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Sustainable Energy Imaginaries: Utilizing Mie Optics to Reengineer Photobioreactors and Reimagine the Socio-spatial Conditions of Autonomous Energy Production

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Sustainable Energy Imaginaries:
Utilizing Mie Optics to Reengineer
Photobioreactors and Reimagine the
Socio-spatial Conditions of Autonomous
Energy Production

A Senior Project submitted to
The Division of Science, Mathematics, and Computing
of
Bard College

by
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Abstract

In order to build a more sustainable future, society must transition toward carbon negative energy production and infrastructure. Algae photobioreactors have proven to be an efficient producer of lipid rich oil which can be synthesized into carbon neutral biodiesel. However, the neutrality of such a technology rests in its ability to yield adequate algal biomass through photosynthesis. In order to reach maximum quantum efficiency of algal cells, solar flux must be transformed so that photon absorption can occur without oversaturating the constituent matter. This project looks at the scattering effects of iridocyte-like structures and their potential to create cost effective solar transformers by utilizing the principles of geometrical optics, spherical harmonics, and Mie theory. Additionally, the socioeconomic implications of energy autonomy are considered across communal scales, along with a reimagining of the socio-spatial arrangements behind decentralized energy production. In this way, the project serves as a model of multidisciplinary collaboration and the importance of use value in technological analysis—both of which will prove vital as we reorganize grid infrastructures to accommodate renewable energy.

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Dedication

For Mom and Dad, who always know how to ask the right questions.

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1

Introduction

Climate change is a wicked problem. Here the term wicked works in a twofold manner: first its connotation of wrongdoing and malintent. Second, its literal, technical definition being a problem that transcends disciplines, becoming so complex in its reality that it appears impossible to solve. Indeed, climate change poses a threat to all living species, with pollutants and rapid urban development disrupting the natural order of ecosystems... this we already know. At the same time, climatology as a field is trying to reconcile the second ‘wicked’ as fast as it can. The discipline has been rapidly absorbing other fields of study under its wing as climate models become even more robust, using countless hours of computing power. Yet, there is still massive variation between these simulations. Why?

The problem is not just scientific. Climate physicists can calculate the enthalpy of the lowest part of the atmosphere over San Diego and the effects of dust clouds above the Sahara in the purest form of mathematics, but it does not account for the variations we as humans bring to the table. Climate change is anthropogenic, and understanding the behavior of humans, the organization of space, the global macroeconomy, the politics of environmentalism, among a host of other aspects of the world we live in must be understood if we are to make meaningful progress in the fight against climate change.

But it is obviously not that easy. Scientists have asked what the point of making climate models is if we are just going to wait for them to come true anyways. As accurate as we want our predictions of the future to be, we get in our own way when it comes to doing anything about it. The danger is that the multidisciplinary nature of the problem itself has bled into the public discourse, making it a debate about how much we should care about it with respect to more immediate problems. The irony is that the more immediate problems of today are symptoms of climate change, and yet we continue to try and stop a flood with a cork. Global pandemics, wildfires, loss of property, and loss of life are all pieces of this puzzle—reminders that the planet can hurt us just as we have been hurting it.

In the spring of 2020, the beginning of the Covid-19 pandemic, most of the world was forced into lockdown. During this time, reports of cleaner air and bluer skies were sprinkled in as positive news amongst feeds of grim statistics. We understood that our lack of driving, lack of factory production, and lack of deforestation for that short period actually had visible effects on our planet and our atmosphere. While that was not shocking, the circumstances themselves were. We were living through an unforeseen circumstance; however, the part that was so unforeseen was the pause in the round the clock cycle of production, not a global pandemic.

That spring was the embodiment of the words of Mark Fisher who said that “it is easier to imagine an end to the world than an end to capitalism.” Just as the discourse surrounding climate change hinges on the economy, so did world leaders place GDPs above human lives. However, it is not all so bleak. We understand that the problem needs to be attacked from all academic disciplines. We understand that in order to make lasting changes to our current trajectory, we need to overhaul our perceptions of the planet. And finally, we understand that if we are to do this quickly, we are going to need drastic change that targets the sources of our behavior as citizens of planet Earth.

This project seeks to explore the idea of clean energy production as a spatial and temporal problem, utilizing urban design, philosophy, and engineering to make a small dent in the question regarding a sustainable future. Chapters Two and Three deal with situating

technology as a historical and political phenomenon, both of which provide implications of their use beyond their technical innovations. Chapter Four begins to take the framework provided in the previous two chapters and use it to analyze the discourse surrounding green technology, specifically how governments and corporations are approaching sustainability. Chapter Five then looks at a specific piece of green technology, the photobioreactor, and how its form and function can be a vital piece in the transition away from fossil fuels. Additionally, Chapter Five looks at how to improve the problem of irradiance in a photobioreactor through Mie theory and the physics of light scattering. Chapter Six deals with simulations and analytical solutions for a film that can be integrated into the photobioreactor design in order to improve upon this problem and make them more efficient. Chapter Seven deals with the spatial implications of incorporating solar solutions like a photobioreactor into the urban landscape. Chapter Eight concludes the exercise by proposing site based design solutions and engaging with the temporal aspect of transition technologies.

