Gardening the Cybernetic Meadow

Fostering ecosophic care using microbial fuel cells as a temporal aesthetic medium

Student Name: Matthew Halpenny

Student #: 20203022

Supervisor: Thierry Bardini

Co-Supervisor: François-Joseph Lapointe

M.Sc. Individualized Studies

Université de Montréal

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ABSTRACT

Gardening the Cybernetic Meadow is a research-creation project that engages with the fields of interdisciplinary art, ecology, and sustainable energy technologies drawing energy from bio-matter (soil microbes). Microbial fuel cells (hereby MFCs) are a type of bio-based fuel cell, or more broadly a soil-based generator and battery. MFCs are a regenerative energy technology that use soil as medium and uptake energy through collecting by-products of microbial metabolism. The outcomes of *Gardening the Cybernetic Meadow*'s research-creation are disseminated through multiple modes of knowledge sharing, shifting away from a primary reliance on the traditional written thesis. Inspired by research-creation frameworks of scholars such as Natalie Loveless (2019), it distributes the thesis' research results through three methods. 1) an interdisciplinary, participatory art installation (sharing the title of this thesis); 2) an open-source microbial fuel cell fabrication guide generated through the documentation of the research-creation process; 3) this component, the written thesis. Guided by theoretical frameworks encompassing critical making, relational aesthetics, and temporal aesthetics, the project not only challenges traditional modes of research dissemination but also offers a tangible platform for engaging diverse audiences across artistic and scientific domains. *Gardening the Cybernetic Meadow* aspires to reshape future inquiries by propelling investigations into sustainable energy, ecological interdependence, and experiential learning. This undertaking exemplifies the fusion of creativity and technology while nurturing a dynamic ecosystem of collaboration, contemplation, and transformative thought.

Keywords: Research-Creation, Interdisciplinary Art, Ecosophy, Microbial Fuel Cells, Temporal Aesthetics, Ecologies of Care, Relational Aesthetics, Experiential Learning, Open Knowledge, Ecology.

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"I like to think (and
the sooner the better!)
of a cybernetic meadow
where mammals and computers
live together in mutually
programming harmony
like pure water
touching clear sky."

- Richard Brautigan

All Watched Over by Machines of Loving Grace,
1967.

1. INTRODUCTION

Gardening the Cybernetic Meadow is a research-creation project that engages with the fields of interdisciplinary art, ecology, and sustainable energy technologies drawing energy from bio-matter (soil microbes). Its subtitle, *Fostering ecosophic care using microbial fuel cells as a temporal aesthetic medium*, communicates several core philosophies that inform the work, while outlining how the technical research on microbial fuel cells is situated inside the art-creation of the project. The outcomes of *Gardening the Cybernetic Meadow*'s research-creation are disseminated through multiple modes of knowledge sharing, shifting away from a primary reliance on the traditional written thesis. Inspired by research-creation frameworks of scholars such as Natalie Loveless (2019), it distributes the thesis project's research results through three methods. 1) an interdisciplinary, participatory art installation (sharing the title of this thesis); 2) an open-source microbial fuel cell fabrication guide generated through the documentation of the research-creation process; 3) this component, the written thesis.

Having alternative modes of knowledge dissemination is critical to the interdisciplinary nature of the project. The thesis combines theories, methodologies, and critique from artistic disciplines with scientific disciplines through an inclusion of scientific research, bioengineering, and a collection of writing on varied ecological fields. Its intended audience exists between the multitude of artistic and scientific disciplines that inform *Gardening the Cybernetic Meadow*'s research. Just as interdisciplinary collaborations between artists and scientists were inspirations for this thesis, the outputs of this thesis aim to fill in the identified gaps of dissemination diversity between disciplines working with sustainable technologies (i.e., microbial fuel cells) and artistic modes of experiential knowledge sharing; Hopefully this may further inspire other interdisciplinary researchers to explore the varied methodologies used in this work to address that dissemination diversity. First, I must introduce the primary technology and artistic medium utilized within *Gardening the Cybernetic Meadow*, microbial fuel cells.

Microbial fuel cells (hereby MFCs) are a type of bio-based fuel cell, or more broadly a soil-based generator and battery. MFCs are a regenerative energy technology that use soil as medium and uptake energy through collecting by-products of microbial metabolism. The microbes present vary depending on the type of soil used and the ecosystem they are naturally situated in. This variation determines which type of MFC is best formatted for hosting them and how the MFC collects their metabolic by-products. Each type of MFC uses a varied arrangement of electrodes – an anode and cathode - to capture these by-products, often positioned above and below the soil medium. One electrode is always exposed to oxygen, which fuels the energetic reactions captured. The form of the MFC relies on how the medium can be arranged to expose this electrode to oxygen and where the MFC researchers are using the cells. For example, MFCs placed in natural ecosystems for powering digital monitoring systems will sometimes be partially submerged in soil or water to be in contact with other other-than-human organisms (Schievano, et al., 2017). A presentation of MFC form and variation appears in Section 3 (MFCs: Technical Outline) alongside technical explanations of MFC function, microbial energy harvesting, power circuit design and the research-creation methods that made their development possible.

MFCs were selected as the primary artistic medium within this thesis due to their potential to act as a temporal aesthetic medium. I will expand on the notion of a temporal aesthetic medium and how MFCs reflect the theoretical basis of this thesis throughout the following section, Theoretical Framework & Methodology. This section, Section 2, is divided into six subsections outlining the fundamental theories and methodologies that inform the project and shape the physical forms of its outputs. Each of the subsections overlap and interconnect in a manner that need not be strictly linear, but for ease of mapping how they flow between one another, they are ordered in the follow way: Critical Making; Research-Creation; Complex Systems, Ecologies, & Ecosophy; Relational Aesthetics; Temporal Aesthetics; and Gardening: Care and Maintenance. These topics will be touched upon again and defined throughout the introduction. It is necessary to first ask why the theories and methodologies of these subsections were selected for this research. This can be answered by exploring the research problems they address and how these problems demand novel research frameworks that function outside of traditional disciplinary boundaries.

The majority of global power systems rely on extractive energy sources such as hydrocarbons (e.g., coal and oil) (Parikka, 2015; Daggett, 2019). Hydrocarbons generate an abundance of energy, but at the emissive cost of releasing millions of years of geologically compressed carbons (Ibid, 2015). While MFCs currently operate on a much smaller scale than extractive sources, they have the potential to act as a localized counter to the current dominant modes of extractive energy production through their slow, regenerative production of metabolic microbial energy. The ionic energy harvested from the MFCs can only exist within communal microbial metabolic processes (Yang, 2012; Bombelli et al., 2016). Alongside their practical applications of harvesting energy, MFCs encapsulate an ideology of a more slow, caring, and symbiotic cultural relation to energy technologies. Unlike most energy technologies where humans, their technologies, and natural ecosystems largely remain separate, MFCs require each of them to be within an intentional, persisting, and symbiotic unison. MFCs house an ecological mesocosm, an environment that becomes akin to a garden that requires ongoing symbiotic exchanges between humans and other-than-humans. The other-than-human exchange in this relationship provides the MFCs with microbial energy, and the mesocosm with water, sunlight, and human care. In contrast to extractive energy, microbial energy is innately communal and cannot be extracted from the ecosystem it occurs in (Ibid, 2016). This means MFCs cannot utilize more ions than these communal processes are generating, hence we must be patient with our energy, abiding by a "slower" temporality in relation to the geological deep time of extractive energy sources it (Nixon, 2013; Ibid, 2016).

The socio-economic forces behind the extractive energy paradigm are driven by temporalities rooted in immediacy and capital gains (Foster, 1999; Taffel, 2021). John Bellamy Foster coined the term "metabolic rift", an extension of Karl Marx's concept of metabolic crises that "describes a rift in the flow of materials and energy, the form of which is shaped by social relations" (Ng, 2019). The social relations driving this flow can be seen within the environmental impact of digital technologies – all of which are designed, manufactured, and disposed by social ecologies. Digital technologies are intricately bound within the extractive energy paradigm through their materiality – the geopolitics of their material origins – and the embodied energy of their manufacturing process (Bhowmik, 2019). Even within the creation of sustainable energy technologies like solar panels, the energy required to manufacture them, to transform them from extracted material into a marketable product, can release emissions outweighing the emissive energy saved in the solar panel's lifetime (De Decker, at al., 2020). This is the result of hidden layers in their industrial pipeline, each requiring energetic input that is largely fuelled by extractive, deep time energy sources (Taffel, 2012). "Indeed, the digital technologies used to understand the effects of climate change and to study the ecological effects of mining rare earth minerals are somewhat ironically built using these very same minerals and are powered by the fossil fuels that are driving climate change" (Turnbull, et al., 2023).

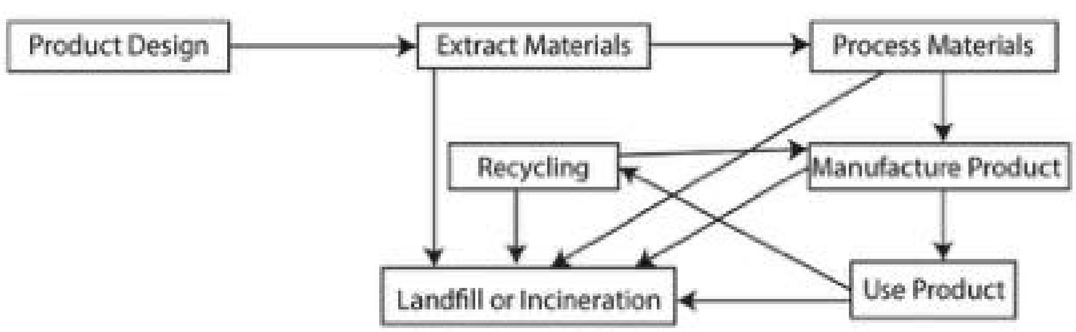

Figure 1: Industrial Production Model (Taffel, 2019, p. 183)

These entangled relations are addressed in Section 2.3 (Complex Systems, Ecologies, & Ecosophy), which expands on the properties of complex systems and how social ecologies cannot be separated from environmental ecologies. The impact our digital technologies have on the environment cannot be separated from the sphere of human influence, humans cannot be separated from nature, and through this, humans cannot be separated from that which is *other-than-human* (i.e., other-than-human organisms, non-living matter, climate systems, etc.). This idea is more eloquently unpacked through Félix Guattari's philosophy of Ecosophy which addresses the dualistic human / nature divide he witnessed in many ecological frameworks and seeks to define them as monadic (Guattari, 2014). This philosophy requires more background than I can provide within the Introduction but after Section 2.3 the role of ecosophy within the theoretical framework and outcomes will become a recurrent threading.

Considering the entangled layers between the social, the technological, and the environmental, the research problem begins to take shape as a need to form new research frameworks for examining the complex relational nature of climate change (Taffel, 2019; Giraud, 2019). This thesis specifically examines how interdisciplinary practice and experiential artistic interventions can address complex problems and build novel research frameworks. This call has been addressed by others through a range of scholastic interventions such as Isabelle Stengers' "ecologies of practice" (2005). Through this framework she highlights the importance "that no practice would be defined as like any other" (Ibid., p. 183). A practice must be felt at its borders, used as a tool for "thinking what is happening" (Ibid., p.184). It does not rely on preconstructed frameworks but examines the "happening" as an examination of present circumstance free of the projection of any given discipline. Speaking on "terms of transition", Lauren Berlant suggests an examination of the present, or in her words, "a glitch of the present" (Berlant, 2016, p. 394), which requires a collective examination of the commons that links economic crises to ongoing emergencies. "To attend to the terms of transition is to forge an imaginary for managing the meanwhile within damaged life's perdurance" (Ibid.). In the face of complexity and eco-anxiety, how do researchers create these links and how is that research disseminated in a way that is socially mobilized, one that exists for and within the commons?

Gardening the Cybernetic Meadow uses the practical and theoretical potential of MFCs to discuss the role of interdisciplinary practice and experiential artistic interventions as a means to address complex problems such as climate change and the role extractive energy, digital technologies, and social ecologies play within this problem. The research is socially mobilized through the Open-Source MFC Creation

Guide, prioritizing its existence within the commons as open access. Accessibility is a core axiology of the project, as will be demonstrated in later sections such as those on Critical Making and Open-Source Projects. In relation to alternative modes of dissemination, having varied modes of presenting the research such as immersive experiences, visual art, and storytelling, amongst other art forms, allow the research to reach a wider audience. Through socially mobilizing the research towards audiences that may not read scientific research or technical papers, it creates an inviting space for engaging in the research across disciplines (Escobar, 2017; Irwin, 2019). This process is by no means exclusionary, the hybridized dissemination provides several methods of understanding the research and is presented in an accessible way to interdisciplinary audiences. As will be seen in this written portion of the thesis, the scientific research elements are made accessible to those outside the sciences while the art theory is made accessible to audiences outside the arts. In *Gardening the Cybernetic Meadow,* one is able to engage with the interdisciplinary research through the temporal and relational aesthetics of the art installation, the experiential learning of reproducing the critical making process, or by reading about the theoretical framework and methodologies of the research within the written thesis component – which one may find reduced in size from the traditional graduate thesis, a by-product of how the research is shared across dissemination modes.

Alongside the theoretical framework and methodologies forming *Gardening the Cybernetic Meadow*s research-creation process, this written component will refer to artistic inspirations throughout. Some artistic references will be ones that inspired the form of the installation work, some will be inspirations towards artistic practice and process, such as collaborative making or Fluxus. The latter, includes artworks that place process over product, a durational practice rather than a concretized art object (Higgins, 2002). Some artists exploring Fluxus define their work as the operations of daily life (Ibid.), a definition close to the heart of this project, gardening. Many of the references to artistic practice found within the theoretical framework section will may loosely be categorized as Fluxus (i.e. care and maintenance, or relational aesthetics), yet each have their own defining characteristics. Reference to form and process are not contained in the theoretical framework but will be found within the sections on MFCs and research outcomes. While those in the MFC section will be solely in relation to artists working with MFCs, those found in the Outcomes will restitch artistic references from throughout back into the artwork produced within *Gardening the Cybernetic Meadow*.

The installation artwork produced and presented for this thesis, *the Cybernetic Meadow*, is a durational, mixed media installation presenting an indoor garden of MFCs, a collection of E-Ink screens, a solar powered text database, and a single switch to be used by participants throughout the timeline of the installation to alter the output of the work. It will be exhibited at World Creation Studio's gallery space on March 21, 2024. While the components of the work are introduced here, each component will be expanded on in Section 4.2, including details on the technical and aesthetic motivations behind their selection as the media for the artwork. Rather, this introduction of the artwork aims to weave together a summary that illustrates the visual form of the installation, the creative flow of the work, and concise technical descriptions.

*The Cybernetic Meadow'*s MFC garden is composed of varying types of MFCs, some are digitally fabricated ceramics woven into intricate patterns, others are small 3D printed MFCs housing mosses, and some take more DIY forms such as simple bucket containers used in balcony gardening. The E-Ink screens throughout the garden continually display their monochromatic pixels without drawing power unless updated. They present a fragmented series of text. The words displayed on each represent a segment of text in relation to a collection of writings generated throughout the duration of the installation by the solar database. The generative writing that appears on the screens is dictated by natural language processing (NLP) algorithms that are only turned on for a single cycle when mechanically toggled by a participant's use of the switch. Each cycle drafts a new word per screen, drawing from the text generated so far and a collection of texts that inspired this thesis (e.g., media geologies, extractive energy materiality, and relational aesthetics) each of which is stored on the solar database. The database is mounted on a wall behind the garden, a small black box powered solely by a solar panel of equal size. The collection of texts it hosts, all referenced to in this thesis, range from papers to full books. The code generating the E-Ink text uses these as NLP templates, which in essence align the words, sentences, and paragraphs generated with traces of the vocabulary, style, and rhetoric of the selected texts. As the exhibition of the artwork progresses, the generated text will grow and evolve, working towards a collection of writings with theoretically no end outside of one selected by the artist. Regardless, the generative text output cannot carry on indefinitely without a reliance on gardening and care as the energy required for the output to continue is produced by the MFC garden.

Like any garden, the MFC garden within the artwork must be cared for to continue growing, generating microbial energy, and survive throughout the duration of the performance. This request for an ongoing process of care and maintenance is directed towards the audience. There is nothing demanding action from the audience, only the opportunity to provide water when prompted by a screen within the garden, or a request not to be watered when the soil is saturated (detected by a series of moisture sensors).

The evolving health of the garden, and ultimately its fate, are informed by the works participatory nature – a factor highly dependent on how the audience relates to the work, making them an integral part of the artistic process. To be considered symbiotic, each organism must be benefitting from an exchange (Margulis**,** 1967). Gardens traditionally give back in the form of fruits, flowers, or crops; within *the Cybernetic Meadow*, this occurs is in the form of energy from the MFCs, which in turn power the mechanism needed to generate the fluctuating creative output of the work. The interface for this mechanism is the switch, a simple mechanical on/off toggle placed in front of the garden and raised off the ground to be within reach off the participants. The switch is connected to the dispersed screens by a series of wires, one for each screen. The wires arch downwards, lifting back up to meet at a single opaque box below the toggle switch, housing the circuit that gathers energy from the MFCs. The temporal caveat is the drastically "slow" speed of generating energy with MFCs – slow being put in quotations as a term relative to the current capital-centric extractive energy paradigm. On average, MFCs take between 12 hours to a day to generate enough energy to power a small electronic device for short bursts lasting less than a minute (Yang, et al., 2014). These metrics change with the device being powered and the quantity of MFCs being drawn from, but due to the type of MFCs used within the installation work the estimated timeline for enough energy to be collected remains near the 12 to 24-hour window. This element of the installation addresses part of the thesis' subtitle, how the research-creation and subsequent artwork use "microbial fuel cells as a temporal aesthetic medium".

The meaning of "temporal" in temporal aesthetics likely does not need to be clarified but the term aesthetic may be misunderstood. The term aesthetics in both temporal aesthetics and relational aesthetics refers to an artistic process rather than the outward image or beauty of an object (e.g., a painting or sculpture). Throughout this thesis it refers to the prior, an artistic process, which is given its own subsections in the theoretical framework but can shortly be summarized through its etymology. Aesthetic in reference to artistic process is a return to its usage preceding its usage as a denotation for beauty. (Harraway, 1988; Loveless, 2022). Aesthetic referred to the form of an object, but one did not know its form through solely looking at the object. Rather, aesthetic referred to a more situated "knowing" through experience. Considering this definition of aesthetic, my usage of the term temporal aesthetic in the context of "using microbial fuel cells as a temporal aesthetic medium" can be understood as the use of MFCs as an artistic medium with the intention to produce temporal conditions that generate knowledge around a subject through experience. Within the subtitle of the thesis, the subjects of the knowledge being generated (or "fostered") through experience are "ecosophic notions of care". Ecosophic notions extend beyond just care throughout the theoretical framework of *Gardening the Cybernetic Meadow*. These notions are frequently cited in direct relation to ecosophy due to a broad shared palette of disciplinary and theoretical roots including ecology, systems, and complexity. Due to the interwoven role of ecosophy within this thesis, it will be fully detailed in Section 2.3 of the theoretical framework. Having been introduced to ecosophic notions of care, MFCs as a temporal medium, and the dissemination modes of this thesis, we can look at its core research questions.

Research Questions

The three dissemination streams of *Gardening the Cybernetic Meadow* are motivated by two main research questions:

1) How can installation art using an interplay of living media and technology such as the MFC garden, use relational aesthetics, situated temporality, and experience to explore alternative modes of knowledge dissemination such as experience-based learning?

2) How can research-creation methodologies and critical making frameworks (i.e., critical engineering) translate the process of learning and prototyping new technologies into dissemination formats that facilitate accessible knowledge-sharing?

2. THEORETICAL FRAMEWORK & METHODOLOGY

The theoretical framework and methodology presented in this section serve to contextualize the interdisciplinary nature of the project, drawing from a diverse range of sources that encompass both the artistic and scientific domains that inform it. As the culmination of the research yields both a written portion and an artistic installation, the project prerequisites a review that includes a research foundation for the practical engineering of biotechnologies, power management systems, and embedded electronics. This literature review will embrace the full interdisciplinary framework of the project, weaving together research that may usually be categorized under separate disciplinary boundaries. Through exploring the theoretical and technical underpinnings of the research together, this review charts an interwoven system of key concepts, theories, and advancements that inform the feasibility and planned implementation of the project. In addition to connecting the relevance of the research to the future implementation of the project, the analysis within this section aims to situate the work within the broader discourses of research-creation, bio-art, and critical design.

2.1. Critical Making

Critical making, a term that combines "critical thinking" and "making" (Hertz & Ratto, 2019), proposes the process of materially engaging with or prototyping a technology enables the “thinking through [it’s] complex individual, social, and societal issues” (Ratto & Hockema, 2009). To deconstruct or (re)construct a technology, one must go through at least three iterative research phases (Ibid.). The first stage is quite literally embodied through the literature review. One must understand the basic concepts, theories, and technical aspects of the technology in question to map ideas to material action. Material action, the second phase, would be considered the iterative prototyping phase. In the context of this project this may manifest as open-source MFC design revisions developed for the installation, iterations of the E-Ink embedded hardware, or even updates to the code repository controlling said hardware. The last phase involves critique, discussion, and knowledge sharing with communities outside one’s personal research - through community collaboration is welcome in any step. This step would be activated through the proposed open-access publication on MFC fabrication.

Other interdisciplinary art-science scholars, such as Jennifer Gabrys, are using these critical making methods to develop fabrication guides and kits to ripple their findings through communities of makers, citizen scientists, and artists. Gabrys has written about her use of these methods within her explorations of embedded air monitoring toolkits, stating she hopes her “prototype kit could play in engaging people to ask questions about environmental data (Gabrys, 2019). Moving through an approximation of the three steps allows for the synchronization of “two disconnected modes of engagement with the word - ‘critical thinking’, often considered as abstract, explicit, linguistically based, internal and cognitively individualistic; and ‘making’, typically understood as material, tacit, embodied, external and community-oriented” (Ibid.).

Critical making does not have one distinct framework to follow and looks more like a relational system where the politics and ontologies behind the design process follow patterns developed by “communities of practice” (Wenger, 2011). These communities are not bound to discipline, they just share the same passions and concerns, naturally leading to collective learning through regular interaction (Ibid.). Since critical making is so expensive, subcommunities have emerged such as critical engineering. Critical engineering practice defined by the The Critical Engineering Working Group and published through their manifesto, *The Critical Engineering Manifesto* (Oliver, et al. 2011). Like those within critical making, the group does not assign it a specific definition but rather offers a numbered series of values that inform its axiology as distinct from critical making. Though both share similar methods and epistemologies - that hands-on making can "supplement and extend critical reflection on technology and society" (Hertz, 2012) - the axiology of critical engineering takes a more active stance towards their critical reflections on socio-technological-design entanglements. I refer to both critical making and critical engineering throughout this project, but I feel most aligned with the axiology of critical engineering. To illustrate some of the differences their manifesto states "it is the work of the Critical Engineer to study and exploit [technical] language, exposing its influence"; "raise awareness that with each technological advance our techno-political literacy is challenged"; and "the Critical Engineer expands 'machine' to describe interrelationships encompassing devices, bodies, agents, forces, and networks" (Oliver, et al. 2011).

