclusions

- PMFCs are a hopeful **renewable & sustainable** energy source, producing 1 mW/dm^3 24h/7.
- To address the **commercialization challenges** (startup time, durability, MPPT ad hoc), EIS can **assist** in understanding underlying **electrobiochemical processes** which rule PMFC state.
- EIS can also be leveraged to develop **self-powered biosensing**: we are investigating the use of EIS as **plant health monitor**.
- We designed a **batteryless EIS node** to validate this biosensing principle and to prove that EIS can be executed with PMFC power input levels.
- **Batteryless** nodes' activity is determined by their capacitor **buffer size**: CapDYN provides **autonomous dynamic capacitance**, with the goal of **improving reactivity** and **end-to-end efficiency** of batteryless nodes.

Q & A

EnerHarv 2024

PSMA International Workshop | 26-28 June, 2024 | Perugia, Italy

Thanks very much for your time and attention!

Questions/comments???

TECHNICAL SPONSORS

ORGANIZER

HOST

COMMERCIAL SPONSORS

MEDIA SPONSORS

UNIVERSITÀ DI TRENTO

References

- [1] Sharma, Iti & Ghangrekar, Makarand. (2017). Evaluating suitability of tungsten, titanium and stainless steel wires as current collector in microbial fuel cell. Water Science and Technology. 77. 10.2166/wst.2017.621.
- [2] Zhao, Pingping & Song, Y. & Dong, Kaihui & Shan, Dayong & Han, En-Hou. (2019). Effect of passive film on the galvanic corrosion of titanium alloy Ti60 coupled to copper alloy H62. Materials and Corrosion. 70. 10.1002/maco.201910937.
- [3] Rusyn, Iryna (2021). Role of microbial community and plant species in performance of plant microbial fuel cells. Renewable and Sustainable Energy Reviews, Volume 152. 10.1016/j.rser.2021.111697.
- [4] Ueoka, Nagayoshi & Sese, Naoko & Sue, Mayu & Kouzuma, Atsushi & Watanabe, Kazuya. (2016). Sizes of Anode and Cathode Affect Electricity Generation in Rice Paddy-Field Microbial Fuel Cells. Journal of Sustainable Bioenergy Systems. 06. 10-15. 10.4236/jsbs.2016.61002.
- [5] Bill Yen, Laura Jaliff, Louis Gutierrez, Philothei Sahinidis, Sadie Bernstein, John Madden, Stephen Taylor, Colleen Josephson, Pat Pannuto, Weitao Shuai, George Wells, Nivedita Arora, and Josiah Hester. 2024. Soil-Powered Computing: The Engineer's Guide to Practical Soil Microbial Fuel Cell Design. Proc. ACM Interact. Mob. Wearable Ubiquitous Technol. 7, 4, Article 196 (December 2023), 40 pages. https://doi.org/10.1145/3631410