2

Situating Technology

2.1 Technology as a Backbone

In an attempt to achieve interdisciplinary discourse, the fields in question need to connect on some common ground or goal. The future of sustainability and renewable energy hinges on the fields of economics, policy, environmental science, sociology, engineering, architecture, and urban planning among others. In order to create a more environmentally conscious future, technology is going to be the backbone of such change. However, it is not that we need to adapt the other fields to fit around the latest feats of engineering, but rather incorporate the scholarship of those fields in our technological choices. Thus, it is imperative to go through the exercise of understanding what it means to be a piece of technology and how it fits amongst nature. While the question is itself metaphysical, it is nonetheless important because the act of understanding the philosophy and politics that inspired our modern definitions of science and technology can allow us to see how the same logic has persisted in other fields as well. In our case, making sense of the disciplines of architecture and engineering through a common lens will help us to identify problem areas in how these two fields interact. Additionally, we are able to see more clearly how the modern iterations of these disciplines operate out of the economic, political, and social conditions technology has helped shape. The following chapter seeks first to understand the basis of natural philosophy and contextualize views of the environment and

economy that stem from the religious underpinnings of the Scientific Revolution and the Enlightenment. The hope is that this will give a historical and philosophical grounding for how society began to produce technology. Next, we will examine the entanglements of capitalism and colonialism with this original philosophy, and how it helped to drive society in the direction of control, extraction, and production. We then shift toward how this historical background has shaped the political nature of technology and its employment in society. This leads us to question the feedback of technological and societal development leading up to the present day. Finally, we will assess the discourse surrounding climate technology more directly, emphasizing both the current state of what it means to be green and the lack of communication among the disciplines in this regard.

2.2 A Biblical Prophecy

“And God blessed them, and God said unto them, ‘Be fruitful, and multiply, and replenish the earth, and subdue it: and have dominion over the fish of the sea, and over the fowl of the air, and over every living thing that moveth upon the earth’” (Gen 1:28). Natural philosophy is predicated on this principle; try to understand the world around you and control it, harnessing its fruits for the good of humankind. While this is a very anthropocentric way of looking at the planet, we have based our ideas of what it means to be modern on the ability to dominate our surroundings. How much can we abstract ourselves from the environment? Can we devise more clever means of extraction? Despite the above quote’s religious origin, the notion of what we have come to view as ‘technology’ is still dependent on the ideas of extraction, consumption, and domination.¹ Progress is contingent on knowing more and more about our surroundings and interacting with them less and less. In order to better understand the current discourse around technology, and more specifically climate technology, it is worthwhile to look

¹“The word technology comes from two Greek words, transliterated *techne* and *logos*. *Techne* means art, skill, craft, or the way, manner, or means by which a thing is gained. *Logos* means word, the utterance by which inward thought is expressed, a saying, or an expression. So, literally, technology means words or discourse about the way things are gained” (Funk 1999, para. 1). The usage of technology as a term is actually a fairly recent occurrence, gaining traction at the latter half of the 19th century and popularity in the height of the Second Industrial Revolution.

at the impact of this philosophy on our view of nature and the social conditions that gave rise to such a lens.

The idea of dominion has always existed in humanity's interpersonal history, yet the scale and force with which it drove society to involve itself with the natural world became more prominent at the start of the Scientific Revolution in the mid 16th century. Nobody was a bigger proponent of this "ethic sanctioning of the exploitation of nature" than Sir Francis Bacon (1561-1626) (Merchant, 1980, p. 164). Nature appeared as a *tabula rasa*, a clean slate with which to build, expand, take hold of, and shape. Suddenly, the craftsman became a "new class of natural philosopher" where they would take raw materials and help them realize their true form and purpose in the world (Merchant, 1980, p. 174). In the Aristotelian sense the world was an infinite reservoir of possibility that needed the steady hand of human guidance to fulfill its potential as a useful tool.

Not only did nature possess the raw form by which humans could create new artifacts, but those same substances could be commodified to enrich whoever maintained possession of them. Lewes Roberts points out this fact in his *Discourse on Forraign Trade* (1641): "The earth, though notwithstanding it yieldeth thus naturally the richest and most precious commodities of all others, and is properly the fountain of all the riches and abundance of the world...in these our days, is by many too much neglected and omitted" (as cited in de Acosta & Mignolo, 2002, p. 500; Merchant, 1980, p. 187). Upon the expansion of colonialism in the late 15th century, 'New Worlds' were seen as the hottest commodity possible due to the bounties they could yield. Through conquest, capitalism began to take shape as a system of organizing space, labor, and resources on a larger scale. In order for such a system to be successful, the commodification of nature needed to occur, and more specifically, what Jason Moore defines as "Cheap Natures" (2016, p.14). Moore notes that the cheapening of nature is not only in its "price moment" to reduce production costs in the extraction craft making process but also in the second sense of the word cheap, meaning "to treat as unworthy of dignity and respect" (Moore, 2017, p. 600). When looking at the language that comes out of the Baconian camp, the latter definition

becomes more apparent. Descartes writes that humans will eventually possess enough knowledge through scientific inquiry to “render ourselves the masters and possessors of nature” (Merchant, 1980, p. 188). Similarly, Robert Boyle in his *Experimental Essays* (1661) writes, “For some men care only to know nature, others desire to command her (as cited in Merchant, 1980, p. 189).” The use of more explicit language surrounding command and mastery leaves little room for interpretation about the envisioned power dynamic between the natural world and humankind. Moving beyond the biblical sentiment of control, mastery implies a need to show force, for humankind to flex its combined muscle in order to completely exhaust the planet for all it has to offer. Thus, coming out of the same time period, the extraction and consumption of capitalism and the control and organization of colonialism became the fully justified economic and political means of carrying out such a religious plan of action.

What we have today is a present that has subscribed to the same logic of domination and consumption precisely because of how deeply rooted it was in the creation of modernity. Yes, we are more conscious of our actions from an environmental standpoint than we were a few centuries ago, but this is only because we are starting to see the consequences of this type of thinking; we continue to function within a framework based on the Baconian model. It is this framework that renders the notion of the “Anthropocene” as something incomplete when trying to define an era of environmental degradation.² What Paul Crutzen and Eugene Stoermer (2002) deemed the “Anthropocene” is a new age where humans have become the primary geological force (*anthropos* meaning human and *-cene* meaning period). The Anthropocene is precisely dated to have begun in 1784 with Watt’s invention of the steam engine, thus signaling the age of industrialism (para 1). It is important to note that this date also coincides with the conclusion of the Scientific Revolution and the progression of the Enlightenment. According to Crutzen, the turn of the 19th century brought about the first measurable increase in global carbon dioxide and methane emissions from air trapped in the polar ice caps (Crutzen & Stoermer, 2002, para.