Open-Source and Open Access

Access was an issue when considering the project's aim to share knowledge on MFC fabrication openly. If one lacks the required institutional credentials for these papers, they become almost entirely inaccessible. This issue is the motivating force for later literature review around critical making and open-access information. If one does have access to these papers, the disciplinary jargon, niche mathematics behind their data sets, and intellectual property (IP) claims make the translation of their fabrication process extremely difficult for those who do not have a background in biology or engineering. And lastly, these IP claims often determined how the paper layout was structured. Almost always, this resulted in MFC papers that shared portions of their data while leaving out key fabrication processes such as fuel cell designs, circuit schematics, integration methods, etc. Through critical making, small pieces of the fabrication puzzle – scattered amongst the literature review on MFCs – enabled research outcomes through iterative prototypes. Although these pieces were difficult to discover during the review, I was fortunate to find a few research papers revealing their fabrication process and designs (Bombelli, et al., 2016; Jannelli, E., et al., 2018). Alongside this project's open access axiology, the difficulties encountered during the MFC literature review led me reflect on how my own critical making MFC fabrication process could be repackage in an accessible format. This reflection became an outcome of *Gardening the Cybernetic Meadow*'s research, the Open-Source MFC Creation Guide. The guide translates the knowledge generated on MFC fabrication into an accessible form that's not bound to prerequisite disciplinary training while simultaneously providing a guide to reproducing one's own critical making process. By guiding readers through the embodied processes of making rather than solely providing technical details, a door is left open for furthering the research or simplifying the creation and distribution of MFCs. Through my reflections on critical making, I constructed a hybridized research methodology that is further unpacked throughout the following subsections.

The issues I have discussed in this section have to do primarily with *open access* (i.e., openly hosting knowledge vs financially dependent access). *Open source* is differentiated by offering an open software or hardware through code or schematics. This may simply be released to the public by an individual, but if a company is involved it often follows one of many licenses that dictate how the technology can be used. One such license found within the hardware selected for *Gardening the Cybernetic Meadow* is a GNU General Public License. This license was created by the Free Software Foundation, Inc. to "guarantee your freedom to share and change all versions of a program--to make sure it remains free software for all its users" (Free Software Foundation, Inc., 2007). This includes modification, distribution, patent use, private use, or commercial use. The primary reason the MFC guide is open-source rather than open access is due to its paired release with open-source MFC design files that can be used or modified openly.

Transition Design

Gardening the Cybernetic Meadow's uses the methodology of critical making to explore the fabrication of MFCs while simultaneously documenting the learning process, prototypes, and failures along the way. This sum of this research is not solely a final designed object (MFC), but the pathways taken, the knowledge of what to avoid, and built tools to shorten the road. Through design methodologies aligned with those of research-creation, this process can be packaged into socially mobilized design and co-creation opportunities that help tackle complex issues. Design strategies within the sciences and engineering often take single solution top-down approaches to reimagining our energy futures (De Decker, et al., 2020; Latour, 2013), especially when operating through capital-centric funding structures. Top-down modalities, such as attempting to solve a problem through engineering a single technology or disseminating research without considering the mobilization of said research (Godin & Zahedi, 2014), do not consider the social, political, and affective multifaceted aspects of large-scale *wicked problems* such as climate change (Buchanan, 1992).

"Wicked problems" is a concept introduced by Horst Rittel and Melvin Webber, which they defined as complex and dynamic challenges that defy straightforward solutions (Schuler, 2021). They are characterized by their unique nature and a multitude of factors constantly in flux, evolving, and changing. In order to address them researchers move away from largely quantitative, reductionist approaches and instead create research frameworks that are qualitative and holistic. Due to the "wicked", complex nature of these problems, it is often not the case that one of these holistic frameworks already exists for the researchers' goals, requiring unique frameworks to be created, tested throughout the research, and adapt as new issues arise. The research outcomes these frameworks aim for often involve multiple stakeholders with conflicting goals and unclear objectives. Therefore, addressing wicked problems usually requires innovative and interdisciplinary approaches that allow varying disciplinary vantage points to fill in blind spots within traditional disciplinary frameworks that operate as the status quo within their field (Gabrys, 2019; Loveless, 2022). These problems span a range of critical global issues, making them significant subjects for exploration within interdisciplinary art research due to the ability of interdisciplinary art to offer creative, alternative perspectives. When examining complex problems, the artist's perspective is a valuable asset and a valuable research tool for constructing new research methodologies. Critical art practices attempt to make visible social issues that slip through the cracks of societal perception. These issues can become comfortably invisible within the structures of their respective disciplines. In these cases, interdisciplinary artists are especially an asset due to their familiarity working between various mediums and through their experimental navigation of traditional disciplinary bounds through alternative research methodologies such as critical making and research-creation. By borrowing methodological frameworks from a range of disciplinary toolkits (Zahedi, et al., 2017), interdisciplinary artists have the potential to expose issues largely passed over within these traditional disciplinary boundaries and make them visible through critical discourse. In relation to this thesis, I propose this experience lends itself to a higher degree of ease creating new and unique frameworks for approaching research topics that include complexity and wicked problems.

One method for addressing wicked problems explored within this thesis borrows its research design methods from that of "Transition Design", which suggests addressing complex problems through local, community action (Escobar, 2018). This bottom-up approach addresses identifiable pockets where climate action can be taken, such as through providing communities with an independent source of sustainable energy. To design for social and ecological transitions, this method requires that the process be replicable, allowing adjacent communities to organize their own creations from the same foundations without intervention. An artistic example that perfectly blends between installation art, interdisciplinary collaboration, and transition design is the work *Korallysis* by Gilberto Esparza (See Figure 2). His project aims to solve an environmental problem, the loss of coral reefs, by engaging collaborators from a range of disciplines. "The creative development process has involved art students, engineering, biology and physics, pottery craftsmen, and civil associations such as Oceanus A.C. and Restore Coral made up of marine biologists and a range of specialized scientists, dedicated to reef restoration of coral in Quintana Roo" (Esparza, 2020). The artistic manifestation results in a sculpture that contributes to environmental restoration while equally being about the process of the work. Through its creation new sites of interdisciplinary collaboration and knowledge sharing were forged, generating new experimental frameworks for artistic creation towards solving complex problems.

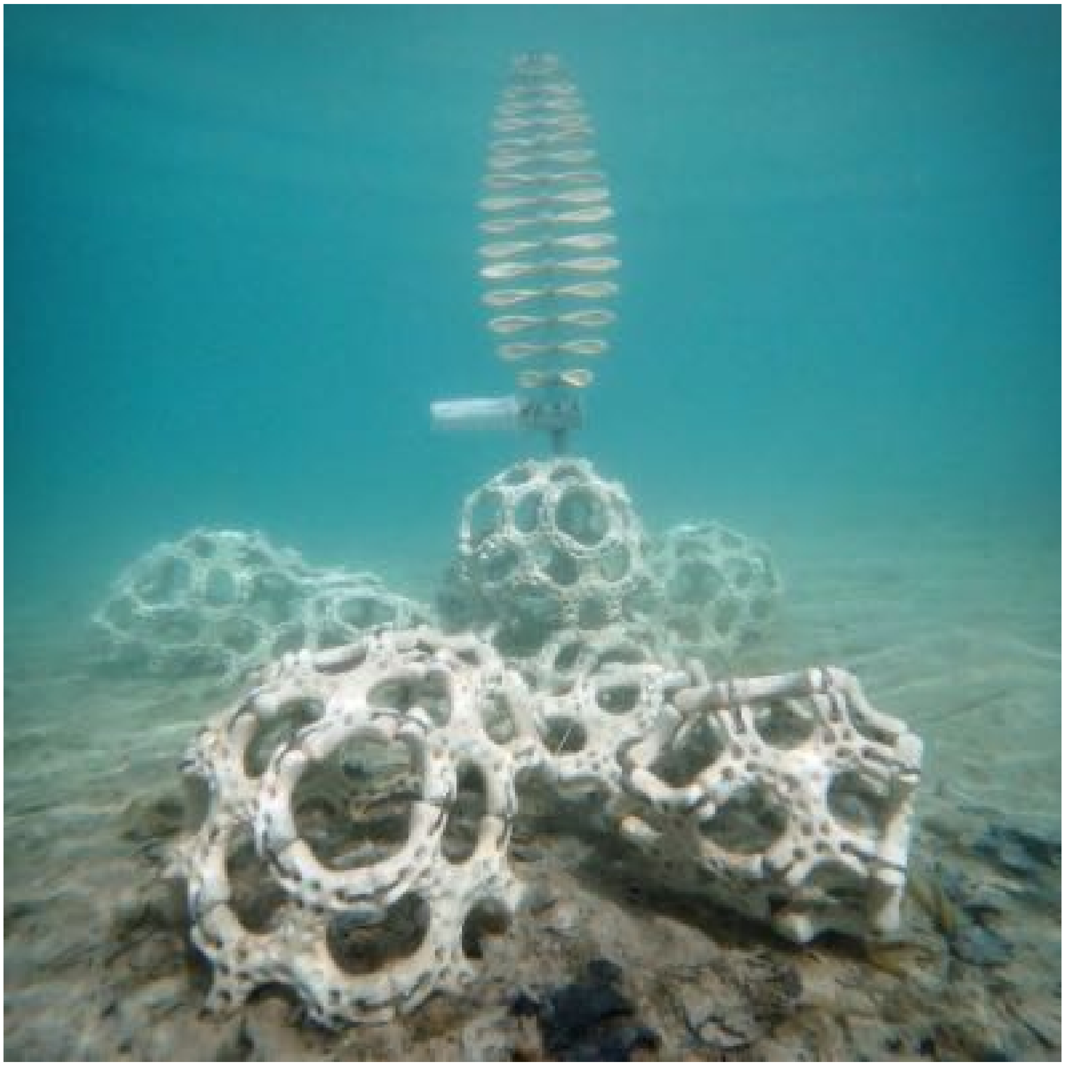

Figure 2: The interdisciplinary collaboration artwork, *Korallysis*, by Gilberto Esparza (2012-2020).

Prior to any research explorations through critical making, Transition Design had heavily informed my research axiology, steering it towards the inclusion of social mobilization methods as core values. To ensure the research outcomes of this thesis may be socially mobilized, part of its dissemination must be able to provide research replicability and remain accessible to audiences outside the disciplines of art, biology, and engineering that contribute to the formation of the project's theoretical framework. These values influenced the structure of this written portion of the thesis, the form of public engagement within the installation artwork, and the inclusion of the Open-Source MFC Creation Guide. Out of all three dissemination modes, the guide most effectively reflects these social mobilization values as its form was molded to provide accessibility and replicability. It does this through its open access publication status, an avoidance of unnecessary disciplinary jargon, outlining MFC fabrication through actionable steps, providing Open-Source 3D printable MFC files, illustrating MFC schematics, and the inclusion of multiple modes of creation that consider the availability of materials and equipment. In addition to providing replicability and accessibility through the Open-Source MFC Creation Guide, this thesis also socially mobilizes its research by creating interest, engagement, and an ongoing discourse through public engagement with the arts (Escobar, 2018, Bourriaud, 1998). Both the methodologies utilized to assemble the guide (i.e., the making and documentation process) and social mobilization through public engagement with the arts, are critical foundations to *Gardening the Cybernetic Meadow*'s research-creation frameworks.

2.2. Research-Creation

In the context of this interdisciplinary thesis project, the research-creation methodology serves as a bridge between the artistic and scientific domains. This hybrid approach integrates diverse perspectives and methods to generate new knowledge, experiences, and forms of expression that could not be achieved through a purely artistic or scientific lens. Research-creation projects can vary in their methodology, this project models its methodology after what Natalie Loveless classifies as *research through art and design*. This method merges "'practical' art or design production with written analysis relevant to that production, and results in a hybrid written thesis and artistic object, installation, or action exhibited and documented" (Loveless, 2019). Other scholars, such as the artist-researchers Andrew Brown and Daniel Mafe, have developed multifactor criteria for their practice-led research, a variant of art-research with similar features to research-creation. The variation in fields of artistic research is in part due to geographic location, research-creation being predominant in Canada. Owen Chapman and Kim Sawchuk suggest the importance a network of terms linked to research-creation, including practice-led research, arts-based research, and creation-as-research (Chapman & Sawchuk, 2015). Aside from these terms having a degree of geographic separation, they may vary in how the role art is defined within academic research. As Chapman and Sawchuk suggest, the subtle differences between definitions can be useful during one's own formation of a research-creation framework as they provide alternative guidelines for how artistic research can exist within academic settings. When considering the methodology for this project I took inspiration from Mafe and Brown's criteria for practice-led research.

> 1) differentiated from previous work of the researcher and field such that the elements of exploration and discovery are identifiable;
> 2) rendered accessible/available through either publication and/or exhibition as a public activity, one open to scrutiny by peers;
> 3) transparent and clear in its structure, process and outcomes – that it provides clear explication and explanation that is usually exegetical in nature;
> 4) transferable so that information or outcomes are useful beyond the specific research project or applicable in principle to other researchers and research contexts. This requires that the practice and outcomes are adequately theorized, described, and contextualized.
>
> (Mafe & Brown, 2006, p. 1-2)

In addition to these criteria, the construction of *Gardening the Cybernetic Meadow*'s research-creation methodology was molded around the primary medium used, MFCs. The methodology and medium heavily define the research, but even before their inclusion research-creation frameworks require the artist and researcher to ask themselves "what form best fits the research to render it public?" (Loveless, 2022). The methodological approach is formed to address the proposed research questions and their corresponding theoretical framework. The choice to explore MFCs as a temporal-aesthetic medium for *Gardening the Cybernetic Meadow* is multifaceted and therefore addressed throughout the subsections of the theoretical framework and methodology section. In relation to its applicability as a medium within academic research, I'll return to this in the following subsection, Research-Creation Methodology.

Research-creation allows the artist to experiment with research tools outside of traditional disciplinary boundaries. As an interdisciplinary artist, I ask myself this question for each new work. To decide on an appropriate form within research-creation, requires the artist to consider how the artistic form may contributes to the research in new, insightful ways. Since artists work with a variety of media, one of their skills is the ability to channel and translate a question into experiential forms. These forms expand the possibilities for rendering the research public through varied media, but the process of translating the research into material form or practice forces the artist to reflect on how the research is most effectively communicated to the public. Interdisciplinarity offers similar avenues to generate new insights by breaking down the methodological barriers a discipline has in place and presenting the researcher with new disciplinary tools to engage with. The interdisciplinary artist may be exploring a knowledge gap in a subject, but often it is a perceived lack in *how* a subject is being discussed. By approaching a research subject with a range of disciplinary tools outside those traditionally used, the artist can approach a research subject from novel vantage points. The use of new disciplinary tools does not always have to produce an expected outcome to generate new insights, and failure can produce equally valuable insight. For example, using a critical making methodology to design MFCs was expected to, and did, hit many bumps along the way. As will be discussed in Section 4 (Outcomes), failures during the creation process led to revisions in design that were not expected based on a literature review but led to research outcomes with a more embodied and robust understanding.

Interdisciplinary research and collaboration operate more as a system than a set of predefined rules to follow (Zahedi, et al., 2017). A simplified version of this system can be seen in Figure 3, consisting of six criteria that produce an outcome – the subject, object, tools, community, [disciplinary] rules, and division of labor. While dependent on interdisciplinary *collaboration*, an interdisciplinary artist working independently will always need to collaborate between disciplinary communities of practice (Wenger, 2011). Arguably, one never works alone in interdisciplinary settings as they are reliant on existing knowledge and borrowed tools. If the artist is exploring the scarcely charted borders between given disciplines, their methodology must be borrowed and composited from multiple sources, potentially retooled, and always open to adaptation as the methods are tested. Where these methodological frameworks cease to exist, research-creation offers guidelines for stitching together new research methods and the appropriate forms that follow.

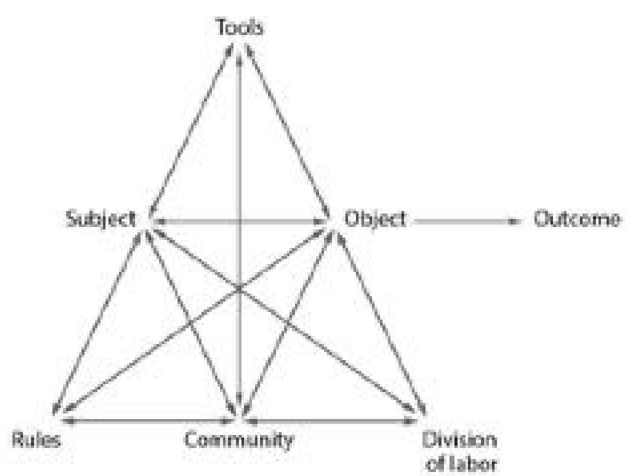

Figure 3: Interdisciplinary approaches through Activity Theory. Illustration by Zahedi, et al., 2017.

The research-creation ideology of Andrew Murphie bridges the research-creation frameworks that I have already discussed with those formed by the methodologies within Critical Making and Transition Design. He uses the term "technics" to encompass "technologies and techniques that are crucial to the activity of research-creation" (Murphie, 2018, p. 2). For Murphie, technics allow the researcher to create new conditions for tacit knowledge and embodied learning outcomes. This is possible through envisioning new ways to utilize technics that may lie outside of disciplinary fields. The researcher may explore critical making methodologies by re-tooling existing technologies to operate in novel ways. In the case of *Gardening the Cybernetic Meadow*, this is done through the exploration of MFCs, E-Ink screens, and Text Generation. These all may be considered the technics as they are arranged to operate with each other and participants through techniques that create an atypical temporal environment and experiences. For Murphie, the relation and interaction between technics and participants is vital to how research-creation generates knowledge. Our identities are not solely defined by our interactions with others; they are intricately shaped by our relationships with ourselves, our environment, and our technologies. Technics allows one to create new experiential environments which allow a rearranging of the participants relations and an embodied reflection on how these relations shifted and why the art produced through the research-creation process aimed to create this shift. Murphie's research-creation framework involving with technics becomes one integral part of this thesis' research-creation framework and shapes its methodologies.

Research-Creation Methodology

Understanding the theoretical framework of research-creation and its flexibility constructing research methodologies, *Gardening the Cybernetic Meadow*'s methodology can now be examined. Due to the project's interdisciplinary nature, the methodology is hard to define within the scope of a single section; each section within the Theoretical Framework and Methodologies contributes to a methodological praxis. The section opens with Critical Making as it is one of the core methodological contributors and acts as a fundamental outline for the embodied learning and open access axiology of *Gardening the Cybernetic* Meadow. While writing about artistic research-creation for publicly engaged art-research, Jon Bath notes that Critical Making is not always research-creation, though it easily fits within its framework (Bath, 2019). Bath's statement is influenced by Critical Making pioneers like Matt Ratto and Garnet Hertz, stating it is not the physical things made that are to be considered the research output. Instead, "Critical making emphasizes the shared acts of making rather than the evocative object … through the sharing of results and an ongoing critical analysis of materials, designs, constraints, and outcomes" (Bath, 2019; in citing Ratto, 2011, p. 253).

To outline how *Gardening the Cybernetic Meadow'*s methodologies qualify as academic research, I borrow the criteria outlined by Mafe and Brown for practice-led research (and by extension, research-creation). As research-creation can be amorphous, hard to define, and has varying academic expectations depending on one's location, these criteria act as a loose map to align the research with criteria proposed by other academics but are not absolute. I would like to note that this research-creation methodological mapping applies to the goals, process, and outcomes of the research to its academic qualification, but additional methodologies within the creation portion of this thesis, such as Critical Making, have their creation methodologies outlined within their corresponding sub-section. Mafe and Brown use four criteria, but to better outline the qualifications of the creation methodologies used within this thesis, I have added a fifth category that is shaped after Ratto's definition of a Critical Making outcome within research-creation.

> 1) *Gardening the Cybernetic Meadow* differentiates from the previous outcomes of my artistic practice and academic research in several ways, primarily through the medium used (MFCs), its exploration through temporal aesthetics, and the theoretical framework of the research;
>
> 2) It is rendered public through both a publication and an exhibition, the latter being subject to peer review;
>
> 3) A critical examination of the structure (i.e., Technics and the experiential potential), process (i.e., Critical Making methodologies), and outcomes (i.e., the MFC Creation Guide, the experiential artwork) exists through this written component of the thesis;
>
> 4) The project outcomes, especially the MFC creation guide, are documented with accessibility in mind (i.e., the avoidance of discipline specific terminology) and with the intention of openly sharing knowledge through open-source, open access, and reproducibility;
>
> 5) The outcomes of the work are critically examined not just by tangible products, but by the "shared acts of making" and "an ongoing critical analysis of materials, designs, constraints, and outcomes" (Ibid).

Experiential Learning

The notion of learning through experience is at the core of this research-creation project. The intention behind the thesis and the reason why the objectives steer towards installation and making is due to the belief that both those environments offer valuable opportunities to learn by experience, by an embodied sensory knowledge. This idea goes under several names, each with varying terminology and subtleties. When doing the literature review for this project, one of the first scholars that resurfaced was New Bauhaus director Lazso Moholy-Nagy. Moholy-Nagy coined the term *experiential learning*, defining it as a methodology to teach human-centric design to his students via sensory knowledge. In some lessons, rather than lecturing, he taught his design students about the essence of the materials they would be using through tools crafted to convey visual, tactile, and auditory information; he placed an emphasis on experience as the methodology, which in his words would allow the 'crystallization of the whole' (Moholy-Nagy, 1974). The crystallization he refers to is a moment of understanding, of knowing, that went beyond words.

The complex nature of systems can be hard to reduce to individual points that can be mapped out through writing due to their existence being perpetually in flux, especially when researching a system from the outside. Situating research inside of the ecological spaces that make up these systems can be a powerful tool leading to insights on how networks of social-political, environmental, and material factors have shaped the information and knowledge structures that exist for a given system (Tuck & McKenzie, 2015). Knowledge structures are also subject to biases of those that record them. It has been suggested that there is an identifiable gap in the diversity of learning styles deemed valid within academic contexts, which may be the product of removal from experiencing systems as well as recurring cycles of researching knowledge structures through the same recorded sources and formatting. This repetition is susceptible to slowly weeding out voices and methods that do not fit the status quo. A growing number of scholars are proposing that some individuals are much more capable of learning from embodied and experiential models of learning (Hutchins, 2016; Whitehead, 2010; Nerenberg, 2021). Re-evaluating the role of experiential learning as a research and dissemination tool not only helps include a wider diversity of minds but may lead to new insights through alternative modes of experiencing and perceiving patterns within complex systems.

2.3. Complex Systems, Ecologies, & Ecosophy

Art can be an be used as an effective experiential tool towards better understanding the complexity behind global systems (i.e., the bio-social entanglements of climate and energy). Galleries are becoming a more open environment to explore this complexity through experience (Piatti, 2015), yet remain limited in accessibility due to the spatio-temporal constraints of exhibitions. By offering hybridized research outputs in the form of experiential installations *and* critical inquiries into the theoretical framework of experiential systems, this thesis aims to bridge accessibility gaps by offering multiple avenues for critical discourse. In addition to using experiential art as a tool for localized knowledge mobilization, this thesis explores the theoretical framework of *why* systems theory plays an important role in creating experiential conditions. Therefore, this sub-section of the Theoretical Framework and Methodologies examines systems theory, its precursors, and their relation to art.

Systems Theory is both a scientific framework for understanding complex phenomenon, and a theoretical framework due to the difficulty reducing systems to discrete ideas or events commonly found in the sciences (Bateson, 1973; Fritjov, 1988; Stengers, 2010). It was defined by Ludwig von Bertalanffy as "predominantly a development in engineering science in the broad sense, necessitated by the complexity of "systems" in modern technology, man-machine relations, programming and similar considerations which were not felt in yesteryear's technology but which have become imperative in the complex technological and social structures of the modern world" (von Bertalanffy, 1968, p.vii). He describes systems theory as a tool for examining "parts and processes in isolation, but also to solve the decisive problems found in the organization and order unifying them, resulting from dynamic interaction of parts, and making the behavior of parts different when studied in isolation or within the whole" (Ibid, p.30). Systems are formed by interrelated and interdependent parts - both living and non-living – where the interactions and relations between parts as a "whole" manifest emergent properties and patterns of behaviour. A biological example of emergence can be seen within the emergent social behaviour of ant colonies, such as their collective navigation, divisions of labour, and agriculture (Parikka, 2010).