²The Anthropocene has been described as “an argument wrapped up in a single word” (Moore 2015). This classification is accurate as it tries to establish a window of causality through data and historical record, and boil down those facts into a name. This effort becomes more difficult as one tries to parse out where causality starts and ends. The question becomes: how do those choices impact the scope of what we view as the effects?

6). While this definition is scientifically accurate, its basis for dating the Anthropocene neglects the more societal ideals of the Enlightenment, mainly taming nature and explaining phenomena that had been previously rooted deep within the Christian doctrine. I admit, a dating of the period of man-made climate change should be based upon scientific data, but only partially (just as climate change is only partially a scientific one). Looking at the climate crisis only as a scientific phenomenon misses the fact that the way we organize bodies in space, conduct our daily lives, and participate in a global economy all contribute to climate change. It is the purely scientific lens that is the fallacy of modern climate discourse. If problems were only scientific systems, engineers would run the world. The mechanization of the world as a means of organizing nature and society, and the management of nature in terms of scalable plots can both be viewed as primarily architectural problems that contribute to the climate crisis. Thus, we could define an age in which the logics of how we interact with space, people, or nature began to contribute to climate change on a larger scale. In order to work toward meaningful solutions, parsing out the undertones of societal logic are equally as important as the effects they produce.

2.3 On Mechanization & Control in Architecture and Technology

Using the previous section as a basis for understanding the choices of early scientific thought, we can begin to examine how the principles of mechanization began to permeate capitalism and colonialism in the ways they help to organize society, employ technology, and exploit nature. We can then usher in new *-cenes* that more accurately encompass the philosophy that yielded climate change beyond industrialism.

Mechanization, more broadly, laid the foundation for the development of a global economy. While the mechanical interaction of man and planet was mediated through technology, in the Leviathan order the mechanism that mediated man and man was the existence of capitalism (Merchant, 1980, p. 212). There was a clear set of rules and logic about the market economy that integrated both the planet and its fruitful abundance and the everyday cohabitation of people within it. Therefore a seamless connection was made between the management

of nature and the management of people under the arm of a market based economy. Merchant notes, “the management of natural resources depends on surveying the status of existing resources, and efficiently planning their systematic use and replenishment for the long term good of those who use them” (Merchant, 1980, p. 235). Whether through their use value or their commodity value, nature has become a scalable entity and the lowest class. Nature could now be exploited without repercussion for the betterment of man. Through this exploitation, the modernist built environment arose, where designing planetary scales and individual scales alike seemed to be indifferent to the effects they imposed on the planet.

As society began to develop technologies that became more efficient in their exploitation of nature, mechanization became a principle of controlling the populace. It was easy to observe the world as a machine, and we, as bodies, functioned as smaller machines within the bigger system. From the camp of architecture and urban planning, the entanglement of mechanization and modernism played a role in how the built environment was designed, mass produced, and organized around the “modern man.” Architects of the 19th century began to use these principles to standardize a way of living and determine scales of urban development (Joseph, 2018, para. 13). The Haussmannization of Paris in the 1850s is a prime example of how land was seized and repurposed in order to control the lower classes of French society. Suddenly, the built environment was a tool to construct social behavior by using a mechanical order.

The entanglement of Baconian logic and capitalism gives rise to a new definition of anthropogenic climate change that is more rooted in the logic of the market, the Capitalocene. The term Capitalocene is defined in a period after around 1450, “with Columbus and the conquest of the Americas” and “with the first signs of an epochal transition in landscape transformation” (Moore, 2017, p. 596). The significance of this definition lies in the idea that man made climate change did not just occur one day, when the carbon dioxide concentration increased as a byproduct of industrialism, but rather that this was a symptom of a larger issue that had been brewing for centuries. As Moore points out, the idea of the Anthropocene hinges on the idea of the human as some “undifferentiated whole” that lives in complete separation from nature (Moore,

2017, p. 595). The separation of these two entities—human and nature—leads to a discourse that situates both groups as homogeneous abstractions. A distinction between where man ends and where nature begins perpetuates the logic of the modernist, where humans suddenly do not take part in the everyday life of the planet, and that the planet is just a vessel for society to function. Repeating an earlier sentiment: viewing climate change as a set of data points neglects the impacts of the *systems of interaction* that give rise to the ways we as a species interact both with each other in general society and with the planet. The endless pursuit of consumption and accumulation of capital can rightly be tied to such Baconian modes of thought. Indigenous logics of conservation and preservation are seen as obsolete in the doctrine of dominion over the planet i.e. the land has value, but not as a commodity, thus making it a non-participant in the game of capitalism. Human/nature binaries which abstract society from its environmental influence provide a justification for the pursuit of order and the control of nature as well as the alienation of man from what he views as his ‘product.’

In Moore’s view, the Capitalocene is more about an exercise in perspective, trying to look at the nonlinear relationships between humans and nature. He notes that it is a common historical fallacy to look at linear progress (like a modernist would) as the primary timeline for climate change.³ Older ways of thinking underlie the organization of society, constantly recapitulating themes from past philosophies. Moore notes that by viewing cause and effect so directly, “industrialization still often appears as a *deus ex machina* dropped onto the world-historical stage by coal and steampower” (Moore, 2017, p. 608). Additionally, power structures within capitalism influence how people exist within nature. This structure can be most easily visualized through the history of colonialism.