Systems Theory is a core component to this theoretical framework due to its holistic and emergent vantage point, offering the researcher a tool for examining the relations between the biological, social, and technological spheres. It directly overlaps with the framework's discussions on ecologies and ecosophy, which additionally explore the semiotic nature of systems as an elusive "weave of differences" (Manithottil, 2008). Addressing complex issues require joint investigations between disciplines, investigations that examine complex social issues with research methodologies that move away from scientific methods and instead provide space for the holistic relational properties of systems (Stengers, 2010; Guattari, 2014). As this project is an interdisciplinary thesis working at the convergence of biology, art, and environmental philosophy, ecosophy is a crucial research tool for bridging its disciplinary discourse. To understand the occasionally abstract nature of ecosophy, this section is sub divided into theories that build up that foundation through Cybernetics, Systems, Ecology, Ecosophy, and their integration within art practices (i.e., systems-based and ecosophic art practices)

Cybernetics & Systems

There are various theoretical contributions that led to the formation of Systems Theory by Ludwig von Bertalanffy (1969). These pieces can be seen throughout this section, the most important of which for this thesis is the field of Cybernetics. To best understand to relationality found between art and systems, I will briefly speak on the influence of Cybernetics within the Theoretical Framework and within the title of this thesis. Cybernetics arose in the 1940s as scholars from varying disciplinary fields such as Mathematics, Sociology, and Biology, began sharing notions of perception, feedback, and environment at gatherings such as the Macy conferences (Fritjov, 1988). Feedback was examined as a force between organism and their environment, existing in continuous loops of either positive feedback (chaotic and consuming) or negative feedback (control based). The Biologists, Maturana & Varela, first proposed this negative feedback operates within cells to self-form membranes and regulate internal processes (Maturana & Varela, 1978). Other cyberneticists applied the notion of self-regulating feedback to humans, technology, and machines, such as the Mathematician Norbert Wiener did to formulate how humans could predictively operate anti-aircraft guns in WWII (Wiener, 1968). What began to set cybernetics and systems apart was the notion that systems were more complex due to the sprawling set of actors within them, and that the properties of systems were adaptive and always in flux (Fritjov, 1988). For a time, cyberneticists – and through their influence, ecologists – believed systems always moved towards a balanced state (BBC, 2011). This belief shifted to understand systems as complex and adapting, where complexity is considered "a group of 'agents' (individual interacting units, like birds in a flock) … existing far from equilibrium, interacting through positive and negative feedbacks, forming interdependent, dynamic, evolutionary networks" (Lynn, et al., 2011). Returning to the emergent behaviour of ant colonies, "an individual ant does not 'know' its role in the system, it is acting on a combination of sense, instinct, and adaptation… Each individual action relies on feedback from the whole and as the number of agents grows, new patterns emerge that are not the intention of any individual; emergent behavior is the tipping point where the behavior of the whole does not reflect the [intent] of the individual" (Matthew Halpenny, 2020, p.3).

Understanding this, one can more easily understand the etymological shift of the word *ecology* to include the social and complex systems. "Ecological awareness, in that deep sense, recognizes the fundamental interdependence of all phenomena and the embeddedness of individuals and societies in the cyclical processes of nature" (Fritjov, 1988, p. 23). Within this theoretical framework, the notion of ecosophy reframes any disciplinarily rooted notions of *ecology* into an expanded interdisciplinary notion of *ecologies* centered around relationality. This ecosophic notion of ecologies facilitates a better understanding of the cross-connections and inter-relations between an expanded set of disciplines, specifically, the relationality and role of art-making and artistic practice as research tools within an expanse of disciplines (Guattari, 2013; Bourriaud, 1998).

Ecology & Ecosophy

When working between disciplinary boundaries, terminology can become muddled with multiple meanings. One term that absolutely needs clarifying due to the disciplinary overlaps is the ecosophic notion of *ecology*. While the term often defaults to the biological field of ecology, the ecosophic notion of ecology is more aligned with its original definition by Ernst Haeckel as the study of relations (Egerton, 2013). While this definition is not excluded by the biological field of ecology, it is used by Guattari to describe the relational nature and interconnection between “the environment, social relations, and human subjectivity” (Guattari, 2014 p.28). This ecological viewpoint is shared as a fundamental element of *Gardening the Cybernetic Meadow.* Where the two slightly differ is this projects exploration of relationality between human, environment, *and* technology. One of the ecological notions the installation work tries to communicate is the interconnected nature of human action and environmental consequence, but the temporal differences between the processes of geological timescales and those of human timescales can make that difficult to see. Specifically, the installation uses temporal aesthetics to explore how experientially relating to an idea can influence social action, which in influences our environment. This idea was initially influenced by Gregory Bateson’s “Ecologies of Mind” a theory he discusses throughout his collection of writing *Steps to an Ecologies of Mind* (1973), a key inspiration towards Guttari’s formation of the three ecologies and ecosophy (Guattari, 2014, p. 27, 70-71, 93-94). Within this framework, one can consider the act of “fostering ecosophic notions of care” as discussing notions of care through an understanding human and environment are inseparably part of the same complex system. “Relationism has an [ecosophic] value because it dispels the belief that entities or people can be isolated from their environment” (Guattari, 2013 p.33).

The examination of process and the interdisciplinary exchange between art and biology (i.e., how one understands an installation space vs. the MFC garden as a network of non-organisms) has been discussed by scholars such as Tim Ingold, who discuss “the concepts of becomings, biosociality, and multiple agency [as having] garnered active epistemological reflection across fields” (Hawke, 2015). He discusses biosociality goes against the paradigm of neo-Darwinism where organisms are assumed to individually act under a *survival of the fittest,* rather than a collective mutualism suggested by researchers in the sciences and humanities alike (Margulis, 1967; Bateson, 1973; Debaise, 2017). When considering ecosophy’s monistic view of the social and biological, the term biosociality becomes an unnecessarily defined synergy. I therefore avoid referring to biosocial relations and in its place substitute ecosophic terminology or I adopt Haraway’s term “sympoiesis”, denoting symbiotic interspecies collaboration a mutualism through “making-with” (Haraway, 2016 p.58). “Making-with”, or sympoiesis, is defined as a contrast to autopoietic notions of self-making (Maturana & Varela, 1978). On the same page Haraway relates to sympoietic thinking to "tentacular thinking", a means of thinking about interspecies ecologies that aligns with, and is perhaps best understood, through the synchronous suggested shifts towards modes of thinking that are "rhizomatic notion of relations" (Palsson, 2013, as cited in Hawke, 2015. P 126). Palsson uses the term "rhizomatic" in reference to its definition and ideological framework by Deleuze and Guattari. Their framework uses the rhizome – an underground stem differentiated from root systems – to outline "principles of connection and heterogeneity: any point of a rhizome can be connected to anything other and must be. This is very different from the tree or root, which plots a point, fixes an order" (Deleuze & Guattari, 2019, p. 7). Rhizomatic principles can be seen in each section of this theoretical framework and are a primary influence on the form of Gardening the Cybernetic Meadow's output.

The entanglement of social ecologies and environmental ecologies echo the principles of "making-with", but ecosophic explorations are not inherently optimistic. Therefore, I use the term sympoiesis in reference to speculative interspecies collaborations. Sympoietic speculation is at the core of *Gardening the Cybernetic Meadow*'s installation artwork. The artwork creates conditions for speculating on how technologies produced within social ecologies may resist anthropocentric design. It produces imaginaries around symbiotic technologies that create conditions of mutualism. Through the process of MFC gardening we are offered an ongoing, rhizomatically structured creative text output. In return, the organisms within the MFC garden are continually cared for and nourished. The organisms involved in the artwork's sympoietic collaborations range from human participants to soil microbes, host plants, *and* myriad of interrelated species within the garden (i.e., pollinators, fungi, etc.). Artistic practices are a useful tool for speculating on technological design as non-anthropocentric or as symbiotic parts of environmental systems (Halpenny, 2020).

Systems & Art

Experiential art and systems-based art (or systems art) have the potential to offer this. Systems art began gaining attention in the 1960's due to cyberneticists like Foerster and Pask (Halsall, 2008; Willats, 2011), who began exploring artworks that resist a static form – artworks of any medium that project a sense of permanence and allow their form to remain constant in time. Static art need not arise by static process. The artistic process is always yielding variation due to the embodiment process of art-making, yet within static art it is the apparent permanence of the object that is considered over that process.

> A major illusion of the art system is that art resides in specific objects. Such artefacts are the material basis for the concept of the 'work of art'. But in essence, all institutions which process art data, thus making information, are components of the work of art. Without the support system, the object ceases to have definition; but without the object, the support system can still sustain the notion of art. So we can see why the art experience attaches itself less and less to canonical or given forms but embraces every conceivable experiential mode, including living in everyday environments (Jack Burnham, 1969, p.116-117).

If we want to experientially communicate the processes of complex systems, such as climate change, we can use systems-based art and Fluxus art to help reframe how the participant relates to the environment around them. Static art objects often fail to encapsulate the adaptive, shifting nature of the systems we interact with throughout our lives, especially since technology-centric objects are often presented as static when they actually have far-reaching implications on biological systems through their pollution and extractive requirements for manufacturing (Buchanan, 1992; Parikka, 2015). System-based art is intentionally designed to follow the properties of feedback, cybernetics, and complex systems, while centering the impact of their design on how they may affect both human and other-than-human. By mapping the invisible exchanges between organisms, technology, or environments to perceptible signals such as sound or imagery, systems-based art installations offer new ways to better understand the processes of systems and hence better understand systemic issues while allowing a participant to witness their own or communal influences on the work.

An inspiration for my project, the artwork *Symbiome* (2016), does this through the design of a speculative symbiotic technology for plants. Saša Spačal's work, *Symbiome*, "explores the entanglement of symbiotic interspecies relationship that is constantly adjusting according to trophic requirements and environmental conditions" (Spačal, 2016). In the center sits a hydroponic chamber with red clover (Trifolium pratense) and the mycorrhizal bacteria Rhizobiaceae. The system indirectly measures aspects of the exchange between species (e.g., nitrogen fixation in exchange for photosynthesized sugars), which in turn influence the frequency of dripping water, which "caus[es] ripples that transcend symbiotic biofeedback loop of red clover and rhizobia into extended environment" (Ibid). This work is a great example of how systems art, in this case living systems, can translates ordinarily imperceptible interactions between other-than-human organisms into a wave of sense output that we as humans can perceive, leading to a more intuitive understanding of the exchange through experience.

Figure 4: *Symbiome* by Saša Spačal (2016).

Artistic process provides a methodology for of exploring novel sympoietic approaches to how our technological design process can consider organisms beyond humans; a design process synchronized with ecosophic notions of the inseparability of human and environment, one that refutes the removal of socio-technological contributions to ecological impact. “Our day and age is certainly not short of political projects, but it is awaiting forms capable of embodying it, and thus enabling it to become material. For form produces and shapes sense, steers it, and passes it on into day-to-day life” (Bourriaud, 1998 p. 83). Aligning with the ecosophic views of Bateson and Guattari, *The Critical Engineering Manifesto* discussed in Section 2.1, re-enforces the idea that design, art, and “written code expands into social and psychological realms, regulating behaviour between people and the machines they interact with” (Oliver, et al. 2011). The manifesto suggests this is a call-to-action “to reconstruct user-constraints and social action” (Ibid.), to design technologies and artworks that shape new ecosophic formations and ripple current paradigms of social, technological, and environmental interaction.

While situating itself between these social, environmental, and technological ecologies, *Gardening the Cybernetic Meadow* explores how participant-engaged art may reshape one’s notions around the aforementioned ecologies through a sympoietic lens of mutualism and care. It nurtures an optimistic view of the relationship between environmental ecologies (i.e., the gardens we choose to care for) and the technologies we design (i.e., energy harvesting MFCs and embedded creative composition devices). A fundamental motivation for this theoretical framing of care and mutualism is aligned with (and inspired by) the poetic relationship between the machines, meadows, and forests in Brautigan's poem *All Watched Over by Machines of Loving Grace* (1967), using Aesthetic artistic frameworks to form the installation artwork and its relation to the public that become audience and participant.

2.4. Relational Aesthetics

Relational Aesthetics is a term coined by art curator Nicolas Bourriaud used to discuss art as process based – a continual formation and reformation determined by complex [social] systems - rather than defining art as static 'complete' objects (Bourriaud, 1998). The process-based art within his definition of Relational Aesthetics often centers around social contexts and discusses many artists within the Fluxus movement. It neatly ties together much of this thesis' theoretical framework thus far through an interweaving of process-based art, relationality, experience, and ecosophy. While unpacking the interconnected social ecologies within art, Bourriaud even specifically mentions Guattari's writings on ecosophy, relating Relational Aesthetics to "an artistic, ecosophic practice" (Bourriaud, 1998, p. 47). Relational Aesthetics is an etymological return to previous notions of aesthetics and form within art. It refutes the modern association of *aesthetic* with strictly visual forms, static art objects, and beauty (Harraway, 1988). Originally, the form of something overlapped with the aesthetics of it but referred to the perception of a thing, to know it was rooted in embodiment and experience, not beauty. In these terms, the aesthetics of an artwork was not to visually perceive it but to stir an embodied awareness of it, to understand the artwork even when its meaning isn't visible (Harraway, 1988; Stengers, 2014). The redefinitions attempt to return to systems analogous definitions of what art can be, away from beauty and static object to its origins in 'relation' and experience (Bourriaud, 1998; Loveless, 2022; Burnham, 1969).

Experiential learning and relational aesthetics go together, the installation to be created through Gardening the Cybernetic Meadow, could be defined as presenting both. The two terms don't define the specific object to be understood, which loosely isn't an issue but if one were to be more precise with definitions one could say the installation focuses on experience-through-environment rather than the objects involved, or place-based experiential learning (Russell & Hutzel, 2007). When the artwork is fixed in one place it presents the audience with ample opportunities to revisit it. If revisitation and engagement become regular, the artwork then has the potential to become a social sculpture, where the dematerialized nature of social engagement becomes the medium of the artwork (Bourriaud, 1998). Social sculptures represent complex relational networks of individuals, leading to unintentional performances where the score cannot be predicted (Burnham, 1969; Halsall, 2008). To become this type of systems sculpture, the placement of the artwork usually requires some anchor point to revolve around. Aesthetics is often associated with beauty in object form, yet it is originally defined as to perceive or to embody (Harraway, 1988; Bourriaud, 1998). Social sculpture aligns itself with this original definition, providing a space for embodiment and perception of the work through participation. It allows communication of ideas through situated learning, whereas top-down frameworks can be difficult to understand to the public as statistics and policy are more abstract. This framework positions the MFC garden within the installation artwork outcome, a place where one of these social anchors may exist.

Eduardo Kac's *Genesis* (1998/99) was one of my early influences for understanding how artworks can operate as systems, explore relational aesthetics, and facilitate participation with technology. The worked is designed to integrate the human use of network technologies (the early Internet) into a system that mutates genetic information based on remote participation. "Remote participants on the Web interfere with the [work's] process by turning [a] UV light on. The energy impact of the UV light on the bacteria is such that it disrupts the DNA sequence in the plasmid, accelerating the mutation rate. The left and right walls contain large-scale texts applied directly on the wall: the sentence extracted from the book of Genesis" (Kac, 1998). The selected portion of text from the book of Genesis undergoes continual transformation, birth, and rebirth, eventually ending in an unpredictable new text.

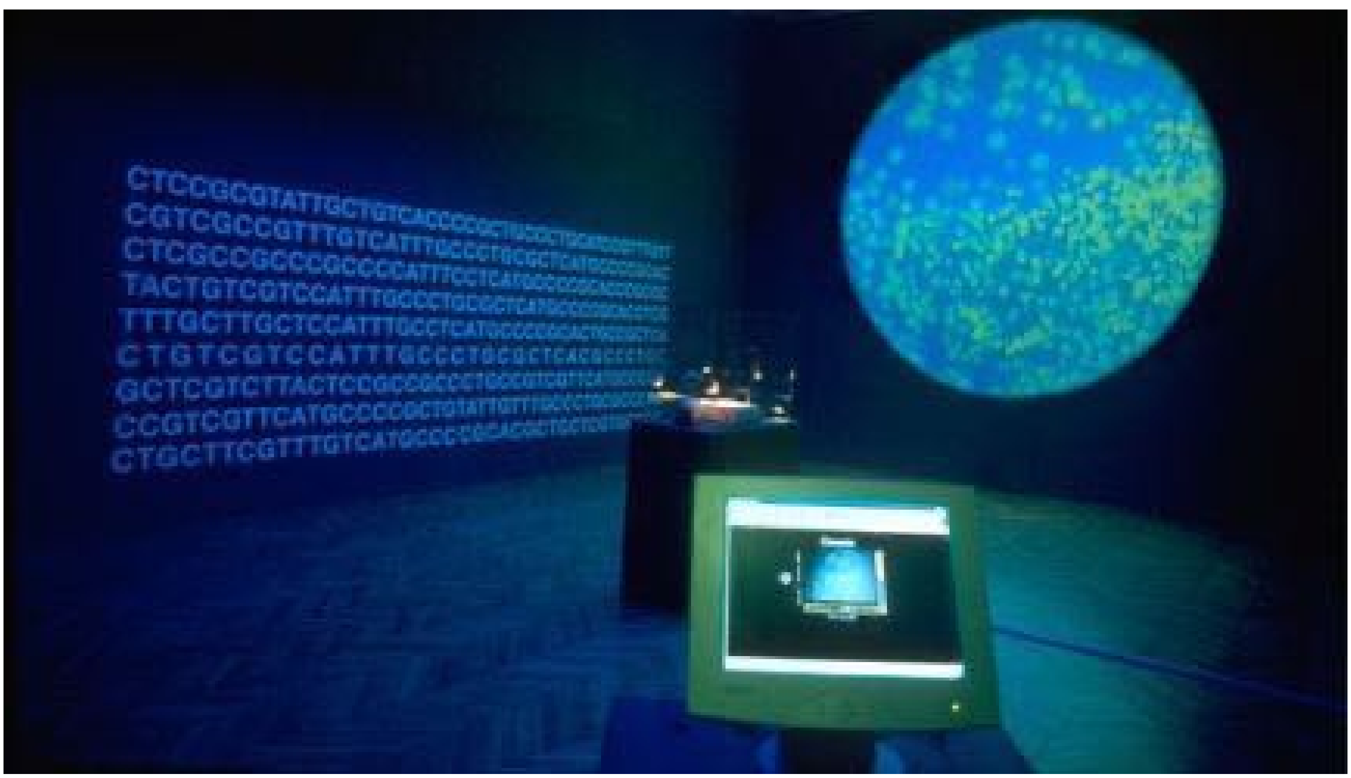

Figure 5: Genesis by Eduardo Kac (1998/99).

2.5. Temporal Aesthetics

The anchoring incentive goes beyond curiosity when considering the required maintenance of the plants, potentially sparking a flux of care that intrinsically pairs with temporality through "slowness" of the work. The experience of slowness and alternative temporalities offer us an expanded view of relational aesthetics towards what some scholars denote "timelapse aesthetics" (Tung, 2020). Timelapse aesthetics is recognizable within the eco-arts for performance works like in Francis Alÿs' *Paradox of Praxis I (Sometimes Making Something Leads to Nothing)*, where the artist pushes a block of ice through Mexico City for 9 hours until melted and gone. In these kinds of durational work, an ending is anticipated; I believe the term timelapse suggests an end point within these works. When discussing temporality, climate, and the Anthropocene, referring to time as having an endpoint can be problematic – if we want to move away from pessimistic notions of the Anthropocene and catastrophe (Fornoff, Kim, & Wiggin, 2020), I believe exploring time as evolving and non-bound more aligns with this thesis' discussion of relation and systems and therefore should be called *Temporal* Aesthetics. Though he does not use the term *Temporal Aesthetics*, Bourriaud discusses similar alignments within his notion of aesthetics through his dichotomous classification of temporality in art, monumental and factual time. "Monumental Time" is available at any time for anyone (i.e., the static art object), whereas "Factual Time" is temporal and situated, examples of which are social sculptures and live performance (Bourriaud, 1998; Loveless, 2022).

Temporal aesthetics help generate experiential knowledge around the temporal aspects of geologic and biologic systems around us. This is specifically in line with Rob Nixon's discussion on "Slow Violence", which communicates the difficulty in witnessing the damage humans put on ecological systems and climate (Nixon, 2013). He suggests that this damage goes unseen by some due to a slow "leaking" damage instead of identifiable events. In the same vein, microbial energy could almost be considered a slow "leaking" of ions in a non-damaging way. The use of MFCs within the experiential installation may therefore help generate situated knowledges aware of these temporal "leaks". The slowness of MFCs is of course relative to human perception. In ecosystem terms, they operate on a communal "real-time", relying on the collaboration of microbes, plants, microfauna, and fungi to recycle waste products into usable resources.

Unlike fixed extractive energy sources like coal and oil, microbial energy is processional. Extractive energy is a product of millions of years of geological labor, which some scholars refer to as "deep time" (Harmanşah, 2020; Fornoff, Kim, & Wiggin, 2020). There is variation in the temporal period scholars refer to when using the term, but for our sake it could be anything millions of years in the past and beyond. While extractive energy sources offer vast amounts of energy immediately upon combustion, the quantity of CO^2 is tied to a much "deeper" temporality than humans witness (Daggett, 2019). The asynchronous nature of geologic timescales and human experience may use the term "human time" as a contrast to "deep time" (Harmanşah, 2020). The processional energy of microbial communities is much closer to human time than deep time, but still lies outside the immediacy we have come to expect from extractive energy. To turn away from deep time sources, speculative energy futures may look to regenerative energies such as MFCs, which can live alongside human temporalities as long-lasting and mutually beneficial relationships.

Other-than-Human Temporalities

While acknowledging the wide temporal differences between geologic processes and human processes can be glaringly obvious due to their vastly differing timelines, the situated "knowing" of these temporal differences is more complicated to conjure into experience. How can we explore a situated awareness of the human-deep time gap within our technological energy use? Energy has temporal costs and material roots, yet when we consume electricity, we often see neither. The labor the biosphere has invested into the slow production of hydrocarbon-based energy and slow formation of the underground minerals is often hard to miss due to its existence on a vastly different temporal range than human experience. The minerals (i.e., lithium, cobalt, neodymium, etc.) used in our electronics can take millions of years to form. This is no different for the hydrocarbons, the oil and coal, being extracted and burned to harness the energy powering many modern digital devices. The immediate spontaneous release of energy and the immediate acquisition of materials extracted from nature gives off the illusion of cheap resources. In a capitalist sense, these resources are cheap. Humans can easily extract them from the Earth and profit off their abundance for a low immediate cost; yet this cost is anything but low. The millions of years of compound pressure that form the Earth's minerals have a heavy temporally price tag and if exhausted, they would be impossible to renew within any conceivable generational human timescale. Temporality is therefore infused within the materiality of our electronic devices, which themselves run on a computational clock cycle far beyond human temporalities. We have been promised and come to expect the computational abundance of our devices, just as we have come to expect the abundance of our energy systems so often fueled by deep-time extractive hydrocarbon temporaries. Artistic creation provides a useful window into how these temporal boundaries can be disrupted.

Figure 6: The YoHa art project's *Coal-fired computers* (2010).

The YoHa art project's *Coal-fired computers* (2010) is one such installation that visually displays the energy requirements of modern computing through the live burning of coal. Not only does the work visualize the materiality of the energy consumed by computing devices, but it also displays the material effect on living bodies mapped through a database record of miners' lung disease. "Data demands [extractive] ecologies, one that is not merely a metaphorical techno-ecology but demonstrates dependence on the climate, the ground, and the energies circulating in the environment" (Parikka, 2015). The experiential potential of temporal aesthetics in research-creation and interdisciplinary art allows us to form new, direct experiences of macroscopic global climate phenomena may be read but rarely seen in its complex web of temporal relations. To examine other-than-human temporalities through the temporal aesthetic medium of MFCs, Gardening the Cybernetic Meadow turns to the temporal and relational potential of gardening to enable the "embodied experience of time [through the act of] making time for soils" (Puig de la Bellacasa, 2017 p.200).

Figure 7: An early research prototype as part of a workshop facilitated for the Digital Ecologies 2022 conference series at the University of Bonn, GE. Photo by Karolina Uskakovych (2022).

2.6. Gardening: Care and Maintenance

Contrasting with the environmentally destructive extraction methods used in many energy technologies, MFCs have the potential to work together in a garden-like configuration, acting as foil to eco-destructive practices and instead replanting and reseeding soil. The notion of gardening implies a sense of continuity; to thrive and provide continuous harvest, gardens need ongoing care, maintenance, and patience (Mattern, 2018). By forming a symbiotic relationship with the garden one must listen to its needs, not solely ask of it. When one truly listens to what it is asking of you, one can start to better understand the embodied, aesthetic qualities of the relationship which may lead to two realizations. Firstly, maintenance necessitates the consideration of relation, the garden as a system - soil, sun, water, microbes, insects, etc. Maintaining a garden involves "drawing connections among different disciplines, [it] is an act of repair or, simply, of taking care — connecting threads, mending holes, amplifying quiet voices" (Gabrys, 2018). The second is that individuals must learn to listen and engage in a "more expansive"environmental politics that account for relations, and that tune in to the world-making projects of other organisms" (Haraway, 2016). Within spaces of eco-collaboration, it is hard to ignore the collective responsibilities and difficult to know where relations start and the individual ends.

A garden symbolizes the connection between humans and other-than-human organisms, requiring symbiosis to flourish; it is a space of "making-together" (Dempster, 1998; Haraway, 2016). In *Gardening the Cybernetic Meadow*, the garden takes on a hybrid form, which I term an energy garden. When we care for the garden, we receive energy. This garden must exist in a post-extractivist world, as excessive extraction (e.g., ionic extraction) could cause the microbes to die. We cannot exploit or displace them; instead, we must listen and adjust our energy needs to theirs, resulting in a slower pace of energy consumption. Naturally, this concept applies to all forms of gardening, which require gardeners to adapt their sense of time to the natural cycles governing growth and harvest. Laurie Cluitmans, discussing the relationship between art, gardening, and botany, describes this as a shift from "calendar time" to "circular time" (Cluitmans, et al., 2021). *Gardening the Cybernetic Meadow* aims to instill this sense of kin-based, meditative circularity by allowing users to experience the "slow" gardening of a novella. As a research-creation project disseminating knowledge in the hybrid form of experiential knowledge and written thesis, the notion of writing's ability to translate knowledge is a pivotal point of the work. Throughout this work I will never argue against writing as an important tool, nor do most scholars working within research-creation (Loveless, 2018). It is important, however, to examine why alternative modes of knowledge dissemination may occasionally offer greater accessibility and deeper understanding. In addition to my arguments of the importance of experience, I believe some barriers are in part due to the temporality associated with writing.

Anne Carson, author of *Eros the Bittersweet* (1998), poetically weaves together the relation between temporality, writing, knowledge, and gardening by contrasting Plato's discourse on writing (De Vries, 1969) and the gardens of Adonis – an Athenian festival observed by growing seed of wheat, barley, and fennel, unseasonably fast during the festival's eight days. The crops grown during this festival were subjected to unnatural growing conditions within broken, shallow terracotta pots, resulting in a rapid blooming followed by an immediate withering of the plants. While seemingly trivial, the festival pays homage to Adonis' untimely death at the hands of Aphrodite. Referencing Plato's account of a dialogue between Socrates' and Phaedrus, Carson writes:

> No gardener serious about growing plants would indulge In the hasty, cosmetic agriculture of the gardens of Adonis, Sokrates and Phaedrus proceed to agree. By the same token, no thinker serious about communicating thoughts would choose to "sow them in ink with a reed pen". Gardens of letters, like gardens of Adonis, are sown for fun. Serious thoughts need different cultivation and time to grow.
>
> …

> The gardens draw our attention… to the factor of time that is at the core of Plato's worry about reading and writing. Written texts make available the notion that one knows what one has merely read. For Plato this notion is a dangerous delusion; he believes the reach for knowledge to be a process that is necessarily lived out in space and time. Attempts to shortcut the process, or package it for convenient reuse, as in the form of a written treatise, are a denial of our commitment to time and cannot be taken seriously (Carson, 1998 p.187-188).

Gardening the Cybernetic Meadow reincorporates writing within its temporal aesthetics to create a link between experiences in time and space, and the slow process of gardening as a method to generate a deeper understanding of texts. By creating spatiotemporal conditions that require the audience to return to the work, day after day. It facilitates a slow reading of the text that allows new interpretations and a nurturing of ideas that may otherwise be quickly extracted and left to wither like the plants in the gardens of Adonis. This provides a temporally aesthetic meditation on our ecosophic relation to technology, energy, and the environment through MFC gardening. The temporal aesthetics of gardens may even hold the potential to shift "trajectories of productive futurity in technoscience" (Puig de la Bellacasa, 2017, 200) towards a slower, regenerative, and ecosophic future technological imaginaries. Imaginaries that understand how the social design of technologies feedback into environmental systems (Escobar, 2016; Bateson, 1974), how adjusting our embodied understanding of energy and technology temporalities (e.g., slowing expectations and designing for more-than-human's ecologies). Bridging this theoretical framework to Maria Puig de la Bellacasa's optimistic speculation on "the embedded [slow] temporality of [gardening]" (Puig de la Bellacasa, p. 200), *Gardening the Cybernetic Meadow*'s framework aligns with the desire she quotes as, "to work with the soil, the water, and plants, learning about more than human working patterns and how to foster abundance, envisioning that we might actually change something, one garden at a time" (Ibid, p. 158).

3. MFCS: TECHNICAL OUTLINE

Gardening the Cybernetic Meadow's use of microbial fuel cells serves both practice and theory by acting in part as a guide to fabricating sustainable energy harvesting technology, and in part forming an installation work that acts as a mirror to reflect the complex relationships between humans, our technologies, and the natural environments we are inseparable from. To gain a comprehensive understanding of the interdisciplinary role MFCs play within the context of this project, this section investigates MFC literature within both scientific and artistic realms. This exploration includes the technical foundations, subsets of MFCs and their relevance to the project, key researchers, and interdisciplinary artists working with MFCs.

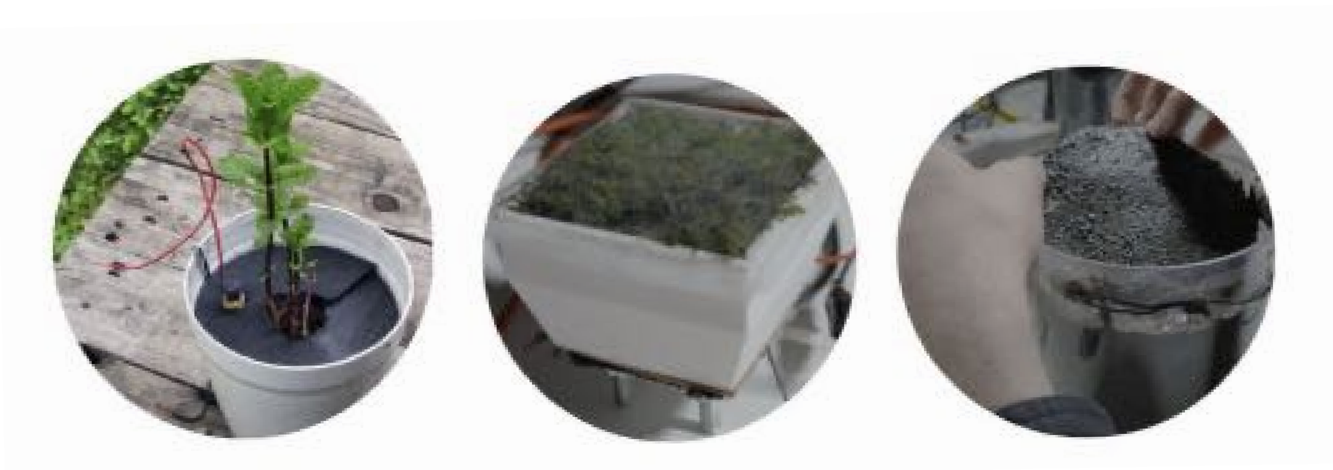

Figure 8: Varying types of MFCs: a P-MFC (left), a Bryo-MFC (center), and an Anaerobic MFC (right). Photos by Johann Duraffourg (left, 2017) and Guillaume Pascale (center & right, 2022).

3.1. Microbial Fuel Cells

MFCs are bio-electrochemical energy technologies, meaning they can convert the chemical energy of organic waste. This conversion specifically harnesses the metabolic by-products of microorganisms living in various soils to generate electricity (Yang, et al., 2012; Bombelli, 2016). Due to the layout of MFCs, they can relocate these metabolic by-products, which in simple terms are soil-bound ions, through their electrodes, into a specialized circuit. The circuit of the MFCs is primarily a power management circuit (PMC), which allows the MFCs to store and use the ionic metabolic energy on timescales in line with the microbes' natural processes, rather than forcing standard energy generation temporalities on them–- which if done would irreversibly harm the microbes. MFCs act as a counter to the current dominant modes of extractive energy production and are uniquely situated within ecological zones such as soils, where most sustainable technologies are removed from their material origins in nature (Laubichler, 2019). These natural origins are critical to understanding how our technologies and energy use affects climate change. Technology and ecology are often not considered as integrated practices and not often socially mobilized together, yet this is critical to how we engage with the climate crisis (Ng, 2022).

While reviewing the literature around MFCs, I came across four common variants used within research projects, anaerobic MFCs using swamp or bog mud as a medium; Bryo-MFCs using bryophytes (mosses) grown within special electrode "pulp" (Bombelli, 2016); Plant MFCs (P-MFCs), which use the soil surrounding plant roots as a medium through custom planters built with embedded electrodes (Rajeev, et. al., 2017; Cooke, et al., 2010); and wastewater MFCs, which reclaim waste by-products (i.e. urban sewage or certain composts) for use as an ionic medium (Munoz-Cupa, Hu, et al., 2021). Wastewater MFCs add an extra theoretical layer to the use of MFCs within artworks and scientific research. They have a unique ability to remediate the medium used within the MFC, ones that are used in urban wastewater filtration centers offer not only energy, but remediated matter and filtered water (Li, et al., 2013). During my preliminary research on MFCs, I designed and tested several prototypes for anaerobic, Bryo-, and P-MFCs, but unfortunately wastewater MFCs were excluded as working with them would entail the addition of very different critical making methodologies, therefore this review will exclude the MFC categories using wastewater as a medium.

To gauge the feasibility of using various MFCs within an artistic installation formed through research-creation, the basic technical layout of these MFCs had to be reviewed. Each type has variations in form but follows similar mechanics. The ionic energy gathered by MFCs requires two electrodes, an anode (positive) and a cathode (negative), akin to any battery using a chemical medium (Logan, 2007). Figure 9 shows how these two electrodes cycle ions between them and produce a basic circuit with electrical potential. In each type of MFC researched, one electrode must always be exposed to the atmosphere. This exposure facilitates a reaction between hydrogen ions in the soil-medium, and oxygen from the atmosphere to form water (Costilla-

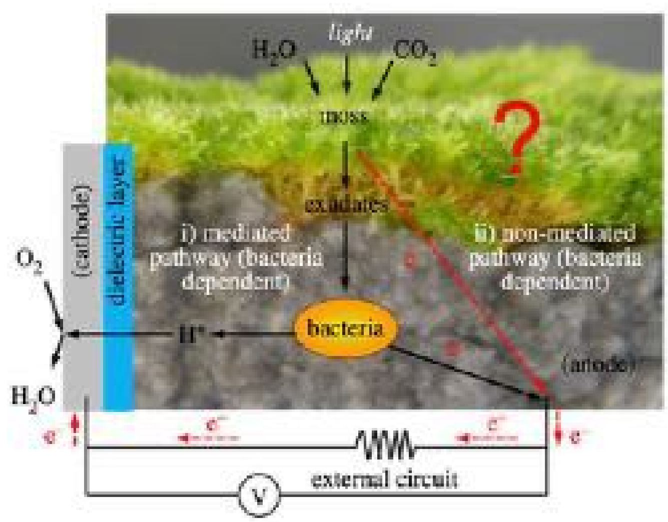

Figure 9: Technical diagram for the microbial energy generation of a Bryophyte MFC. Illustration by Bombelli, 2016.

Reyes, Erbay, et al., 2018). When the water forms, the free electron carried by the hydrogen ion is lost and gets absorbed by the MFC's circuit to be stored and used with other electrons collected to create an electric potential. The electrodes are traditionally made up of activated carbon in the form of paper, felt, or pulp for three reasons. One, activated carbon has the potential to be arranged in a way that conducts electricity (Logan, 2007); two, carbon is non-toxic for organic life, meaning microbes can comfortably live on carbon scaffolds; and three, most these forms of carbon have a high degree of microscopic porosity, and subsequently a large surface area for microbial biofilm growth, and for the surface uptake of ions on the carbon (Santoro, Guilizzoni, Correa, al. 2014), which can be seen in Figure 10.

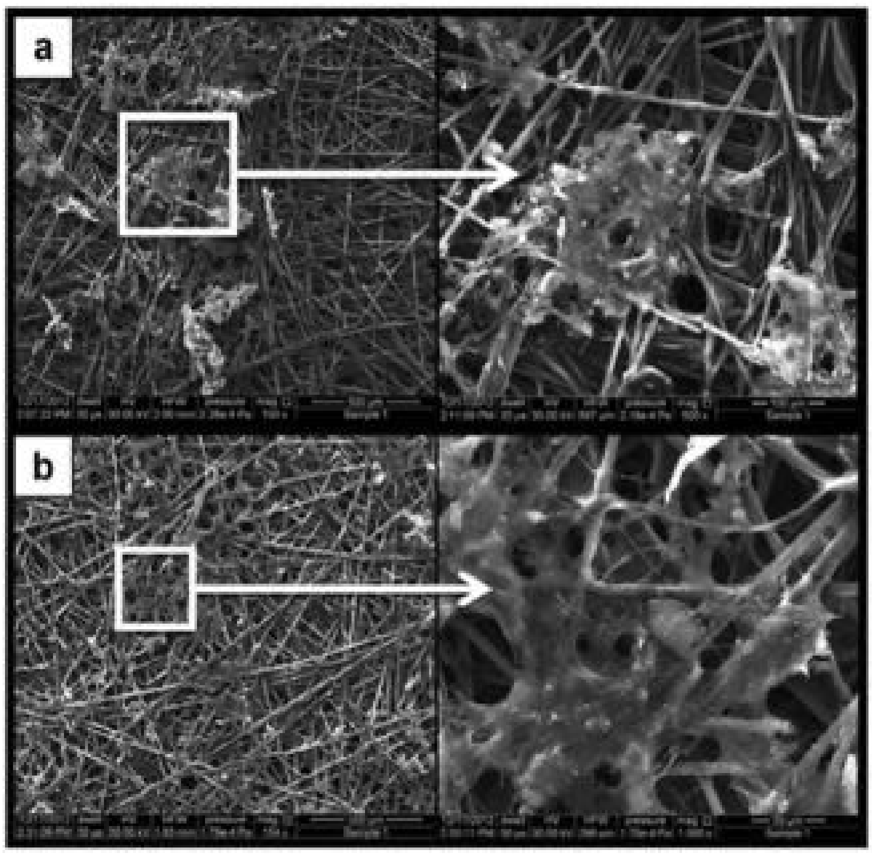

Figure 10: Porous carbon electrodes after biofilm growth. Photo © C. Santoro, et al, 2014.

Lab-grade versions of these carbon materials are often coated in a thin layer of platinum, which enzymatically increases the uptake and electric potential of the carbon (Dumitru & Scott, 2016). The downside to this is most of the sources for carbon electrodes are likely only open to institutional labs, or if not, are quite expensive for the average maker. While my first previous MFC prototypes used these electrodes to eliminate as many variables as possible that may complicate the learning process, this thesis project directs its research towards more inexpensive, materially accessible, and DIY ("do-it-yourself") electrode fabrication methods which will inform the project and additionally appear in the open-access MFC fabrication guide. In reference to the mode of energy generation these electrodes facilitate, the term energy harvesting will be used throughout (Costilla-Reyes, Erbay, et al., 2018). Energy harvesting is an emerging mode of sustainable energy generation that captures (or recaptures) energy from ambient environments (Khan, Rajkumar, et al., 2018). MFCs are not the only energy harvesting technologies, some capture kinetic energy, some thermal energy, and some residual energy form radio frequencies (Forestiere, 2013). Though each shares the same energy harvesting principles, there are several types of MFCs that were considered for this project.

3.2. MFC Form and Variations

Anaerobic MFCs

MFCs utilizing anaerobic mud were explored first due to their relatively high energy output compared to other types. This output is not only higher, but more immediate due to an abundance of metabolic by-products within the mud produced by methanogens, and compressed over time through the slow landscape transitions that occur within wetland (Wetser, 2016; Logan, 2007). The compression that creates the dense ionic mud, highlights how the natural processes of systems can be perceived as subjectively "slow", while having drastic impacts on life, the environment, and energy conversion within ecosystems. Both Bryo- and P-MFCs lack the same forms of natural energy storage found in these muds and must convert their energy in "real-time" (Wetser, 2016; Yang, et al., 2012).

Figure 11: An early anaerobic MFC prototype measuring the real-time energy output of its component's energy harvesting processes. Photo by the author (2021).

Anaerobic mud can be found in a variety of ecosystems, especially swamps, marshes, and bogs. It can form in any area matching conditions like wetlands and is the product of decaying organic debris (i.e. plants, insects, and animals) that forms an air-tight seal (Kimmerer, 2021). The seal creates anaerobic conditions in the mud below where colonies of anaerobic microbes metabolize the organic matter, but due it being a hostile environment for many species, these by-products do not get quickly recycled into the ecosystem (Schievano, et al., 2017). The mud can be mixed with adjacent water from the environment, or even wastewater, to dilute to the correct consistency to create an anaerobic MFC (Superaccu OÜ, 2016). The water content of the mud is important because without sufficient water to create a medium that equally touches both electrodes, there is no route between them for the ions to travel. Yet, despite their higher energy potential, these MFCs pose a few challenges towards their use in a public installation. One such issue is their continued production of a foul smell due to the metabolic by-products of methanogens and another is the difficulty in reproducing their environment in an indoor space due to its expansivity, biodiversity, and their need for an abundance of water. To keep the MFC alive, this environment needs to be replicated for indoor use and for the purposes of this project, is essentially a mesocosm (Odum, 1984). A mesocosm is a replicated environment (usually outdoors but not exclusively) that allows the growth of an organism under controlled conditions, usually for scientific study but in this case, it would be borrowed as an interdisciplinary tool for an installation akin to eco- or bioarts. The mesocosm requirements for anaerobic MFCs are not practical and produce what may generally be described as an unpleasant environment.

Figure 12: Early anaerobic MFC at Hors Piste, Le Centre Pompidou (2021). Photo by: Guillaume Pascale

Bryo-MFCs

Since the mesocosm requirements for anaerobic MFCs are impractical, Bryo-MFCs offer a promising alternative due to the general resilience of moss (Kimmerer, 2019), adaptability, and much smaller mesocosm requirements. Bryo-MFCs are not limited to a specific species of Bryophytes (Hubenova &

Mitov, 2011) but due to the wide range of habitats moss takes on, it is not only easier to gather soil-adjacent moss in opposition to rock-adjacent moss. It is also easier to both reproduce their environment as a mesocosm and less of an impact to harvest as rock-adjacent moss can (in more extreme cases) take hundreds of years to grow (Kimmerer, 2019). Working with Bryo-MFCs would be advantageous for those reasons and advantageous over a P-MFC due to my previous research into building open-source, 3D printed MFC casings for moss. The first successful MFC design I developed in a past project (Halpenny, 2021) was based on an exceptional deviation from the MFC research I had become accustomed to, an interdisciplinary art-science work titled *Moss FM* (see Figure 10). The work was produced by a group named the Materiality Research Group in 2014, coordinated by MFC researcher, Dr. Bombelli, and the artist Fabienne Felder. Their research culminated in the artwork *Moss FM* and a research paper on the process of creating their Bryo-MFCs (Bombelli, 2016). The paper followed a familiar format to other MFC papers I reviewed but one aspect of the publication that strongly influenced the direction taken in this thesis project, was their inclusion of an appended document that detailed the fabrication process of their cells through written steps, sketches, images, and all while using common and accessible carbon materials. If I had to propose one interdisciplinary research-creation project that is most aligned with the feasibility and goals of my proposed project, it would be this work.

Figure 13: Moss FM by Materiality Research Group (2014).

The literature review done towards Bryo-MFCs is extremely useful in terms of interdisciplinary research-creation and practical MFC fabrication steps, but with all research and personal experience considered I believe mosses make it is more difficult to create a mesocosm–- and subsequently care for–- over P-MFCs due to availability of equipment required for the atmospheric conditions of the mesocosm. While Bryo-MFCs take very little space themselves, they require a relatively moist atmosphere due to their natural habitat commonly being found in the boundary layer, an atmospheric “still-zone” close to the soil (Luther, 2016). To recreate boundary layer conditions, one requires a humidifier and atmosphere-tight growing room or container. This increases the size of the mesocosm needed for the installation, requires a closed area, and due to that result in an installation that was less welcoming to audience engagement.

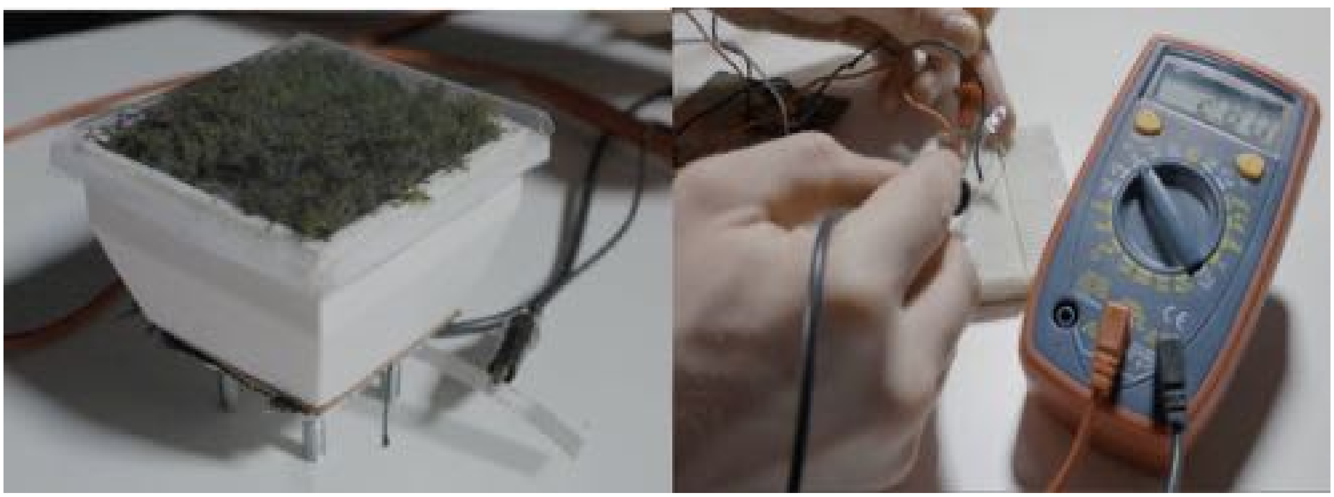

Figure 14: An early moss-based microbial fuel cell prototype for Le Centre Pompidou (2021). Photo by Guillaume Pascale.