And one does not have to look too far past the dating of the Capitalocene to see the emerging power dynamics of colonialism. “The Greek word for colony is *apoikos*, containing

³This is what Bruno Latour notes as the fallacy of modernism, the complete abstraction of man from nature. He realizes that “hybrid networks” and “quasi objects” exist which are neither completely social nor natural. By thinking in binaries man has the false notion that he is progressing, often through the creation of technology which man sees as a purely social construct. By understanding the interrelationships between nature and people and things, one can realize that we are reproducing the same social conditions in different constructions and not “progressing” at all. (Bruno Latour, “We Have Never Been Modern,” (Harvard University Press, 1993)).

a form of *oikos*, home, from which we take the word 'economy', which means something like 'rules of the home', or ways in which the home is conducted" (Summers, 2003, p. 418). Labor, and the land itself was a way to support a capitalist and expansionist economy. At this scale, the basic unit of production was the plantation, leading Donna Haraway to coin, and later Janae Davis to expand, the term "Plantationocene" as a way of expressing the impact of racial interpersonal and interspatial dealings on the subsequent development of human made climate change (Davis, Moulton, Van Sant, Williams, 2019, p. 1). While terms like "racial-Capitalocene" seem to encapsulate the racial aspect of Capitalism like the Plantationocene term tends to, the conditions of the Plantationocene are much more expansive in their scope. The Plantationocene touches upon Haraway's definition of kinship and redefines it as an expression of contentious relationships between "human and non human bodies" (Davis et al., 2019, p. 5). Davis also highlights the ways in which the plantation is an expression of a lack of ecological care affixed within a system that lacks care for black bodies (Davis et al., 2019, p. 5). The entanglement of race and climate change encompasses not only the racial exploitation of labor and native land but also the vulnerabilities that emerge from plantation logics and climate effects. The extent of the Plantationocene extends as a history up until the present. When quantifying the effects of climate change, "there are those who are merely inconvenienced and there are those who will die...with numerous positions between these two extremes" (Pulido, 2018, p. 118). Those who have historically been othered by the plantation-esque organization of colonialism are those who will end up paying the highest price in the end. Indifference within the context of the Plantationocene can both "reproduce racial inequality" (Pulido, 2018, p. 123) while also reproducing the status quo of human nature interaction. Without explicitly addressing the structure and reproduction of the plantation in the everyday world, its logic will continue to reproduce both social and environmental inequality.

The ideas expressed in something like the Plantationocene, which speaks specifically to the intersectionality of race, economics, scalability, and globalization among other things, itself creates a logic about the problem at hand, e.g. this is how humans have thought about or-

ganization, structure, and systems that eventually lead to anthropogenic climate change. There is a clear othering, expansion, and logic of generalization/standardization that is apparent in human-nature relations. While there may be specific systems or events that shape human influence in this sphere, it is the underlying logical structure that appears to remain constant in all these *-cenes*. Consequently, they all lead to the employment of similar agents like technology, raw materials, and energy consumption in their efforts to “modernize” and “develop,” as well as exploitation more broadly as a way of achieving their goals. Now we have a common basis for understanding the big question: what *logics* have caused “The Anthropocene?” What *modes of thinking*? While these questions appear more abstract they can easily be applied to the actors involved (humans) and their usage of media, technology, in order to grow exponentially in almost all facets of life and in turn exploit the planet for its resources. By critiquing these logics and their management we can get insights into how such large systems came into functioning, their ontologies, and how they persist in the present. In turn, we can have a strong basis of understanding of the condition of society’s development through technology, economy, and the built environment. Identifying these principles (scalability and standardization) exposes a thread shared between multiple disciplines, where discourse can become more direct and involved.

2.4 On Scalability and Standardization

Now, it becomes important to define and address the logics that are reproduced by the Baconian capitalist framework directly, mainly scalability and standardization. Scalability is the friend of structure. “When small projects can become big without changing the nature of the project, we call that design feature “scalability” (Tsing, 2012, p. 508). In the market based economy, scalable solutions yield the most profit because they can be applied more generally. Generalizing solutions in this way is what leads to more control and order. In theory, scalability seems to be the key to solving distant problems with minimal effort; one can use the same trick if it seems to fit upon first glance. But in the nature of a capitalist economy, scalability is more so linked to the extraction of profit by using minimal resources. As Tsing notes, “economies of

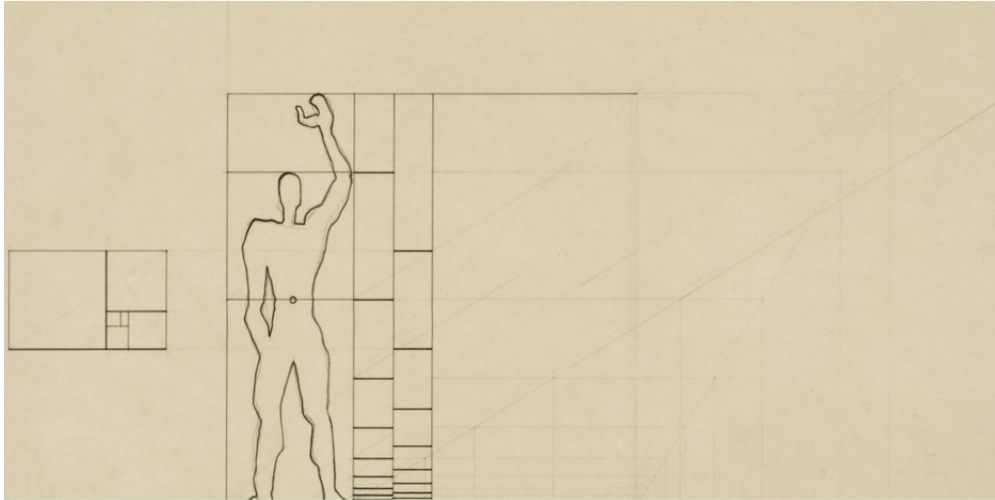


Figure 2.4.1: Le Corbusier's Modulor Man (1946)

scale [are] organizational practices that make goods cheaper because more are being produced.” The problem with scalability is that it is not natural (Tsing, 2012, p. 508). The idea that you can create a basic unit and reuse it over and over again is more about what Merchant (1980) describes as “the mechanization of nature” rather than nature itself. In the plantation, the ordering of slave labor, the layout of agriculture, and the organization of space were scalable entities that could permeate new and unused land and unexploited peoples for the enrichment of a more powerful governing body. In that way, people and nature are cogs in a wheel, generalized abstractions that can be exploited anywhere at any time both near and far.