P-MFCs

Mosses are certainly not alone in their ability to regeneratively produce ionic energy through symbiotic microbial interactions. Researchers studying MFCs tend to select variants that align with goals outside of the MFC itself. Through my review of P-MFC literature I noticed a trend where research questions stopped asking ‘how can we make MFCs efficient’ and started asking ‘how can MFCs best fit into our research goals’. By this I’m referring to the fact that many of the P-MFC research papers I encountered were less centered on electrical engineering or biotechnology (even if published through these disciplines) and more on practices within environmental science such as remote sensing and monitoring ecosystem (Rajeev, et. al., 2017; Rossi, et al., 2017; Pietrelli, et al., 2014). To do this, researchers try to produce P-MFCs out of soils and plant species that occur naturally in the area of interest, resulting in P-MFCs on shorelines, floating on bodies of water, and even in backyard gardens (Schievano, et al., 2017; Cooke, et al., 2010). A creative use of the P-MFC’s versatility in bodies of water can be seen in Rasa Smite & Raitis Smits’

MFC-based artwork, Pond Radio (2014). The floating MFCs monitor their own energy output, translate it into a composition that can be heard remotely (see Figure 15).

Figure 15: Pond Radio by Rasa Smite & Raitis Smits (2014).

Remote sensor P-MFC research allows the P-MFCs to act as slow "batteries" that power remote sensor networks (Rajeev, et. al., 2017). A large portion of the P-MFC research projects I found were based in remote areas, but I was able to find a handful of planter-based P-MFCs (Rossi, et al., 2017; Cooke, et al., 2010). Since my installation creates an indoor MFC garden, there the research was modeled after these P-MFCs. P-MFCs offer their own challenges but also offer a higher degree of resilience to new environments, meaning placing a series of them indoors with an audience was more feasible than other types of MFCs.

3.3. Power Management Circuits (PMCs)

Microbial fuel cells fall under the category of ultra-low energy harvesting, a relatively new field of research. The field centers on devices that can power themselves at energy levels as low as 20mv. Most modern electronics require at least 3300mv at a specific amperage to maintain power. To work with such low energy levels the components had to themselves run on low energy, meaning up until recently the creation of a circuit sensitive enough to harvest low energy sources was impossible. To harvest microbial energy several components are required: a 1:100 transformer, a DC/DC step up converter, an array of capacitors, and a supercapacitor, all of which must be ultra-low energy models. The aspect of MFC research that was perhaps the least accessible to research was the PMC. This in part was to do with a lack of community-centric, open, or pre-packaged tool for the electronics required. Though even if this were the case, the few partial schematics, or references to parts I found often cited parts that were no longer in production as it seems there was a fair portion of PMC research predating 2014. It's a difficult task to keep electronics open-source or DIY friendly over time due to the frequency of discontinued parts, even one can through an open schematic into impossible territory. Maker brands like Arduino are in part beloved for just how little they change their hardware, and when they do backwards compatibility is a priority.

The fabrication research for the other components within MFCs proved challenging to find anything useful for non-engineers, but when enough research was conducted, it at least provided a direction that could be tested with more "entry-level" tools such as a 3D printer or basic CNC machined parts. The PMC requires a higher degree of electrical engineering experience as the parts used are classified as "ultra-low power", a niche subcategory of electronics where little community support exists and any support that is available tends to be for industrial applications and comes with a hefty fee. The PMC fabrication within research papers also tended to be even more cloistered than any other category. The majority of research within my MFC literature review failed to identify the electronic components. Rather, the outcomes related to energy generation often appeared as quantitative data (e.g., PMC yields and efficiency comparisons) without an inclusion of the design process. When names for the included electronic parts did appear, they were often discontinued due to either being experimental parts or low demand within an early, niche market exploring ultra-low energy harvesting (Cooke, et al., 2010; Li, et al., 2013; Santoro, et al., 2014). Fortunately, my literature review did turn up a single PMC development board with an accessible price point for hobbyist and individual use applications, the LTC3108-1 "Ultralow Voltage Step-Up Converter and Power Manager" by Linear Technologies.

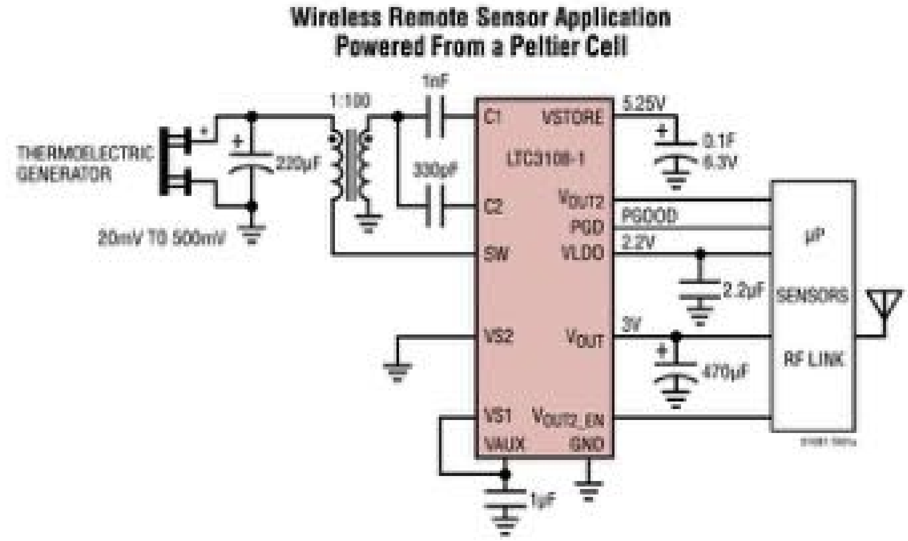

Figure 16: LTC3108-1 schematics, © Linear Technology Corporation (2010).

The LTC3108-1 is a development board, a term which often denotes a ready to use circuit for testing certain applications. In this case that was for energy harvesting–- not one that was MFC specific, but it tolerates the same voltage and current range. The affordable price point comes with the cost of having to source and solder some of the parts on yourself and the board has a datasheet to aid this process, but without some electrical engineering experience the jargon, and discipline specific symbols makes it very difficult.

The PMC was perhaps the largest technical challenge of this thesis project, yet my research-creation on the subject has allowed me to create basic, working PMC prototypes that can be seen later in Section 4.3. as part of the installation component. Outside the installation, instructions for fabricating a replicant PMC are more difficult than the Open Source MFCs and could benefit from further research and literature review from another researcher more experienced with electrical engineering than myself. Regardless, the working configuration I used for the LTC3108-1 is included later in this thesis as a modified version of the Linear Technology's schematic used in Figure 16. I avoid detailing the fabrication here as it has more proximity to the critical making process than the technical outline of MFCs.

Nevertheless, the literature review and research I conducted towards PMCs provided ample data on the energy one can gather from MFCs (Song, Boghani, et al., 2017; Yang, et al., 2012). Despite the PMC, the energy from MFCs will always only be a fraction of what is expected to be the status quo for current, small digital devices. Typically, these small devices, or microelectronics, require power within a standard input range of 3.3V, 5V, or occasionally 12V. According to many MFC researchers (Bombelli, 2016; Yang, 2020; Logan, 2016), the average non-aerobic MFC typically produces around 300mV and 2mA in a lab setting, nearly ten times less energy than what we may expect on the low end of the aforementioned range for digital electronics, 3.3V. If one is to replicate these tests outside a specialized lab, you would likely get similar results to what I received with my early PMC prototypes (Figure 17) - around 100mV and 1mA.

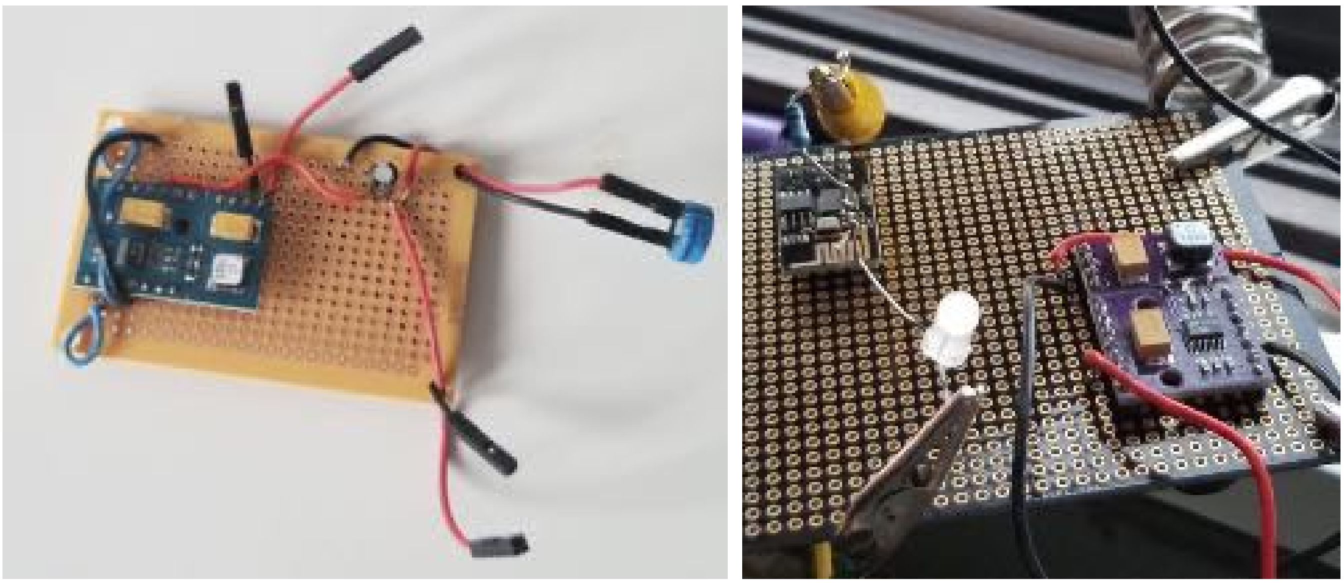

Figure 17: Early prototype PMC using the LTC3108-1 (left) and a real-time [thermoelectric] energy harvesting experiment with the same PMC (right). Photos by the author (2022).

Adjusting Temporal Expectations: Bursts

Collecting ions at ultra-low power (less than 100mV) is a difficult challenge for many reasons, one of which is due to a requirement of the PMC (which collects the ions), which needs to power itself on a fraction of that minute ionic energy coming in. To successfully harvest residual metabolic ions, several components are required. The PMC needs a 1:100 transformer, a DC/DC step up converter, an array of capacitors, and one or more supercapacitors to fit the energy needs of the burst. The core function of the PMC is to use these components to get the initial energy input (as low as 20mV) up to 3.3V for storage in the supercapacitor (Song, Boghani, et al., 2017; Yang, et al., 2012). Since we cannot collect more energy than is given by the MFC, which is far below 3.3V, the PMC solves this ‘slow’ energy problem using a simple fix, patience and time. The PMC slowly accumulates energy in its storage supercapacitor and instead of aiming to compete with the needs of the digital electronics status quo, it times the energy output to be in short, timed “bursts” as can be seen in Figure 18 (Yang, et al., 2012; Rossi, Tosato, et al., 2017).

While one cannot power the microcontroller continually - as one may if it were plugged into the wall - the PMC allows the MFCs to power devices with just the right amount of energy to complete the task. Many biologists and environmental scientists use this technique (and even MFCs) to power remote sensing devices to gather environmental data (Wetser, 2016; Schievano, et al., 2017; Gabrys, 2016). These researchers not only use this method because it eliminates the need to ever replace or charge the battery, but it allows them to monitor the ecosystem without ever having to go back and disturb the organisms living around it.

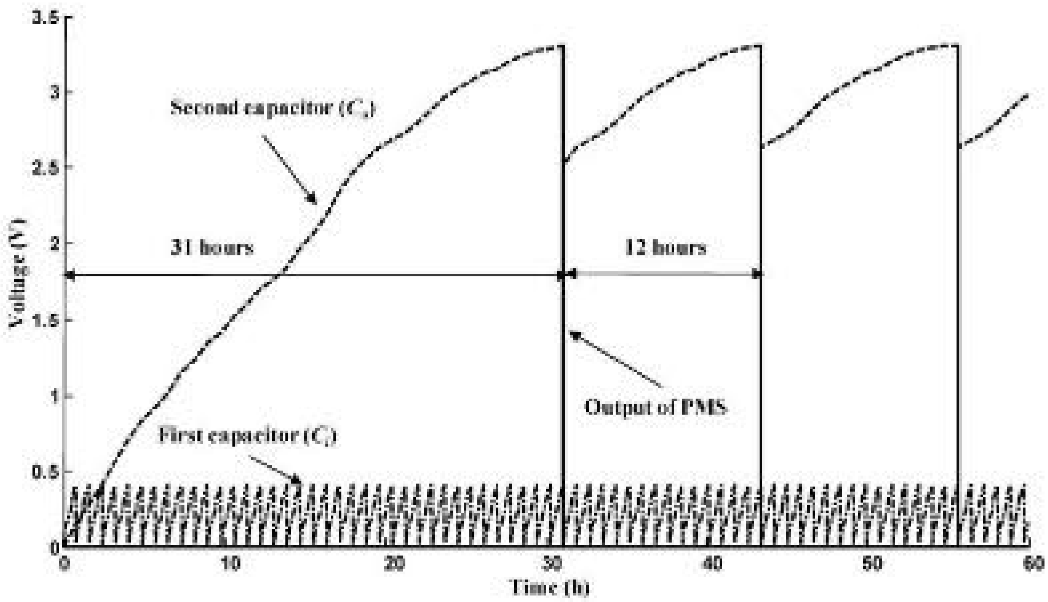

Figure 18: Temporal requirements for the energy “bursts” required to send a radio signal by an MFC powered PMC. (Yang, et al., 2014)

4. OUTCOMES & DISCUSSION

The methodology employed within *Gardening the Cybernetic Meadow* is a culmination of the Theoretical Framework & Methodology section, specifically utilizing critical engineering as a means of creation with an outcome as an installation artwork. The Open-Source MFC Creation Guide acts as a detailed account of this research-creation process, a brief of which can be found below (Section 4.1). The entire guide is listed in the Appendix.

The MFC Creation Guide's documentation and explanation of my MFC research-creation process documents up until the final phase research-creation phase, the production of the installation work, *The Cybernetic Meadow*. By this phase most of the knowledge produced around the research though creation of MFCs has reached a point where designs cease being prototypes, they instead become the work itself. This section, Outcomes is thus split into three subcategories on, 1) the open-source MFC creation guide; 2) the conceptual formation of the installation work–- informed by the theoretical research and research-creation thus far – and the exhibition design for the artwork, which examines the spatial and temporal requirements needed to align the artwork with the theoretical framework and axiology; 3) the final creation process leading to the formation.

The research-creation process on MFCs was done in tandem with the critical making of embedded hardware, algorithms for generative text, solar energy harvesting, and networked electronics (e.g., servers, databases, and microcontrollers). These components are auxiliary to the MFC research and specific to the final installation work (Section 4.2) and were selected as the media components of the installation due to their ability to reflect the theoretical framework through their form. As the installation component disseminates this research through experience and a combination of relational and temporal aesthetics, Section 4.2 will largely discuss the poetics of space involved in arranging the installation, thematic statements, and its methods of public engagement. While 4.2 details the theoretical framework that constitutes the experiential side of the artistic manifestation, Section 4.3 discloses the final creation process of the artwork while focusing on the interplay between creative methodologies and material form. Therefore, each of the following subsections will act as both process documentation for the outcomes, as well as a curated discussion on how each outcome and process was formed and informed by the theoretical framework and methodologies they correspond to.

4.1. Open-Source MFC Creation Guide

The MFC creation guide divides the fabrication of MFCs into several categories, cell bodies, electrodes, and electronics. Each of the categories provides a multi-faceted approach to creation that explores material and equipment accessibility. Not all readers will have access to equipment such as 3D printers, which is covered in the guide as a means to fabricate cell bodies, optionally through the included open-source 3D files produced as part of this research-creation. If the reader does not have access to this equipment through an institution or library, the guide details other equipment-free means of making cell bodies. In the same vein, if a material is inaccessible to the reader, such as lab-grade electrodes, the guide explores methods for their creation with common materials such as activated charcoal. Paired with the MFC Creation Guide is a set of Open-Source 3D files that anyone can print if they have access to a 3D printer. The files are hosted on the same website as the guide; therefore, they can be found under the same link in the Appendix. They are released under a Creative Commons (4.0 International License) with the attribution of Non-Commercial.

Figure 19: Front cover for the Open-Source MFC Creation Guide. Design by the author (2022).

Open-Source MFC Design

The open-source MFC design files are the products of the Critical Making methodologies outlined, leading to a series of iterative prototypes that may be documented and shared. Each iteration revealed unanticipated results to be further research and resolved in the next iteration of experimental prototyping. These unintended consequences occasionally led to "failed" design components that could not be used within MFCs (e.g., the chemical leeching of metal bolts into electrode fabric) but as outcomes of a critical making process, they are valuable research insights. The critical making of each iterative prototype revealed new insights that were not found within the scientific literature review on MFCs. Several types of MFCs were explored within the guide, including the anaerobic and Bryo-MFC types listed in Section 3. The materials used for the varying explorations of each MFC component are listed within the guide but will additionally be listed in Section 4.3 where overlaps exist between the MFC variations used in the development of the installation artwork. The tangible process of making allowed for new insights on the materials involved, producing tacit knowledge through the embodied process of experiencing how they lend themselves to various MFC applications. More importantly, the making process provided a much deeper sense of how each material and each component relates to the whole. As I was conducting research-creation on MFCs with limited access to literature revealing their fabrication process, each component was a stand-alone research challenge. Developing an embodied sense of the relations existing between components was a vital step towards a understanding how to begin prototyping the whole (i.e., a working MFC prototype). The outcomes of this critical making through research-creation not only led to the MFC fabrication guide but a series of iterative MFC prototypes. The “final”, or more appropriately the most recent, iteration within the MFC prototype series became the open-source MFC design distributed alongside the guide.

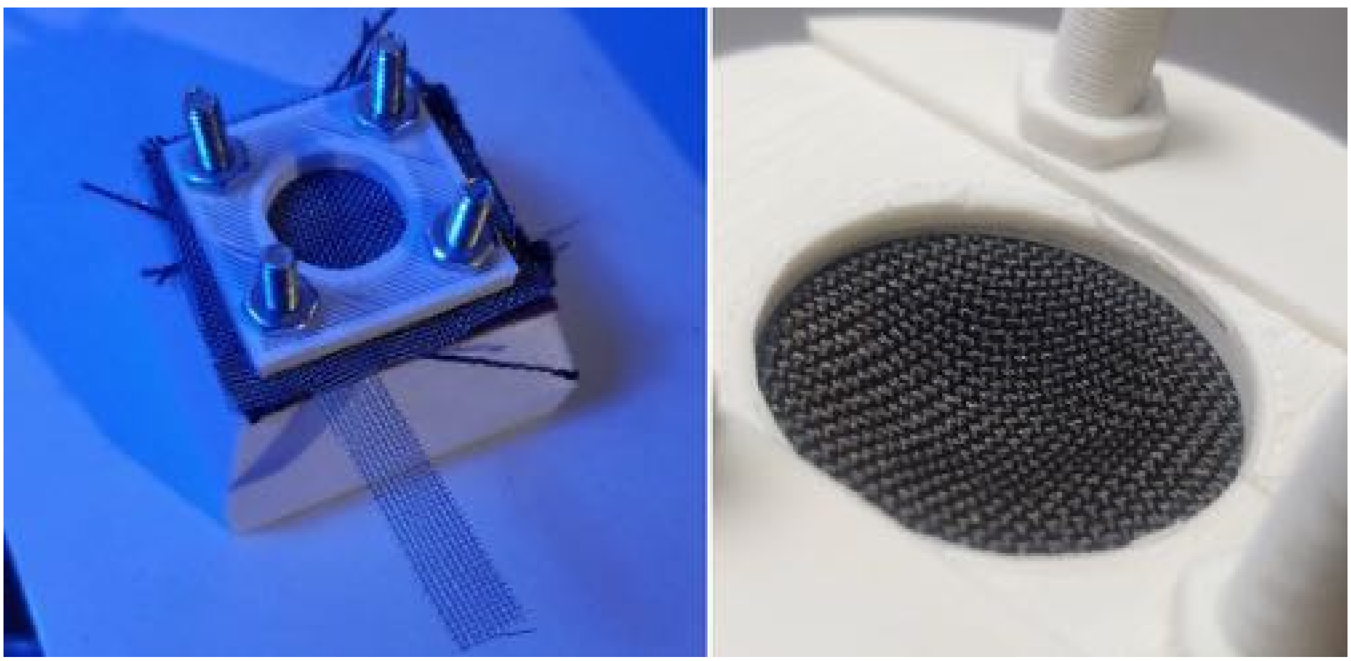

Figure 20: Iterative MFC prototypes – one utilizing metal components (left) and a later version replacing them by 3D printed plastic ones (right). Photos by the author (2022).

I avoid using the word “final” for this MFC design due to its open-source status, the very nature of which encourages modification and further iteration outside of my future plans for the design, it's 3D fabrication file now belongs to the digital commons. The open-source design appears within several figures and the installation component, but they appear in their closed form. It was designed to be modular, existing as five distinct components that can be modified or printed – an upper cell body that holds the microbial medium, a lower cell body for fastening electrodes, a slider for moisture retention over the exposed electrode, custom fitting screws and nuts, and a removable lid to secure the medium while providing light (if it's a Bryo-MFC or P-MFC). These components can be printed together or modified individually to fit specific use cases rather than remodelling the entire fuel cell. The lid screws onto the upper body and the other components are secured by the screws. Outside of these five components the MFC requires two electrodes and a gasket, which are not included as the materials they use are not currently 3D printable. To visually understand how they fit together, a technical illustration of the design can be found below in Figure 21.

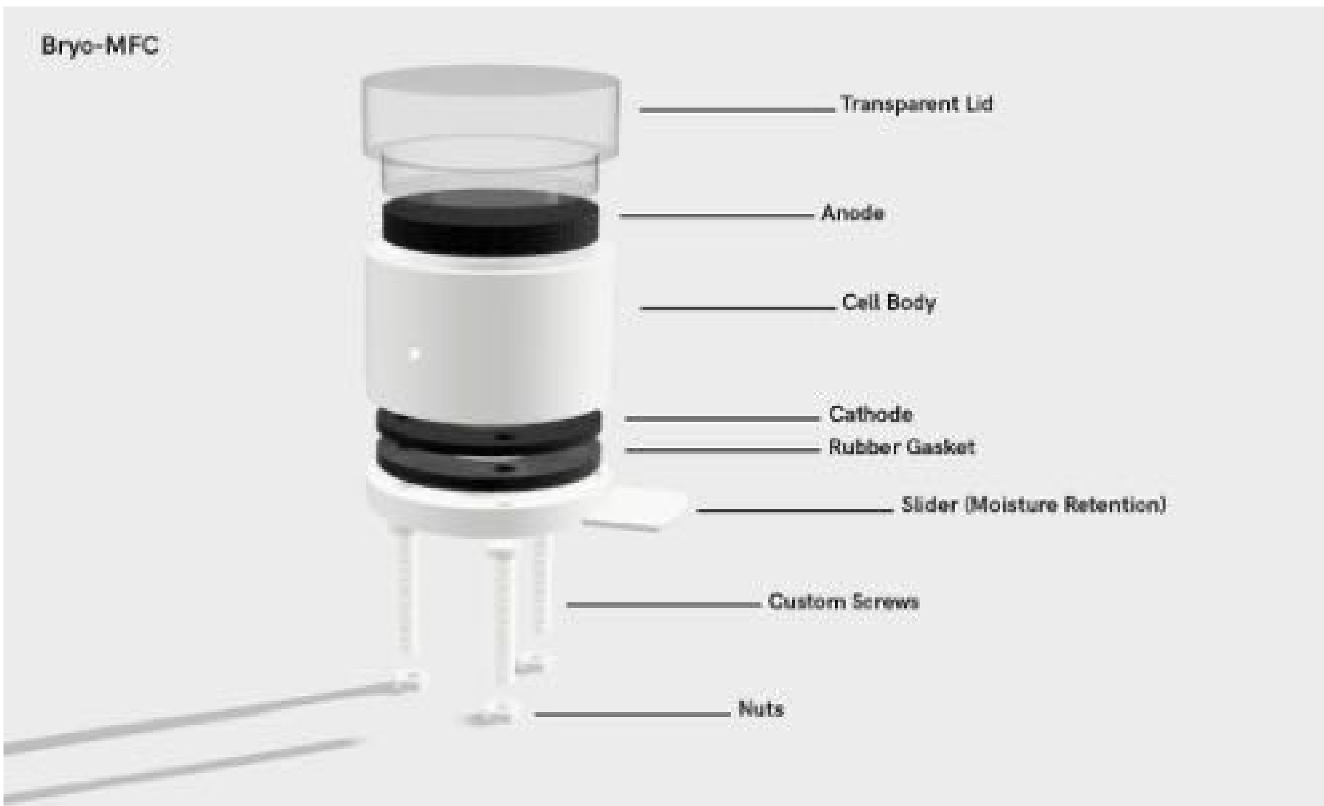

Figure 21: The design outcome of my research towards an open-source MFC. Technical illustration by the author (2022).