Through generalization, comes standardization. How can we make something the same way each time in order to extract the most profit while doing the least? Standardization is also an unnatural phenomenon. There is no one standard human like the modernists of the early 20th century believed, and there is not one standard nature.⁴

Though they seem to be the same, standardization tries harder to put things, people, and nature in distinct boxes where the essence of that thing can be understood in very simple terms. Standardization leads to abstraction and is the friend of scalability. Who gets to decide what

⁴Image Credit: <https://failedarchitecture.com/human-all-too-human-a-critique-on-the-modulor/> Modulor Man (1946) was created by Corbusier as an extension of Da Vinci's Vitruvian Man (1490). Using the golden ratio and mathematical sequences, the modulor man was supposed to be the perfect standard for scaling new architecture.

the standard should be? How does the standard other anything outside of this definition? These questions appear most obvious in the social power structures that exist today, but also apply to the ideas of anthropocentrism seen in the Baconian doctrine. Nature was to be something singular and placed below that of humans. The combination of standardization and scalability has allowed those in power to easily buy into the ideas of consumption and accumulation on a large scale. Standardization and scalability are mechanisms of power. As a tool, these mechanisms create a fundamental worldview centered around “order and power” (Merchant, 1980, p. 236) just as the natural philosophers had strived for in their dominion over nature. Just as the world appeared infinite, so too did our indulgence in its excesses.

One of the largest problems in the current climate discourse is that we continue to try and make solutions that fall into the molds of scalability and standardization. No two places are the same, and thus the effects of climate change affect everyone differently. The standardization of architecture has not and will never work, as the standard built environment becomes incompatible with the surrounding nature and culture.⁵ The scalability of engineering solutions falls apart as the yields and efficiencies of certain technologies lessens at non optimal scales. Thus, the principles of scalability and standardization which arise from the mechanization of society and the economy continue to perpetuate the ideals touched upon at the beginning of this section. We now have a basis for how people in the West viewed structure, order, and nature more broadly.⁶ There is no escaping the philosophies of the past and their influence on how we view the future. In spite of these principles laying dormant in the public subconscious, it is imperative that we identify how they impact(ed) the development of technology.

⁵Pre-Bauhaus architecture schools of thought attempted to create a standard world architecture as a means of achieving worldwide technological progress. What the Weimar Republic found was that this became impossible because the rest of the world is not a carbon copy of Western Europe. Additionally, this school of thought was brought about by the rise of mechanization and mass production in Western architecture and Capitalism. We will see more explicitly in the next section that mechanization became a driving force for technological production and the principles of scalability and standardization.

⁶It is important to note that this train of thought follows a very Western, Eurocentric way of viewing philosophy and the environment. The reason for going through this exercise is that the dominant political discourse in the US surrounding climate technology takes a page from this initial philosophy, and has hence led to the issues we currently encounter.

The next section will touch upon how technology was formed from these economies of scale and the Baconian doctrine, and how it is used as a tool to reproduce societal consumption and extraction. Through this understanding we can better situate technology as a more philosophical tool that continues to permeate architecture and engineering solutions.

2.5 Technology in the Era of Mechanization and Consumption

More specifically, this next section serves to contextualize the economic and social conditions of the pre-Industrial West by looking explicitly at the connections between natural philosophy, religion, and economies of scale. By giving a context for the motivations of technological and industrial production, we can argue that technology has a built-in character of its own stemming from these same ideals.

In the same way that colonialism exposed a way of structuring space and organizing economies of scale, it also seeped into our construction of technology. The world became mechanized for the sake of producing “cheap natures” more efficiently, driving down the cost of labor. Technology is the medium by which humans interact and ultimately experience the surrounding world. As Caroline Merchant puts it:

Machines (1) are made up of parts, (2) give particulate information about the world, (3) are based on order and regularity, (perform operations in an ordered sequence), (4) operate in a limited, precisely defined domain of the total context, and (5) give us power over nature. In turn, the mechanical structure of reality (1) is made up of atomic part, (2) consists of discrete information bits extracted from the world, (3) is assumed to operate according to laws and rules, (4) is based on concrete free abstraction from the changing complex world of appearance, and (5) is defined so as to give us maximum capability for manipulation and control over nature (Merchant, 1980, p. 234).

Machines thus give way to the economies of scale and the concept of the plantation, because without it such modes of standardization and scalability would not be feasible. Going the other

way, the racial and economic structure of colonialism creates an environment of exploitation and extraction by which the innovations of new technologies thrive. Technology becomes an arm of power. The notion of development that comes out of the entanglement of economy and technology hides the vulnerabilities of the world we live in because they create a power structure centered on those who have the means to produce and reproduce such technologies and wealth. To further unpack what it means to produce technology in this reference frame we must understand the psychological aspect of *excess* in economies of scale. By looking into this social logic, we can also identify the primary goals of technological development of this age.

2.6 The Economy of Excess and The Question of Energy

It would appear that all living things engage in some form of economy in order to survive (Bataille, 1949/1988, p. 27). In nature, this is seen in Darwin's theory of natural selection, where the economy is centered around the ability to survive and reproduce. Biological recapitulation is thus entirely bound by competition among species. Currency, therefore, ranges from soil nutrient character, to water access, to adequate pollination, to sunlight absorption. But an economy of this type is not limited to only non-human species. Humans have conceived for themselves a more abstract economy in this sense, assigning values to goods and services which are exchanged for something of equal value; in the modern day, usually in terms of currency or some other abstract marker of wealth like private property ownership. Something has value because we say it has value. However, there is a linkage between the definition of value in the biological economy and the abstract economy because humans exist in both the biosphere and the sphere of political economy. This linkage is energy, as it is the greatest common asset between the two. There is thus a "general economy, in which the 'expenditure' of wealth, rather than production, [is] the primary object" (Bataille, 1949/1988, p. 9). Energy is the universal currency which supplements the existence of life on Earth while providing the backbone of an exchange economy centered on labor, technology, commodification, and development. In the

words of Bataille, “energy [is] translated into the effervescence of life” (Bataille, 1949/1988, p. 10).