Screws and the associated holes were a design choice over each component having their own grooves and threading due to a critical MFC functionality factor revealed during their critical making. In Bryo-MFCs or P-MFCs the exposed electrode relies on atmospheric oxygen to produce energy. If the microbial medium is exposed to air that bypasses the carbon cloth electrode (expanded on within the guide), no current will run through the circuit. The process must occur through the cloth as it hosts a portion of the microbes, the MFC's source of energy. The ions they produce are collected by the electrode housing them, flowing into the PMC. Since the potential current of the produced energy is so faint, the process could not exist without the microbes' physical presence on the electrode. Even when considering these factors, early MFC iterations had a power output too weak to activate the PMC. The screws were added to allow the electrode to sit between the top and bottom cell bodies. By situating it between them and adding in a rubber gasket (expanded on in the guide), the screws allow the gap between the two cell bodies to be tightened, ensuring airflow is directed through the MFC opening and by the electrode. This design eliminates oxygen leaking past the electrode and increases the overall power output of the MFC. This design was inspired by specific lab-grade wastewater MFCs and Bryo-MFCs I encountered in my literature review (Jannelli, et al., 2018; Bombelli, et al. 2016), though I read about the disruptive effects of leaking oxygen in papers exploring various MFC types. The revision addressing this leak through screws and a gasket is just one example of many revisions throughout the iterative prototypes. Regardless, this revision is a great illustration of how critical making and research-creation may generate a deep understanding of operations, relations, and design.

Figure 22: *slow.technology*, the website hosting the OS MFC files and the MFC Fabrication Guide on the solar server. Website design by the author (2023), background graphic by Jun Lin (2022, used with permission).

Further information on the research-creation of MFCs and the design process (e.g., using CAD "computer aided design" software) can be found in the MFC Creation Guide. The guide and the MFC files will be hosted on the installation's solar server (Section 4.3). This server is configured to use the domain ***slow.technology*** (Figure 22), where it will remain past this project date and far into the future to preserve the accessibility of the project files. The solar server will host both the guide and the 3D design files when enough power is available, but traffic will be routed to a backup links when the solar server is down. The slow ideology behind the server is another reminder of our ecosophic entanglement with energy and a will contain a prompt when the server in in down – or rather in hibernation mode for rerouting – asking the user if they would like to wait and revisit the site later when energy is available.

4.2. "*The Cybernetic Meadow*" – Statement & Outline

Artist Statement [Installation Exhibition]

The Cybernetic Meadow (2023)

The Cybernetic Meadow is a slow performance installation centered around notions of the extractive energy paradigm, environment-technology relationalities, and slow temporal aesthetics through gardening. The garden requires collective acts of care and maintenance to sustain the work's creative output, a series of slowly generated texts taking the form of novellas and poetry. *The Cybernetic Meadow* operates as a system where its living components and digital technologies cannot be removed from one another. Each component influences the system and, through this, the outcome of the performance. Each garden seeded for a new performance will result in an emergent outcome distinct from any past iterations. The outcome is not static, it exists throughout the growth of the garden, the evolution of the texts, and the social participation sustaining the garden through invitations to care for the garden.

This process is embodied by a garden interwoven with Microbial Fuel Cells and digital technologies, such as E-Ink screens, microcontrollers, and a solar server. Microbial Fuel Cells (MFCs) are a regenerative energy harvesting technology working in tandem with other-than-human organisms to collect energy. The process they use to harvest energy cannot be removed from the ecosystem they exist within. Microbes within the soil of the garden produce ions as a metabolic by-product during their growth, which is sustained through the photosynthetic processes of the plants and mosses living within the soil. MFCs gather energy through extremely slow means relative to capital-centric extractive models of energy production (i.e., oil & coal). Extractive energy practices are environmentally devastating through their physical destruction of ecosystems for material gain, their emissive by-products, and the inability to renew what is extracted. In contrast, the energy collected through MFCs is regenerative, slowly growing the ions used rather than extracting them.

The slow temporality of this regenerative energy creates the temporal aesthetic conditions within *The Cybernetic Meadow*. The ions produced through microbial metabolism are slowly accumulated by the electrodes of the MFCs and stored in an energy capacitor, a battery-less energy reservoir. A tactile switch sits in front of the garden, connected to the power circuit of the MFCs. The switch communicates with the digital technologies of the garden when toggled, triggering a creative cycle that adds a single word to the textual outputs. Only when the garden's reservoir is full can the switch be toggled by a participant, it cannot be pushed beyond this temporal constraint. If it were, extracting a surplus of energy would result in a depletion of soil and microbial health. The textual outputs and digital technologies are directly linked to the growth, health, and energy temporality of the organisms they share the garden with.

The texts are displayed on three E-Ink screens within the garden, generated through a natural language algorithm that are trained a selection of books and papers thematically linked to the installation, such as *Geology of Media* by Jussi Parikka (2015), *Another Science is possible: A Manifesto for Slow Science* by Isabelle Stengers (2018), and *Slow Violence and the Environmentalism of the Poor* by Robert Nixon (2013). The texts used as reference for creative generation are stored on the garden's solar server, allowing new additions to be continually added through participant recommendations, furthering the emergent potential of the creative text generations through an evolving set of literary influences.

To fully experience the created texts, one must return to the garden to witness progress, encouraging the development of slow, ongoing relationships between participants and the artwork. Through the experience of watching the garden within *The Cybernetic Meadow* slowly compose creative texts critically examining the extractive energy paradigm, our current environment-technology relationalities, and proposals toward slow temporalities of care, the performance invites the participants to reflect on how they use their digital technologies, their temporal expectancies of energy, and how each topic presented in its own way entangled with the current health and future sustainability of our global ecosystems.

<u>*Gardening the Cybernetic Meadow*</u>

The Cybernetic Meadow is one of the three final outcomes of, *Gardening the Cybernetic Meadow,* a research-creation project that engages with the fields of interdisciplinary art, ecology, and sustainable energy technologies drawing energy from bio-matter (soil microbes). It's full title, *Gardening the Cybernetic Meadow: Fostering ecosophic care using microbial fuel cells as a temporal aesthetic medium*, communicates several core philosophies that inform the work, while outlining how the technical research on microbial fuel cells is situated inside the art-creation of the project. The outcomes of *Gardening the Cybernetic Meadow*'s research-creation are disseminated through multiple modes of knowledge sharing, shifting away from a primary reliance on the traditional written thesis. Inspired by various research-creation frameworks, it distributes the thesis project's research results through three methods: 1) an interdisciplinary, participatory art installation (*The Cybernetic Meadow*); 2) an open-source microbial fuel cell fabrication guide generated through documentation of the research-creation process; 3) a written thesis that discusses the theoretical framework, methodologies, and outcomes.

Technical Layout

To visually outline the relationship between the electronic hardware, MFC garden, and participant interact, the installation was arranged into the illustration on the following page (Figure 23). The electronic hardware for *The Cybernetic Meadow* is divided into four components, logic, communication, text database, display and switching. The materials that make up these four components were chosen for the installation due to their potential to convey in the relational aesthetic goals of the artwork, each of which is detailed in Section 4.3.

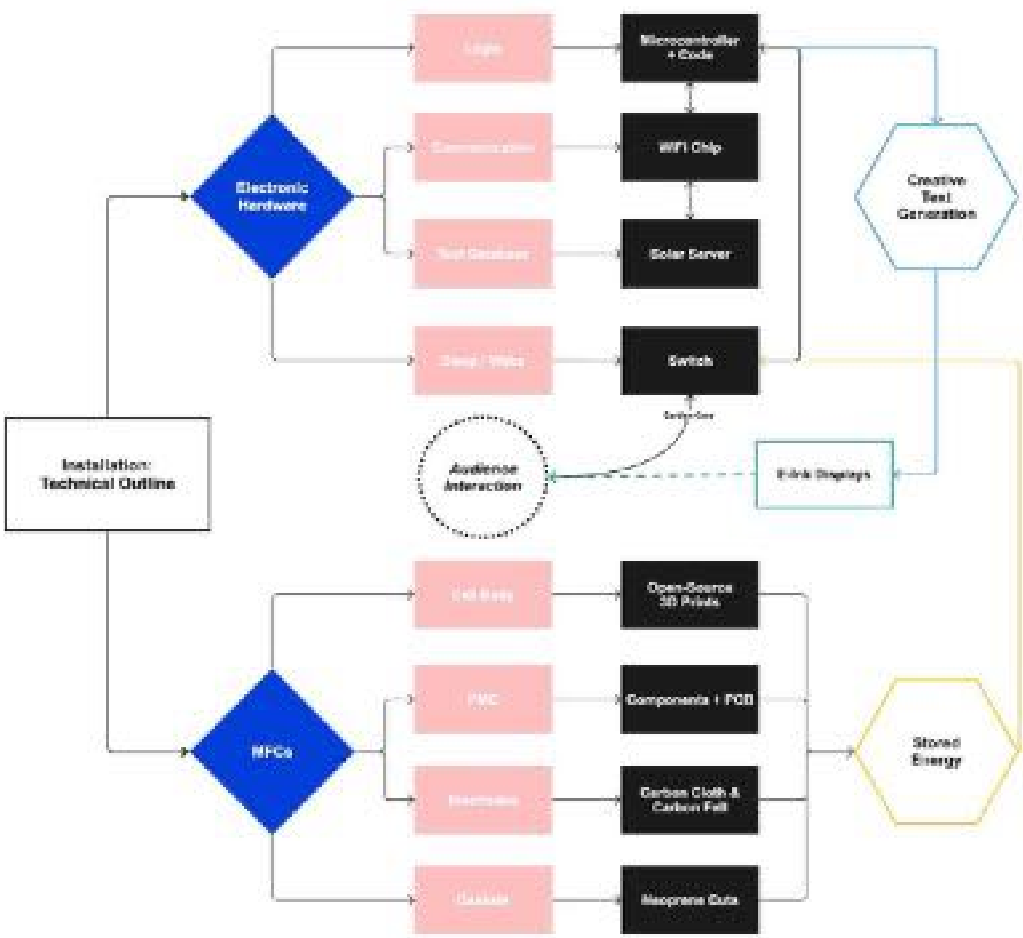

Figure 23: Technical outline of the installation setup for *The Cybernetic Garden*. Illustration by the author (2023).

Installation Exhibition

The installation component was exhibited alongside the other two research outcomes of *Gardening the Cybernetic Meadow* at World Creation Studio (Montréal, QC) on March 21, 2024. In addition to the installation documentation in this section, Section 4.3 will provide documentation of the installation's individual components as their critical making process and motivations are detailed. Outside of this thesis document, I will continue hosting an expanded version of the visual documentation presented here on my personal [artist & researcher] portfolio website. Gardening the Cybernetic Meadow's page on the portfolio site is included as a link in the Appendix.

Installation Documentation

Figure 24: Exhibition of *The Cybernetic Meadow* at World Creation Studio on March 21, 2024. Photo by the author (2024).

Figure 25: E-Ink and P-MFC modules used within the installation of *The Cybernetic Meadow.* Photo by the author (2024).

Figure 26: Exhibition of *The Cybernetic Meadow* at World Creation Studio on March 21, 2024. Photo by Teo Zamudio.

4.3. Planting the Garden: Materials, Aesthetics, and Final Steps

The majority of the MFC research-creation done is detailed in the MFC Creation Guide and the methodologies utilized are additionally listed in Section 4.1. Therefore, this section will not be as expansive in its MFC creation methodologies and instead will focus on the various material, equipment, and digital technologies selected as a culmination of the research-creation process. An emphasis is placed on discussing the stitching between theoretical framework and material (e.g., temporality and its influence on E-Ink development). Critical Making methodologies and the importance of a documentation process remain but follow the same threading as previous Outcome sections. The main difference in methodological approach is that this installation component was developed in the final stages of research. This shifts the focus from the making process into the symbolism of the work and the experiential potential of the components. Though parts of the Critical Making methodology are no longer needed, the "critical" aspect still lingers as each component represents their materiality and embodied energy in a unique way. To create an experiential installation around the theoretical tapestry that has already been woven, this section makes sensory connections between that theory and the material elements of the artwork.

As shown in Figure 23, the components can roughly be divided into MFCs and Electronics. There are two aspects to the MFC research done for the installation portion *Gardening the Cybernetic Meadow*– P-MFC design research and the P-MFC fabrication – which is not included in the fabrication guide but will be detailed here. The electronic hardware and corresponding software development follows the discussion on the installation specific MFC research-creation. Section 3 provided a portion of the artistic inspiration for using MFCs within an installation and will briefly continue in this section. As the electronic hardware components have not yet been discussed outside of the PMC, this section will emphasize their technical development, provide schematics, and list any community contributions or open-source resources used within the creation of the artwork. The code for the electronic components can be found in the Appendix under the GitHub page, which encapsulates all of the coding done within this thesis project, any open-source adaptations, and the images for the open-source platforms used.

Figure 27: World Creation Studio's Interdisciplinary Media Lab, the space used for much of the research-creation done throughout this thesis project and entirely for the installation portion detailed in Section 4.3. Photo by the author (2023).

Materials: The MFC Garden

To develop a new variation of MFC technologies for use as temporal aesthetic medium within an installation artwork, new research was conducted on planters for P-MFCs and biodegradable MFC materials. MFCs are complex biotechnologies that lie outside of commonly used artistic media. They demand an interdisciplinary approach to their creation process due to their components requiring specific fabrication methods (i.e., 3D printing), electronic engineering (i.e., circuit design and soldering), and design adjacent to mesocosms if there's prolonged indoor use. Mesocosms are an enclosed environment for biological samples that aim to be analogous to that of the organism's ecosystem (Odum, 1984). Within each of these realms I can evaluate each component individually, attempt to put the collection together, and adjust where needed. Throughout this process, each component can be weighed against their ease of development and creation methods that are most accessible are documented for knowledge redistribution. Since the research-creation methodologies for these designs follow those mentioned in Section 4.1 (e.g., the CAD process and digital fabrication tools), they can be revisited there for more information on the process.

As MFCs are complex technologies, much of the available information on their function lies within high-level academic research in the form of journal contributions. Many of these contributions do not reveal the entire function of the MFCs studied and primarily distribute quantitative data on the efficiency of various components. Therefore, to understand the function of an MFC, fragmented information on each component must be gathered and tested through the creation of prototypes. It is important to note that the critical making and artistic prototyping methodologies used do not emphasize efficiency, as many of the MFC literature review did. Instead, the goal of this making process is to improve accessibility through documenting the *how*, by detailing the process so it may be reproducible. In reference to media ecologies, which for this thesis closely parallels ecosophic frameworks, Taffel suggests the design and making process "requires the development of an ecological ethics and politics which emphasizes mobilizing actions designed to build equity, commons and mutualisms rather than competitive individualism and economic efficiency" (Taffel, 2019). Therefore, the iterative prototyping aims to create reproducible components that double as visual indicators of their accessible nature to participants in the exhibition.

The fabrication methods I researched for P-MFC prototypes examined using materials that are biodegradable to facilitate prolonged use with plants and their microbial ecosystems while minimizing any harmful leeching of plastics into the soil that could theoretically occur. The use of mosses in my first open-source MFC designs relied on a more intimate relationship between the organism, microbial communities, and the electrodes, the microbial communities within P-MFCs often have a wider space between the organism (more specifically its roots), mycorrhizal microbes, and the MFC electrodes. This is due to P-MFCs requiring an increased amount of soil as a growth medium and due to indoor potting soil having more air pockets in comparison to the moist felt used in a Bryo-MFC or P-MFCs using wetland plants, which are more efficient but not ideal for indoor gardens. Despite requiring less moisture, the P-MFCs designs I researched for use with common indoor household plants also were designed for both an increased use window and for use with organisms outside their natural ecosystems which, depending on the plants and soil used, may have less resilient microbial communities.

A continued use of 3D printing for the P-MFC fabrication was explored with biomaterials to maintain the same availability I discussed within the MFC fabrication guide. Within this project a variety of materials will be tested, such as ceramic printing and bioplastic printing. The bio-plastic (Non-Olien), PLA (a bio-based thermoplastic–- polylactic acid), and PETG (Polyethylene terephthalate glycol) printing was done on a Prusa Mini+ FDM 3D Printer. The technical side of 3D printing and the sustainability of the materials used is additionally found within the MFC Creation Guide. In short, FDM printing stands for Fused Deposition Modeling, a common type of printing within most hobbyist printers. A large range of companies making these types of 3D printers stem from DIY kits produced by RepRap in 2005 (Taffel, 2019). As RepRap's kits were produced as open source or under Creative Commons licences, they inspired many variations of affordable 3D printers from emerging companies (Ibid.).

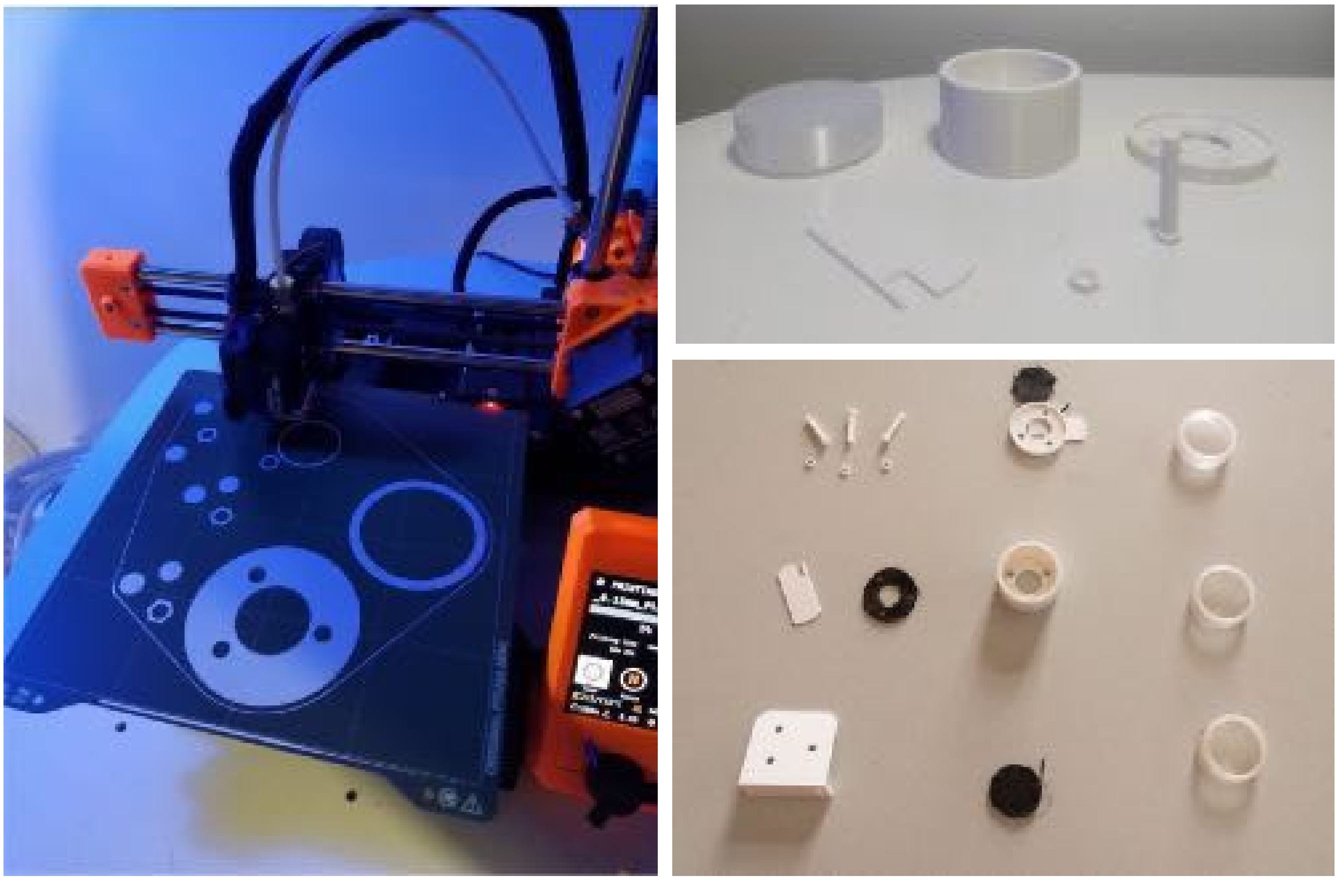

Figure 28: 3D printing all the components for the Open-Source MFC (left), set of 3D printed Open-Source MFC components (top-right), with electrodes and gaskets (bottom-right). Photos by the author and Karolina Uskakovych (bottom-right, 2022).

Many companies, such as the one used within this thesis, Prusa Research, remain true to this open-source ethos and even offer their own free printable files (Prusa Research, 2019). At first glance, 3D printing may seem inaccessible, but even Prusa Research states,

> We wouldn't exist without open-source. Prusa i3 3D printers were born from the idea of an open-source machine and we are still faithful to this ideology. Everything we do, everything we sell, is open-source. What does this mean? All source codes, printed parts, blueprints, circuit board designs… everything is freely available to anyone via GitHub. Because we strongly believe in the community and in sharing knowledge (Prusa Research, 2019).

This ideology is one main reason I included 3D printing within the research's critical making methodology. The installation component also incorporates the open-source MFC prototypes developed during this research-creation, seen in Figure 28 (p. 59) during the process of 3D printing them in PLA and arranging the component parts of the MFC.

Due to the open nature of the Prusa 3D printer I was using, I was able to modify their slicing software - which translates the 3D model to machine code – to work with an extrusion printer that could explore ceramic 3D printing, the Eazao Zero. Extrusion printing allows malleable materials to be laid out in 3D layers and is commonly used to 3D print ceramics. Extrusion printing is slightly less accessible but was included in my methodology for two main reasons. Firstly, it has the potential to add fully biodegradable materials into digital fabrication, including compost, mycelial matter, and clay (Weiler, et al., 2019; Zhong, et al., 2022). Secondly, it enables the direct use of earthen material, avoiding the industrial chain within processed materials (i.e., thermoplastics). If the installation garden was even to be exhibited outdoors or in the microbes' natural ecosystem, these bio-based materials avoid the leeching of microplastics that may otherwise occur.