Viewing energy in this way can more easily analogize capitalism, as a way of thinking and structuring society, as a cause of anthropogenic climate change. It is easy to see that nature is commodified in the extraction of resources. When one chops down a tree to build a house or mines iron ore for the creation of tools, there is a material possession, a thing that is harnessed and seen. The labor force could be humans, but can also extend to draft animals or inanimate prime movers. A water wheel using the flow of a river to mill grain, the use of cattle to plow fields, and windmills for land drainage all exemplify some form of labor power. Energy and power become commodities themselves. There is a constant cycle of extraction, energy expenditure, production, consumption, and othering. Through this cycle, the philosophy of the Enlightenment holds that nature is somehow in need of human stewardship. We can now further contextualize the religious sentiments of the era and its impact on the creation of an economy that is centered around the exploitation of nature and people. That is not to say that the economy was created out of religion, as that is beyond the scope of this paper, but underlying Judeochristian values certainly permeated the hierarchical structures of wealth. Additionally, by looking back to this logic, we can understand how the development of technology as we know it today was centered around this same goal.

In the “Parable of the Talents” it is our duty as humans to take from the Earth, for it is a sin in the Lord’s eyes if we do not take such advantage. “For unto every one that hath shall be given, and he shall have abundance: but from him that hath not shall be taken away even that which he hath/ And cast ye the unprofitable servant into outer darkness: there shall be weeping and gnashing of teeth” (Matthew 25:29-30). The guiding question of the natural philosopher was then justifiably: ‘how do we reap all the goods of the Earth?’ The answer was no longer just in the science of understanding the physical world, but in developing technology that helps carry out this task. That question alone, wedged in the foundations of capitalism, was justification enough to explore technologies that would explode into what we call the Industrial

Revolution. How then, did this philosophy progress into an era like the 21st century, which is dependent on technology to work both for and against this question?

2.7 Central Domains and Technology as an Arm of Capitalism

For natural philosophers like Descartes, Hobbes, Locke, and Bacon, the idea of a machine order was the “central domain”⁷ of their universe. What I mean by this is that the world and the universe it sits within belong to the domain of God, who is the divine craftsman. Thus, the world itself is a machine within a machine, functioning as a piece of an untouched system that only requires the stewardship of God. Everything discovered about the system of the universe was an explanation for the extent of a great machine. If this were the “central domain” of the epoch of the Scientific Revolution/Enlightenment, then the next century could be classified as one with an *economic* “central domain.” As we saw, the machine order ideology seeped into our notion of production and control through the creation of economies of scale (which were not as explicitly religious but still echoed loudly). “A secularization followed in the nineteenth century—an apparently hybrid and impossible combination of aesthetic-romantic and economic-technical tendencies” (Schmitt, 1929/2007, p. 84). A “central domain” is one that constitutes the European view of progress being linear, and from this, how the “intellectual vanguard” views the cultural and systemic problems of society falls under the regime of a single focus (Schmitt, 1929/2007, p. 81-81, 86). So, looking at how natural philosophy transitioned to Rationalism in the seventeenth century suggests that Rationalism quickly became a philosophy centered around economics in the age of Marx, Engels, Smith, and the Industrial Revolution. Technology, coming from the camp of the natural philosopher, was now not mainly viewed as a tool to probe the Earth for knowledge and resources, but rather to use it for production and extraction. The overarching economic structure and class stratification could be reproduced in a system mediated by mechanization. A combination of resource extraction in the name of

⁷This term comes from “Age of Neutralizations and Depoliticizations” (1929/2007) by Carl Schmitt. I find it important to recognize that using Schmitt is a moral quandary, as his solution to the problems he found in society was Nazism. While this is obviously troubling, the problems he identifies in his philosophies and writings are legitimate despite his solution. Thus, we will use his thoughts on the state of politicization and political economy as theory, acknowledging his background.

God, and the production of “stuff” in a more advanced industrial economy, further advanced the notion of the planet as an infinite reservoir because of its seemingly undepleted wealth. Thus, technology helped mediate an economy of excess.

Looking more closely at the relationship between technology and capitalism helps demonstrate the ‘class divide’ made between humans and nature during this period. In the Weberian sense, class is “determined entirely by economic interest” (Weber, 1946/2010, para. 5) and from a Marxian perspective a hierarchy is created by the production process itself. If the economy is seen from the perspective of the human, the interest is extraction and exploitation of both the land and the labor power, while the powerless entity is, capital N, Nature. A class hierarchy is established. However, the commodification of the labor and the private ownership of areas abundant with certain natural resources and access extend us back toward the idea of a plantation that we encountered earlier. This logic is reoccurring in separate “central domains.” Within the economic framework of the nineteenth century, the othering of the Earth now included labor on top of energy and resources (the latter two we had seen in the age of natural philosophy) because technology allowed humans to ‘make the planet work for them.’ The lack of immediate, large-scale, negative environmental impacts and the rapid expansion of industrial economies made it easy to neglect the relationship that humans shared with the planet outside of that of a master.

We may then ask the question: how did technology come to be the main focus of society when economic thought was still so prominent? The answer lies in how new machines were invented to improve energy efficiency and production in the workplace. It lies more theoretically in how the “central domain” shifted during this period. I will focus on the latter for the sake of brevity, as one could look at every historical version of the engine alone as a way of helping to illustrate this entanglement. The late nineteenth and early twentieth centuries ushered in a new age of “technicity” (Schmitt, 1929/2007, p. 87). As new inventions popped up left and right, technology was seen as a way of making progress to solve the world’s ills. Technology itself did not need economy to be considered progress in its own right, however technology was

given a platform as an agent of progress by a nineteenth century fetishization of industrialism. “Technology appeared to be a domain of peace, understanding, and reconciliation. The otherwise inexplicable link between pacifist and technical belief is explained by this turn toward neutralization which the European mind took in the seventeenth century and which, as if by fate, has been pursued into the twentieth century” (Schmitt, 1929/2007, p. 91). Technology was seen as a purely neutral and scientific solution to the more contentious frameworks of economics and religion (Schmitt, 1929/2007, p. 90). It seemed as though technology had detached itself from the philosophical framework it was born out of. However, every new “central domain” is still influenced by the previous ones, and as we will see in the coming chapters, technology is itself not a neutral or apolitical artifact.