Figure 29: Ceramic 3D printing research with an Eazao Zero extrusion printer (left), 3D printed ceramic planters developed while conducting research (right). Photos by the author (2023).

The direct use of earthen material doubles as a provision of symbolism to the MFC the ceramics will house. It creates a direct link to the materiality of the MFC components and embodies future imaginaries where the design of technologies may remain sympoietically tied to environmental ecologies. While ceramic P-MFCs did not appear within the final installation outcome, the custom slicing configurations I researched and developed are included in GitHub repository I link in my appendix. With these slicer configurations, others will be able to replicate the same outcomes I had with 3D printing ceramics, only needing to modify the configuration for their printer size.

To keep the MFC garden healthy, an environment needs to be replicated for indoor use analogous to that of the organism's ecosystem. For ease of use, longevity, and indoor compatibility, a mix of houseplants and resilient garden plants are used with the MFCs. Mesocosms aim to mimic the organism's natural habitat. To do so, the researcher prototyping the mesocosm needs to take atmospheric conditions into account, especially in regions where seasonal temperatures and humidity levels undergo extreme changes. The P-MFCs do not require this element of the mesocosm as the organisms within the installation are commonly selected as houseplants or garden plants due to their versatility and ability to remain healthy within a wide geographic range. For organisms that are more sensitive to atmospheric conditions, such as the mosses within the Bryo-MFCs, My research-creation has found the inclusion of a whole or partial atmospheric lid is crucial for long-term survival – it is included within my Open-Source MFC design (Figure 21). The mesocosm lid seals the artificial ecosystem from the atmosphere, only letting a very faint atmospheric exchange to occur through a minute hole in the lid. For anerobic MFCs, forgetting to include this hole leads to a pressure build-up and potential outward break as gases are released by the microbes. For Bryo-MFCs there is no risk of a break, but the mesocosm lid is still extremely important due to their habitats existing within an atmospheric "boundary layer" (Kimmerer, 2003, p.14). Their reliance on the atmospheric boundary layer is mimicked within the mesocosm through a nearly still atmosphere; a lack of exterior, airborne organisms; and relatively stable, high humidity levels (Ibid). An example design for a mesocosm and MFC design with a biodegradable 3D printed cell, using a lid for atmospheric control can be seen below in Figure 30.

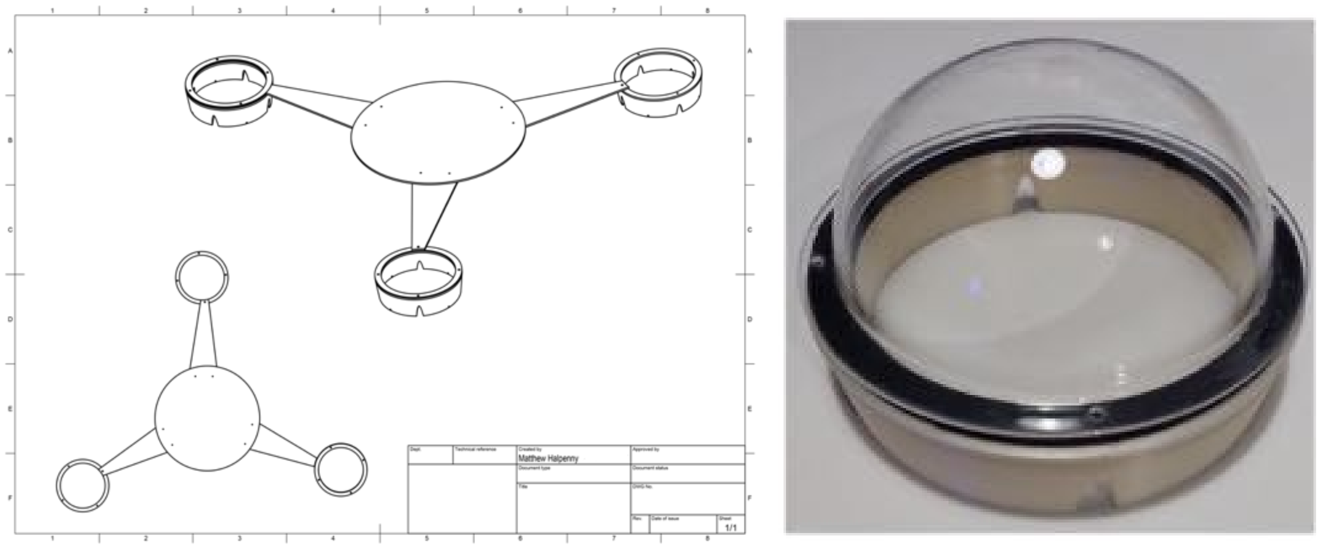

Figure 30: CAD technical schematics for an independent bio-plastic MFC installation (left) and a 3D printed bioplastic MFC example (right). Photo and Illustration by the author (2022).

P-MFCs holding common household plants would not the same atmospheric regulation, nor would it be viable for large plants. The household plants would also require a deeper cell body than ones designed for mosses. With these two factors under consideration, my research-creation on P-MFCs led to the development of a second version of the Open Source MFC (Figure 31). This version has a deeper cell body, allows for suspension (to keep the bottom electrode exposed), and retains a similar circumference to keep electrode costs accessible. As mentioned in Section 3, P-MFCs are often less efficient than other types of MFCs, meaning the configuration of the electrodes is even more important. If one uses a sensitive electrode material to compensate for this, a larger planter circumference can exponentially raise the fabrication cost as carbon-based electrodes are often made in small sheets, larger sheets increase in price and can be difficult to find. If one fabricates their own electrodes, the decreased efficiency vs lab electrodes means the distance between the two electrodes becomes critically important. Without an MFC design that uses gaskets to create a relatively airtight seal, as the Open Source MFCs do, it can be very difficult to get results with a P-MFC. The P-MFC version of Open Source MFCs solves these issues. Even though the P-MFC designs were used while no tangible outcome of the biomaterial research-creation was developed, I believe including the research results and motivations behind the material research was important to allow for replication and continuation.

Figure 31: P-MFC version of the Open Source MFC installed within *The Cybernetic Meadow*. Photo by the author (2024).

Materials: Logic & E-Ink Development

To best understand the research methods leading to these generations, I will expand on the logic component first. The logic component controls both the flow of data and determines how that data can be creatively organized. In any electronic work an artist prototypes that requires computation, sensing, or interaction, one must use a piece of hardware called a microcontroller, or more technically a development board if the microcontroller is paired with an array of electronic hardware that adds additional I/O (input-output) sockets and communication chips. All microcontrollers contain both a logic chip, allowing various computational processes to be coded into it, and GPIOs, or general-purpose input-output pins. GPIO pins allow the maker to add in additional components such as sensors or switches.

When choosing a development board for a project one must plan out and consider what will be required before acquiring any hardware. Often GPIO pins will allow one to add on needed components, but not all microcontrollers will have either the sufficient type of pins or number of pins to add in every module. Therefore, it is important to consider what boards can be used that will come prepackaged with as many modules required by the project and if the boards can handle each additional model needed. Following my critical making axiology, it was important to select hardware for *Gardening the Cybernetic*

Meadow that are open-source, or at least are paired with software (code) that is open-source and community oriented.

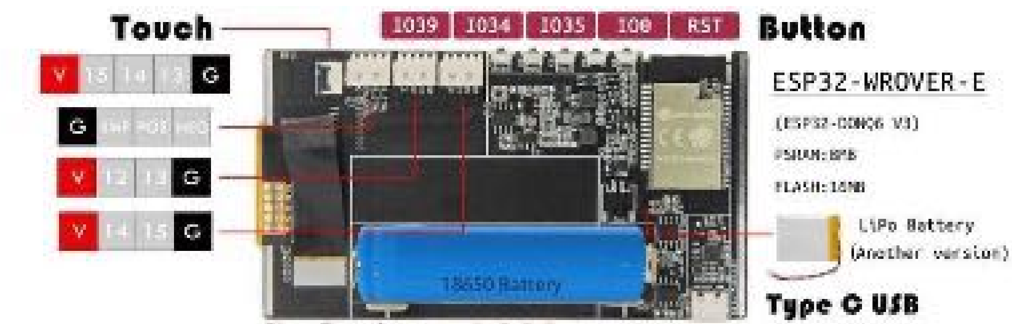

Figure 32: LilyGO T5 4.7” board diagram by LilyGO (2021).

The installation component of *Gardening the Cybernetic Meadow* uses a hybrid ESP32/E-Ink development board, the LILYGO® TTGO T5-4.7 Inch E-paper ESP32 WIFI/Bluetooth Module Development Board. The T5-4.7 was chosen for several reasons – the first of which is it contains the communication component (ESP32 WiFi) and the E-Ink display component in one package, a combination rather difficult to configure independently. This difficulty stems from the wiring prerequisites of an E-Ink screen are complex and require a special I/O socket for SPI (serial protocol interface) that not all development boards contain. Secondly, the board’s design was “committed to low-power design optimization”, allowing minimal energy to be drawn while “sleeping” (a feature I will discuss below, consuming only 170uA). The low-power design also allows the use of a 18650 lithium-ion polymer battery as an ongoing backup energy supply to help sustain additional functions outside the MFC energy used to power the switching mechanism. Lastly, the T5-4.7 is paired with extensive community support through device specific GitHub pages, example code, maker IDE support (Arduino, IDF, MicroPython), 3D files and schematics, an open-source GNU General Public License v3.0 (GPL3), and prewritten scripts for converting text and images–- E-Ink requires a special graphics bitmap format stored in the boards memory separate from the display which is uploaded to the screen when the pixels are magnetized or “flashed”.

Figure 33: An E-Ink module within the installation, enclosed within a custom 3D printed mounting case for the installation. Photo and design by the author (2024).

The T5-4.7 was coded for *The Cybernetic Meadow* to only be activated in direct relation to power availability from the MFCs, which only continue their energy generation when recurringly cared for through audience engagement. The length of time before enough power is stored is not only dependent on the audience but also the location and environmental conditions. Each of these affect the rate at which PMC is harvesting microbial energy and it's switching mechanism can be altered by the PMC's configuration, which I've included below in Figure 34. When the PMC has stored enough energy (determined by the included storage capacitor) it surpasses a threshold, and a pulse is sent to one of the solar servers GPIO pins. This is detected on the server by a python script tasked with sending a message to the JavaScript file responsible for the project's text generation (part of the Text Database component) and the JavaScript file responsible for waking the E-Ink boards by sending a packet to their ESP32 Wi-Fi chips.

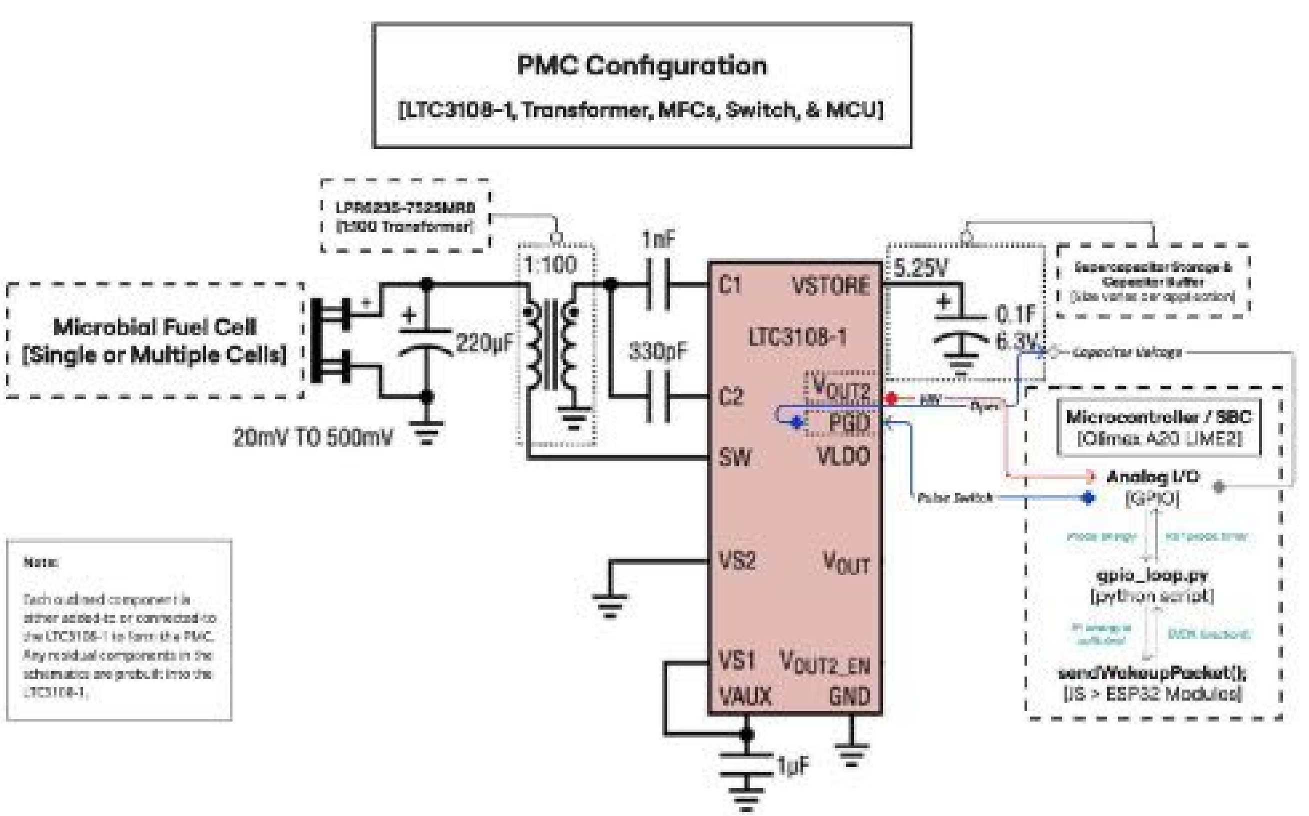

Figure 34: Illustration of the PMC configuration based on research done within Gardening the Cybernetic Meadow, outlining the relationship between the LTC3108-1, MFCs, capacitors, transformers, and the solar server (SBC). Illustration by the author (2023).

The text database will contain a series of text data compiled from theoretical references to the work, including books, papers, and poetry cited in the Bibliography section. The references used were selected due to their influences towards shaping and informing the work; their contribution to the software's linguistic framework leads to new generative texts that speak on the same research problems as this thesis in new, unpredicted ways. Each will be converted and stored as text data through custom coded software, allowing any creative text generations to be inspired by relevant words, adjacent word associations, and theories.

One method of achieving this is using coded Markov models. A Markov model is a mathematical probability analysis of selected text. It measures which words are used and the relations between words. To do this it assigns weights to each word and generates a sequence of words based on probable relations. Open-source code libraries for this exist already exist, such as RiTa.js in JavaScript. RiTa.js "provides functions for simple language processing and generation tasks without the overhead or complexity of a full NLP stack… [its] features include grammar and Markov-based text generation, tools for inflection, conjugation, stemming and tokenization, as well as analysis of English features such as part-of-speech, phonemes, syllables, and stresses. RiTa's customizable lexicon can be searched via partial matches on combinations of any of the features listed above" (Howe, 2020). The use of RiTa within this installation primarily uses Markov models, which is a mathematical probability analysis of selected text (Stamp, 2017). It measures which words are used and the relations between words. To do this it assigns weights to each word and generates a sequence of words based on probable relations (See Figure 35). The MCU used is capable of connection to a server wirelessly, and since most MCUs have limited memory (which is too small for a book), a web-based language was chosen. JavaScript was use in tandem with the library RiTa.js. This library lends the used functions built to construct and use Markov models within language applications.

Figure 35: Example Markov model by Diagram by Eugine Kang (2017).

To get the components to collectively work at a power range the MFCs can trigger through slowly stored energy, the E-Ink boards ESP32 chips will be responsible for "sleeping" at low power unless woken. The updated text is then sent to the Display component to be calculated and visualized as a pixel array. For the display component E-Ink was chosen as a visual medium due to its ultra-low energy requirements, ability to continually display while off, and its conceptual framework around disconnecting. The e-paper screen updates its pixels by magnetizing the screen. During this magnetization either white or black pixels are pulled to the front or back of the screen. Once the pixels are moved the device powers off and the text on-screen remains until re-magnetized. After each word is added a new magnetization cycle occurs to add the word, after which it powers off and is effectively disconnected from any other electronics until the next PMC power cycle, likely the next day.

In the long haul writings have decisively reshaped many debates that animate environmental fallout... This demands an understanding of the manifesto's message. It performs this cartography while present in the view. The body of the delta and its substrates; of megamergers; of disappearing problematic brand names through that act of national reengineering.

James Watt's invention of emptiness, emptiness being the vessel itself for the order of the Western powers typically supported by oligarchs, dictators, and assays. Indeed, aesthetics becomes twisted into a soap bubble, exporting a part of reinvention as pure wilderness. We can read these scenes as intimating the twilight of the mega-dam and, disproportionately, children. However, in consuming oxygen, thereby rendering the deceased immaterial: he was only staged to none of these combined effects; munitions represent a novel. The spread of regional oil wealth goes to a multitemporal reality where the thinking of future burial. To be sure, the World Bank and white environmentalists are humane because they faced a more expansive vision that remains inside a spiritualized and naturalized national frame - it inhibits economic, cultural, and in our technological devices.

Our theories of violence and climate change were associated with hidden deaths and injuries. The result is a requirement of infrastructure and technological lengths to avoid enemy senses into evil powers that make it easier for global corporations and social events by utterly transforming it. The recent turn within environmental studies boom. Something similar applies to any vision of what can counting even mean? The historic track record of human gain. Change is a sufferer. I should note that the expansionist drive of capitalism and the cultures of benediction: Our Own: The Incantor. In addition, slow violence across environmental and postcolonial studies, creating landscapes that linger off-camera.

Figure 36: A generated example text using Markov models. Generation by the author [and the garden], 2023.

The E-Ink and generative text play off Guattari's notion of metamodeling, which "adopt a more playful and constructivist stance towards modeling; here the ultimate aim is singularity rather than standardisation, and this entails appropriation from a multitude of models in order to avoid being 'stuck' within the entropy of a dominant model" (Tinnell, 2012). The modelling in question is the use of RiTa.js to creatively draft new novellas through NLP. The way this process is done is dependent on a selected text database that may be continually added to. When the code randomly selects a book, compares it to the learned linguistic weights so far, and adds a new word in based on the two, the generation is in proximity to avoiding standardization by "appropriation from a multitude of models". The multitude itself does not create an association with metamodeling, the generations direction towards a singularly unique creation ties the concepts together.

The E-Ink screen, or text magnetized on it, may be an art object, but one form the art takes within this installation is the metamodeling of the text output. It cannot be understated that even considering this metamodeling, the human cannot be removed from the equation. It is ecosophic, the social is one model of influence, as is the garden, the artwork cannot exist without either of them. All of these factors, even the selection of text, produce a degree of unpredictability akin to complexity in systems. *Gardening the Cybernetic Meadow* is part systems art through its unpredictable outcome due to an ecosophic weave of reliance, care, and relation; it is part social sculpture through its durational exhibition situated in an everyday setting (i.e., the garden), requesting continual social engagement; and temporal art through its diachronic examination of slower energy temporalities through regeneration and accelerated temporalities through extractivism.

The series of interactions within *Gardening the Cybernetic Meadow* – participant to garden, garden to energy, energy to microcontrollers, microcontrollers to server, server to creative text – are reminiscent of a garden themselves, drawing attention to the ecosophic relationality of technological, social, and environmental systems. "Media systems are nonlinear dynamic systems that are dependent upon external flows of human attention, (primarily electrical) energy, and matter in order to continue sustaining themselves. Without access to these flows, media ecologies would wither and die, just as ecosystems would perish if severed from the flows of solar energy, water and nutrients" (Taffel, 2019). Within the theoretical discussion of systems art discussed in Section 2.3, Jack Burnham discusses the art as the support system, the process behind the material object classically defined as art. The relationality of the garden becomes this support system, defying any status as static sculpture that may exist regardless of the non-static bio-temporalities innate to the microbe and plant participants. The systems-based nature of the creative text output exists outside of any one agent, representing the whole of the media ecologies involved. It is a system of relations and responses between the living and non-living components of the work. Early systems artists, such as Frank Gillette (See Figure 37), mapped out similar relational networks where the art could not exist (or evolve) without the participant. The installation component of *Gardening the Cybernetic Meadow* may be considered systems art in this sense, but this thesis bridges the relational aesthetics of systems art with an ecosophic theoretical framework critical of the material components and social ecologies involved.

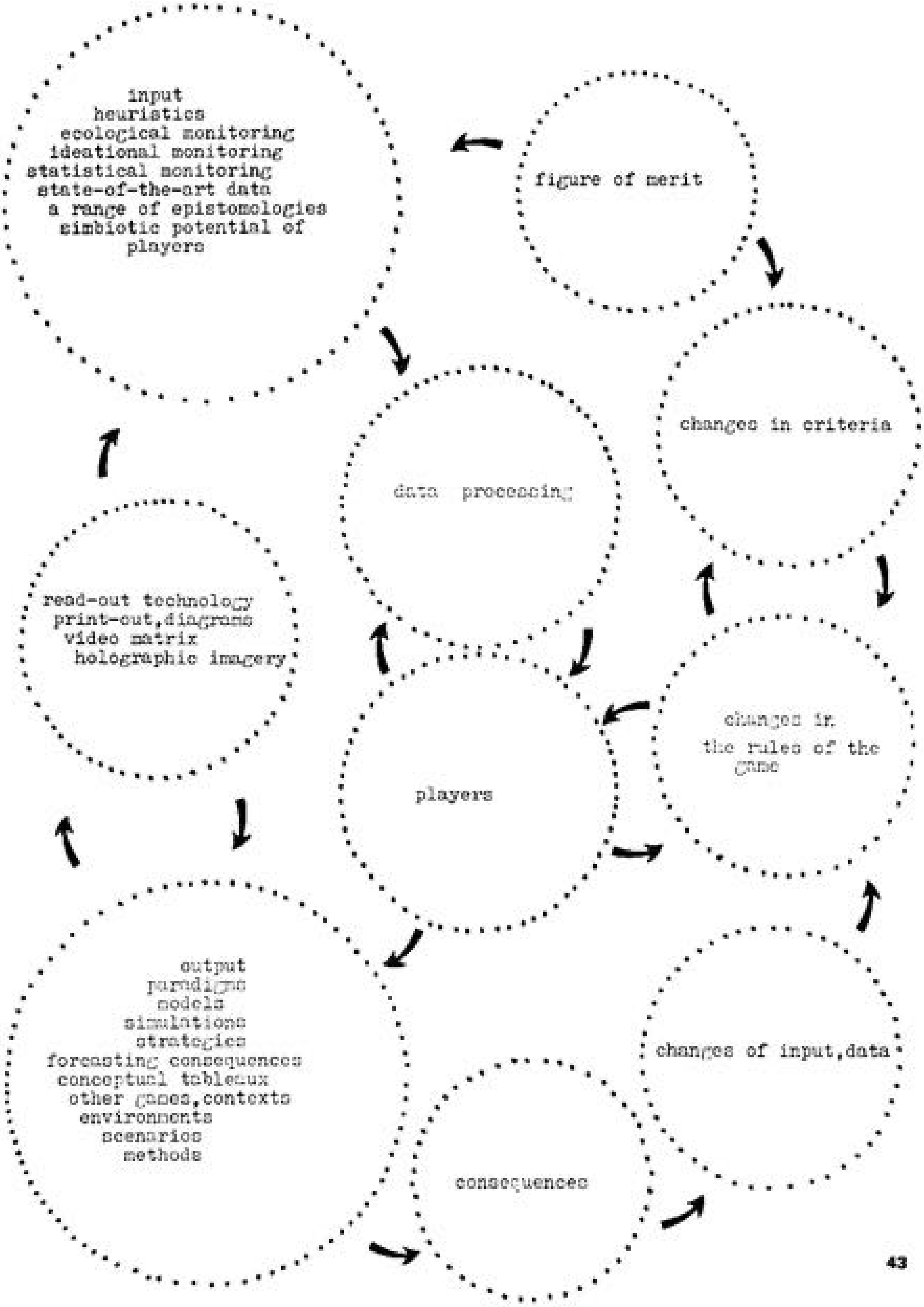

Figure 37: Frank Gillette's **(**1973) "Notes for a proposal of conceptual gamming" in *Radical Software* (p.43).