As technology became the marker of progress rather than knowledge or economic growth, it was seen as the backbone from which those arms extended. It was now the medium by which humans interacted with nature, not God, and not the bank. But because technology has its roots in the notions of extraction and control, which was perpetuated in the era of Capitalism and industrialization, by the twentieth century technology was thought of mainly in terms of accumulation and consumption. How can I get more for less labor? How can I control my surroundings completely? How can I ‘progress’ further and be ‘modern?’ These questions led to an age of energy excessivism. We have come full circle, like the student that becomes the master, the economy of excess that gave rise to technology was now an economy controlled by technological prowess. The economic domain of the nineteenth century gave rise to the need to sustain progress through energy consumption, and thus the planet was banished to serve man indefinitely. George Bataille notes that energy is abundant and the source of life, but that it naturally exists outside our notion of consumption.

The living organism, in a situation determined by the play of energy on the surface of the globe, ordinarily receives more energy than is necessary for maintaining life; the excess energy (wealth) can be used for the growth of a system (e.g., an organism); if the system can no longer grow, or if the excess cannot be completely absorbed in

its growth, it must necessarily be lost without profit; it must be spent, willingly or not, gloriously or catastrophically (Bataille, 1949/1988, p. 24).

There is always going to be an excess of energy resources on, within, or around the planet which can be tapped into for as much as one can take, not necessarily for as much as one can use. There is therefore no immediate punishment for wastefulness. When one invests with their own capital and receives little or no return, one is at a major loss. However, when one plays with the house money there is no loss taken by the spender. This position of leverage is extraordinarily unique in the economy of exchange between humans, which is why energy and the environment are taken advantage of and not seen as some type of currency to be spent wisely. It is also a reflection still of those religious sentiments of relishing in the bounty of God's Earth. There are no budgets, few reviews, and little care heeded to excessive spending. The other aspect of this is temporality. There is no immediate feedback for loss of energy besides, for example, the excessive smoke or lack of heat. Overall, there are short term effects, but no real consequences. So how does technology play into this mindset in the present day if we still remain in the "central domain" of technicity?

If technology is thought of as a vessel of extraction, there exists no boundaries. We can continue to develop and research technology at some exponential pace for the sole purpose of taking as much as possible and spending it all for the use of humans. Nature becomes the bank that technology exploits for the benefit of mankind, except nature is always absorbing all of the loss. Technology becomes a weapon for this cycle to continue, with humans becoming ever better at storing surpluses of energy and expending them without care. Growth, like populations, is no longer a sustainable phenomenon with respect to using up energy without excess (Bataille, 1949/1988, p. 37). This perspective is completely different than that of technology harvesting the 'fruits' of nature as something more readily available for mankind. However, if technology is created with the idea of extraction and expenditure in mind, it is inherently weaponized against nature. The idea of technology being weaponized takes us back to the images of control and mastery from the Baconian camp. Technology had and has fulfilled this promise thus far. If

technology is used as a means of control, and if it can conform to whatever system it is placed within, we must seriously ask the question: is it a neutral entity? Can green technology exist if it continues to work within the systems of economy that lead to environmental degradation? If we are to build a green future, do we need to change the overarching philosophies that permeate our economy and our society through technology?

These questions are certainly not meant to be Luddite-esque, meaning we relinquish all technology and denounce it as something always evil and static. Technology is useful and can be used to create vast positive change if it is understood as something more than an artifact. This exercise in thinking about frameworks, illustrates that technology cannot be viewed as some apolitical actor if it is employed within some political or non-neutral ideology. From the framework of excesses and exploitation, as we saw above (and with plantation logics), industrial technology is employed to carry out goals that do not keep the interests of the planet in mind. If we used new climate conscious technology in order to take our share of the ‘fruit’ of nature and use it without blind disregard for how much we destroy, we could still grow and support our populations. It comes down to a logic centered around our perspective. Instead of how can I take more, we instead must ask how can I better use what I have? Can technology allow me to be more efficient? The bigger question is: will the sentiments of environmentalism in green technology be able to hold up in the framework of capitalism, or will the commodification of ‘Green’ hold us back?

Obviously the ramifications of climate change have shown us that nature is starting to fight back against our more cavalier attitudes in the form of urban destruction. This is precisely why we need to negotiate between the fields of architecture and engineering if we are to build and design a brighter future. We need to further explore the role of climate technology in this paradigm, and how it can best be employed in the built environment. It becomes critical that we analyze the intersectionalities of political agenda, sociology, science, and economics with respect to climate technology in order to define the larger questions at the heart of their potential impact.

3

The Inherent Politics of Technology

3.1 The Character of Technology

Before moving into the specifics of climate technology, we need to focus on the character of technology more generally. “Arendt contended that the question of technology is also a political question; it is, in other words, a question of how human beings live and act together” (Sacacas, 2014, para. 7). We, ourselves, have started to ask whether or not technology is a neutral actor, and this question is vital in understanding how technology can be used more effectively in creating a greener future. The questions posed at the end of the last section appear to be an obvious leaping point for science and technology studies (STS), yet the field of social constructivism appears to dance around them (de la Bellacasa, 2011). Is technology a socially mediated phenomenon like we have seen with its involvement with politics and the economy? Or, does technology mediate social behavior like we saw with a changing of the “central domain” of the nineteenth and twentieth centuries?

As Langdon Winner points out, there is a “redundant” trope echoed in the halls of social constructivism that is the notion that technology is socially constructed. The ideas of who makes the decisions regarding the employment of technological artifacts and systems, or how they end up being employed, are fundamentally ignored along with the questions of how they influence human experience and behavior in such impacted communities (Winner, 1993, p.