Materials: Solar Server Development

The solar server is hosted on a low power SBC (single board computer) called the Olimex A20-Olinuxino-Lime2**.** This hardware is a step beyond the T5-4.7 in its community orientation and open-source mandates. OLinuXino requires the developer to use a variant of the Linux operating system, which is an established free operating system based on Unix. Olimex states their mission with this line of devices was an Open-Source Software and Open-Source Hardware project, aiming to produce low-cost Single Board Computers (SBCs). The website that details their boards are linked with an abundance of supplementary support material including user manuals, open-source schematics and 3D files, extensive hardware documentation, a GPL3 license, and self-hosted community forums.

Figure 38: Olimex A20-Olinuxino-Lime2. Photo by Olimex, 2020.

Due to its low power potential and special power monitoring hardware, the Olimex A20-Olinuxino-Lime2 makes a great option for a small solar server. It has already been situated in a degree of open-source community projects, such as the solar server project by Low-Tech Magazine (De Decker, et al., 2018). This project details the process of creating a solar server with accessible hardware while simultaneously critically examining the embodied energy costs and prioritizing minimal energy use through sleep modes, image compression, and archiving. The authors of the article describing the project was taken a step further by the community through a detailed article on software and hardware configuration options published on a maker website titled the homebrew server club (Abbing, 2018).

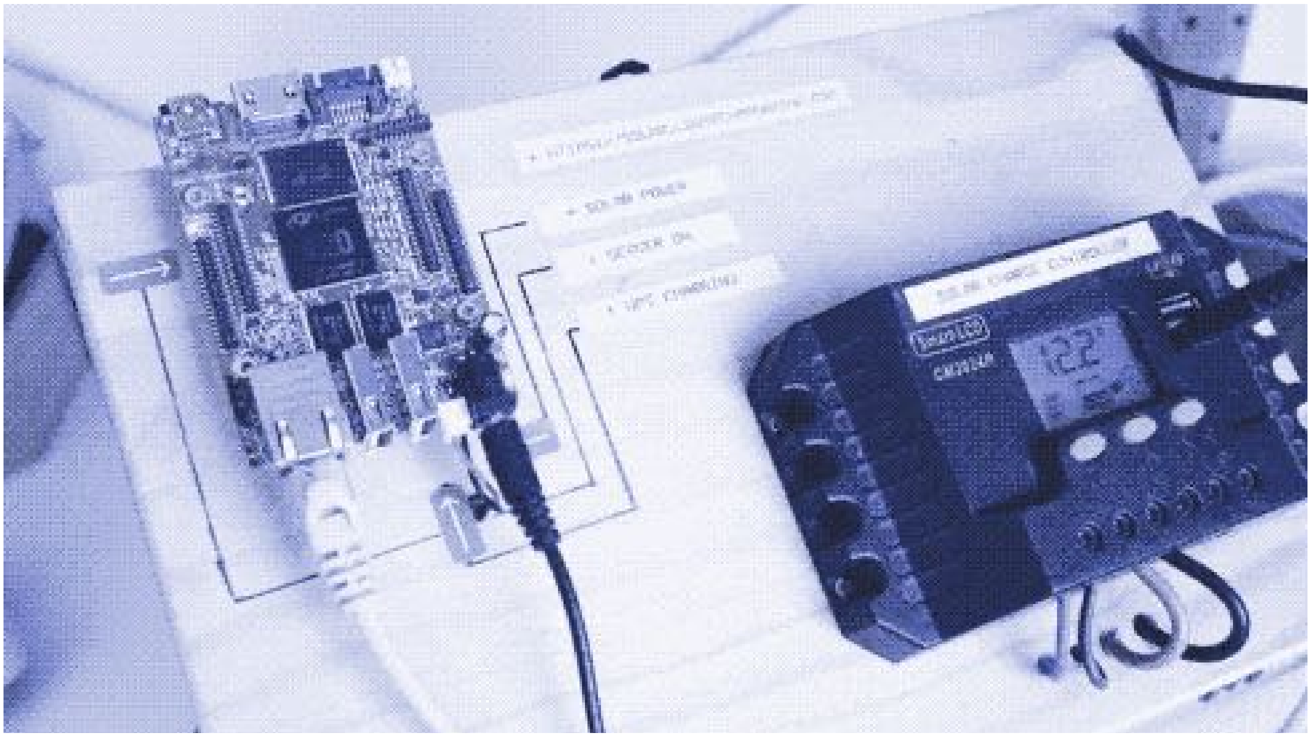

Figure 39: Low-Tech Magazine's original solar server as a compressed image hosted on their solar site. Photo by Low Tech Magazine, 2018.

The software uses the specialized Linux server OS to run a custom configured NGINX server which opens a port to the project's website folder. The NGINX server "serves" an HTML file to the local network (router in the exhibition location) on a static IP, meaning the IP address of the server will never change so that the T5-4.7's code will always know how to ask the location's router how to find it. When instigated by the python script monitoring the PMC, the aforementioned RiTa.js JavaScript code will run and save the updated text in a JSON file format, which is a formatted but minimally sized text file servers use to transmit data. This JSON file will then be sent to the E-Ink device, to be parsed – a necessary conversion by the logic chip to enable its expression as a magnetized pixel array - and displayed. To store excess solar energy the board uses a small solar panel and a DFRobot Solar Power Manager, a voltage conversion and solar power management module. When not in use by the server, the module charges a 3.7V lithium-ion polymer battery with a capacity of 8000mAh for backup energy. When in full sunlight, the module provides the required 5V, 1.5A energy output for the Olimex board, otherwise the backup battery supplies any missing energy. For the installation, each of the components involved in the solar server needed to be bundled in one location and protected from any residual atmospheric moisture that may result from tending to the garden (misting the plants).

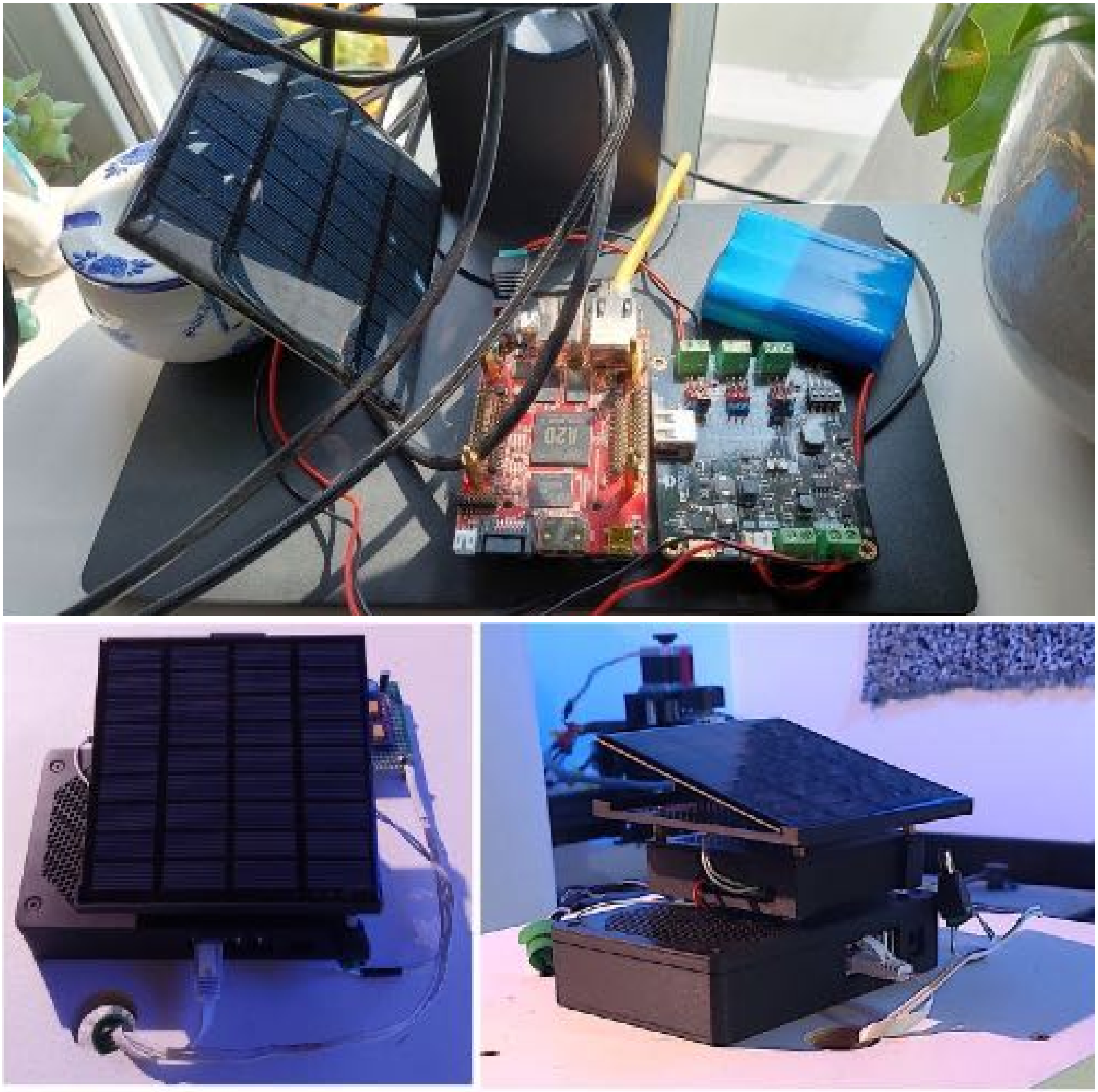

Figure 40: A charging prototype of the solar server during its development phase (top) and its installation setup within the custom designed 3D printed modular casings (bottom). Photos by the author (2023).

Using the same CAD design processes that can be found in the MFC Creation Guide, I created several casings for each of the solar server's components that connect in a modular fashion. Having selected open-source hardware, the hardware dimensions of each component was available through their suppliers. The base casing for the Olimex portion was provided by the company as an open-source 3D files that can freely by modified to fit the makers use case. I revised this file and independently created casings for the solar converter and a mount for the solar panel. I did not include these with my open-source files due to revision of Olimex's files in the overall setup, but I have included the cases I designed for the E-Ink boards alongside the MFC files. Once the files were 3D printed, they were installed on a custom plinth with protection from residual moisture through a removable acrylic dome (Figure 41).

Figure 41: The installation's solar server setup – the modular 3D cases, plinth, and acrylic dome - used within the installation exhibition. Photo by the author (2024).

By incorporating a solar server within the installation, a direct connection is drawn between materiality, code, energy, and interface. In most cases, the servers used to host the data would be cloud based and virtual. As a core theme of the work is highlighting the ecosophic relations between all elements of the project, having this virtual would leave one of the main embodied energy infrastructures (i.e., server farms and cloud computing) absent (Moll, 2018; Taffel, 2019). The information and communication technologies (ICTs) used to support the internet's global network is often unseen, residing in both server farms and undersea cables (Starosielski, 2015). The solar server within the installation outcome of *Gardening the Cybernetic Meadow* uses a combination of relational and temporal aesthetics to bring the materiality and energetic temporalities of this ICT infrastructure to the surface through an experiential environment. Alongside the community centered inspiration of Low-Tech Magazine's solar projects (De

Decker, et al., 2018; Abbing, 2018; De Decker, et al., 2020), the global community project, The Solar Protocol was also a major influence in how the solar server in this thesis was designed. The Solar Protocol is a global network of community built solar servers that act as an open access to hub to guides, exhibitions, and literature on energy, materiality, and critical making (Brain, et al., 2023). The project is well aligned with the theoretical framework of this thesis, specifically through open access community resources, documentation methodologies, guides, and a shared value in artistic research dissemination – all of which is mirrored in this thesis' research outcomes being hosted on its solar server. The axiological overlap does not end there, the Solar Protocol's design and use philosophy follows the temporal logic of the sun.

> The Solar Protocol network explores the sun's interaction with Earth as a form of logic that shapes the daily behaviors, seasonal activities and the decision making of almost all life forms. Solar Protocol honors this natural logic, exploring it as a form of intelligence that is used to automate decisions in a digital network. (Brain, et al., 2023)

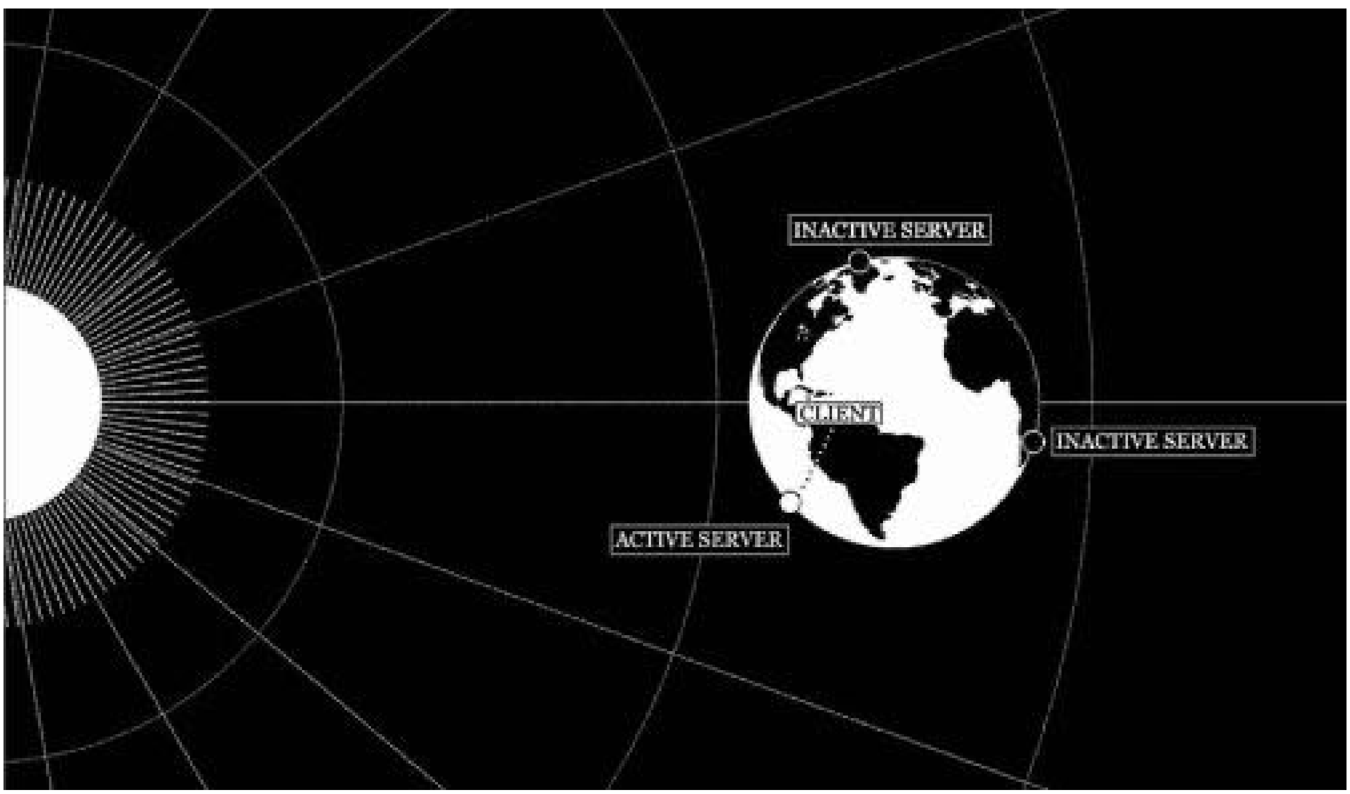

Figure 42: The position of sun relative to earth produces the routing logic of the network. Image by Solar Protocol (2023).

Gardening the Cybernetic Meadow's use of temporal aesthetics is not modelled after the sun directly, but it follows the logic of the living ecologies of the garden. Energy use is tied to microbial metabolism, which in turn is tied to plants, bryophytes, and photosynthesis. By designing technologies to follow these natural rhythms, it creates ripples in the ecosophic bubbles between social ecologies (i.e., how designing technologies influences the social use of technologies) and environmental ecologies (i.e., how the social use of technologies has environmental consequences).

Figure 43: *The Cybernetic Garden*’s exhibition setup using each of the discussed components and a custom indoor greenhouse to aid with participant misting of the garden and to counter Montréal’s dry winter air. Photo by the author (2024).

CONCLUSION

In conclusion, Gardening the Cybernetic Meadow emerges as a multifaceted research-creation project that amalgamates interdisciplinary art, ecology, and sustainable energy technologies. It is a venture that weaves together diverse fields of knowledge to foster ecosophic notions of care, employing microbial fuel cells as a temporal aesthetic medium. This exploration of intertwining living media, technology, and artistic practices not only delves into the intersections of disciplines but also offers a fresh perspective on disseminating research across varied modes. The core philosophy of this work hinges on the intertwining of theory and practice, resulting in an experiential learning journey that transcends traditional research formats. Throughout this research-creation project, the theoretical framework has shaped the form of its process and output, blending concepts from critical making, relational aesthetics, temporal aesthetics, and interdisciplinary methodologies. The embrace of these frameworks was instrumental in directing the research trajectory and informing the creation of the installation artwork, the open-source microbial fuel cell fabrication guide, and this written thesis. By interlinking a diversity of disciplines, the project presents a model for disseminating knowledge that seeks to break down barriers between the arts and sciences, catering to a wide spectrum of audiences who can engage with the research through a variety of accessible mediums.

Through the research's methods of constructing a participatory installation and its methodology behind the transparent documentation process, the work paves the way for other further research and exploration. The project's intricate interplay between care and technology, aesthetics, and ecology, generates novel pathways for potential future investigations. The installation's slow temporality and relational aesthetics open doors to inquiries about ecological interdependence, the implications of energy-generation systems, and the aesthetics of care. The fusion of critical making and research-creation methodologies introduces innovative ways of thinking about knowledge dissemination and collaborative learning across disciplines. Researchers, artists, and practitioners can draw insight from the interactions and technics that create the experiential conditions for new understandings and reformations of the relationality between both human and other-than-human organisms, the temporality of digital technologies, and relational aesthetic methodologies in art-making. Through this, the research outcomes help pave novel ways forward for interdisciplinary investigations towards solving wicked problems within the realms of sustainable energy, ecological interactions, and experiential pedagogies. The symbiosis inherent in the installation–- where care sustains energy, life, and creative outputs of future imaginaries–- invites researchers to delve deeper into the role of art research in communicating ecosophic entanglements between the social, scientific, and technological. By encouraging engagement beyond traditional academic boundaries, the work demonstrates the potential for public engagement and ongoing dialogue around how knowledge can be shared, interpreted, and applied across diverse fields.

Gardening the Cybernetic Meadow meets the five proposed criteria for art-research to qualify as academically sound. 1) The work does not replicate past artistic outcomes and explores the use of MFCs as a temporal aesthetic medium; 2) It was rendered public through a publication and exhibition, the latter was peer-reviewed through an academic committee, while the publication remains online and accessible indefinitely as long as it hosted by myself or is replicated due to its open access status; 3) This written thesis critically examines the outcomes and theoretical framework surrounding the project; 4) The MFC creation guide (and to a lesser degree this written portion) is documented with accessibility in mind and with the intention of openly sharing knowledge through open-source, open access, and reproducibility; 5) The outcomes of the research will continue to exist and be shared online through the MFC Creation Guide, which documents the making process and critically analyzes the materials, designs, and constraints, while this written thesis and the peer-review cycle critically analyzes the research outcomes.

The research situates itself as relevant and important within ongoing interdisciplinary research. Scholars such as Isabelle Stengers have emphasized the importance of exploring qualitative research, including the arts, in places where scientific frameworks dominate (Stengers & Muecke, 2018). Citing aesthetics as a relational way to reframe problems, Puig de la Bellacasa and Anna Tsing have developed strategies for engaging with the material and embodied aspects of technologies (Puig de la Bellacasa, 2018; Anna Tsing, et al., 2017). Despite this research, there is an identifiable gap in how to design bottom-up approaches to address the climate emergency that are rooted in local, collective action. Using art as a means for generating situated knowledge around climate change is not new. Artists such as Gilberto Esparza (2014, 2018), Smite and Smits (2016, 2018), and Micheal Sedbon (2018) have attempted to address this from bottom-up approaches through interdisciplinary art-science and relational aesthetics. They have designed MFC artworks that engage the public and allow for varied modes of experienced learning, but a key issue with this approach is they are not continual. My thesis creates a framework for addressing complex problems locally, and encourages continuity, allowing for ongoing conversations around technology, energy, and climate change. To do this, *Gardening the Cybernetic Meadow* examines the role of experiential art as a tool to develop situated knowledge and ongoing publicly engaged learning experiences around the climate emergency (Haraway, 1988; Hertz & Ratto, 2019). It investigates this through the role of situated art and social sculptures towards critical discussions around the climate emergency. There is currently a research gap on art-science methods of knowledge creation towards sustainable technologies. Based on the literature review I conducted on MFCs, it seems to be currently dominated by scientific dissemination modes. The relevance of the research-creation within this thesis is not formed entirely by the theory, but the interweaving of theory and practice. The work directly socially mobilizes art-science research through its installation and open access ethos.

Gardening the Cybernetic Meadow's installation component creates the experiential conditions to explore the theoretical framework defined in this thesis, while the Open-Source MFC Creation Guide embodies the values of the critical making ethos used in its formation. Both render the research public in modes that extend beyond traditional platforms available to a written thesis. The installation does this through the creation of a spatio-temporal environment, an exhibition that exists as daily process but bound to a timeframe limiting participation and experience. Therefore, the installation currently only exists within a defined period of time. Despite this, the artistic process forming the work give the artwork the potential to exist at any time in the future after its exhibition. Due to a process rooted in relational aesthetics, the exhibition timeline of the work can fit a multitude of forms. With an appropriate setting to host the garden, the duration of the installation could go on indefinitely and truly fit the form of a daily fluxus and maintenance art. This research takes a step towards what Guattari suggests for ecologically focused humanities scholars,

> For (eco)humanities scholars a unique constellation of concepts adequate to these emergent situations; it offers an alternative to the standard "normal science" approach by which critics apply old ideas to the same type of texts, only now in the spirit of environmentalism. By analogy, then, the proper aim of ecosophy (and a properly transversal eco-humanities) is not to produce a more energy-efficient light bulb or a hybrid car, but to reconfigure subjectivity and to remake academic and/or social practices altogether. While scientist and social scientists rightfully pursue advancements in green technology and debate environmental policy issues, humanities scholars should aim to further our understanding of ecological problems in ways that are unavailable to the technocratic perspective (Tinnell, 2012, p.37-38).

In essence, *Gardening the Cybernetic Meadow* is a microcosm that nurtures not only microbial energy but also the growth of novel ideas, interdisciplinary connections, and transformative insights. It invites all who engage with it to become part of the artistic process, tending and caring for the soil to seed knowledge, and participating in an ongoing dialogue between theory, practice, and ecosophy.

APPENDIX

Open-Source MFC Creation Guide

Open-Source MFC Files & MFC Creation Guide PDF (Solar-Hosted)

Open-Source MFC Files & MFC Creation Guide PDF (Drive)

Code for E-Ink, Text Generation, and Solar Server

Github Project Page: GardeningTheCyberneticMeadow

Artwork Documentation

The Cybernetic Meadow - Portfolio Site

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