366). Taking an example from architecture, this lack of sociological thinking by those in STS is evidenced when looking at Robert Moses' construction of bridges along Southern State Parkway in the middle of the 20th century. The bridges did not allow for the use of public transport based on their height and positioning, and the motives for their production and the impacts it had on marginalized communities should obviously be called into question when something as simple as a bridge is thrust into a political context (Kessler, 2021, para. 8; Winner, 1993, p. 374).

In a similar example, the construction of highways after WWII could be seen as a feat of American technological ingenuity. By creating a greater circulation network similar to that of the railway systems of Europe, space and time could shrink, productivity could grow more rapidly, and people, institutions, and information could be more easily connected into a network (Schivelbusch, 1977, pp. 32-55). However, any infrastructural decision is inherently political, and those with governing power are the ones who have the authority on their placement. Ultimately, many highways were constructed on the boundaries of black and white communities as a way to perpetuate segregation (Noel King, 2021, para. 11). Laws that made zoning and redlining more difficult (but did not completely stop these practices) were beginning to be instituted, so creating an infrastructure that could physically separate communities became a political motive for such a banal technology. One could ask: how were these highways maintained in their respective racialized communities? How was access granted and made possible for different peoples? And what were the effects of having large public transportation infrastructures essentially run through the backyards of black and brown homes?

These are all important questions to consider when defining the character of technology as a social mediator in the built environment. The combination of architecture and engineering makes the placement of technology all the more complex. As Winner puts it, this viewpoint is the "social determination of technology" theory where "what matters is not the technology itself, but the social or economic system in which it is embedded" (Winner, 1980, p. 122). There is a struggle between this theory and practice, as exemplified above, because of

the expansiveness of such systems and the need to understand their complex structures, in their entirety in order to determine the social character of technological artifacts. However, Winner proposes that there may be a twofold techno-political nature of such artifacts. The first mode would consist of a technology that is used to achieve some social or political end that is outside the scientific use of the artifact. The example he provides is a mechanization of labor to help dissolve a union, rather than actually produce efficient and cost effective production. The second mode would be technologies that are “inherently political” because they “appear to require, or be strongly compatible with, particular kinds of political relationships” (Winner, 1980, p.123). This mode can be evidenced explicitly by censorship technologies that are compatible with the goals of an authoritarian regime.

Both modes give unique perspectives on the potential for a politicization of artifacts without the necessity of social feedback to politicize them. Whether or not the characteristics of individual artifacts are inherent to that type of technology as a whole, and if the consequences that arise are completely unforeseen remains a question (Winner, 1980, p. 125). It appears that intentionality is where the social constructivism perspective on technology ends. To constructivists, technology is entirely revealed by the social forces which shape its usage. But, as we have seen, the inherent political character of an artifact may be a separate cause that allows us to see more clearly the structures that conceived of it and the social dynamics that it may enter into. Thus, a marriage needs to be made between viewing technology as a socially driven entity and one that is more individually conceived.

There also exists an alternative view to both social constructivism and the theory of inherent politicization that needs to be addressed. In the Ellulian sense, technology is something that shapes humanity more than humanity shapes it. This is an interesting proposition in the sense that we can clearly visualize more modern examples that have direct impacts on psychology and health. Social media is a purely digital infrastructure that leverages algorithms and targeting in order to create a unique experience for the user. Mental health is deeply impacted by this approach, not to mention new ways of human interaction, communication, and expression. It

is from this perspective that Ellul defines technique out of the processes of technology, a means in which humans abstract themselves from nature, constantly redefining the human condition (Ellul, 1983/2000, p. 7).

The same can be said of more infrastructural technologies and the methodologies and mechanization they allow for. As we had noted previously, industrial technologies allow humankind a certain amount of leverage over the planet. In turn, this leverage shapes our view of our planetary dynamic for better or worse. Once we gained the ability to drill for oil and mine for coal, society shifted toward a carbon economy. The recent popularization of green technologies like personal solar panels and electric cars have become a phenomenon linked largely to class. Jacques Ellul would suggest that sociological and cultural shifts like these based on our current technological capabilities demonstrate that “man is increasingly dominated by the tools he has created” (Stover, 1963, p. 319). Despite the connotation of that quote, it merely suggests that we shift our perspectives based on what is technologically new and feasible. Whether this leads to good or bad trends in the economy, politics, infrastructure, and/or social movements is not concrete.

We have now built up an intuition that we, as people, define technology (without explicitly mentioning how yet) that technology itself has its own character, and that there is an effect technology has on society as a whole. Any radical change in the machinery around us leads us to question where we are headed as a people. Does technology lead to specific behaviors in us as a species? If our current “central domain” is technology driven, is the trajectory of humankind based on technology’s effect on us? Are there any parallels between how we define technology and how technology defines us?

3.2 Technology Impacted and Impacting: The New Four Causes

With regard to the last question, we may look at how we have historically tried to identify the true essence of technology with hopes that it may be reversible. Heidegger, who is seen as an alarmist of technology similar to Ellul, appears to take a more ontological approach

to technology. He employs the Aristotelian four causes of being: the final, formal, material, and efficient causes, in order to describe what truly makes something itself (Heidegger, 1977, p. 288). As Andrew Feenberg puts it, “a hammer is only a hammer as it is culturally signified as such. Outside of any cultural context it is just an oddly shaped piece of metal and wood” (Feenberg, n.d. a, p.20). This is an important distinction because it seems to place a heavy importance on society’s influence in the ontological world of technology. However, the four causes themselves are all characteristics outside of the definitions people impose on technology. The formal cause is a design aspect that allows shape to carry out the expression of function. The material cause is the basis for creational usability and feasibility. The efficient cause is the process by which the creator makes something and expresses it into being (Heidegger, 1977, 288). These three are the work of craft itself and give significance but not a higher character or being. Only the final cause, the purpose, seems to express these other three and together all four relate to bridge the gap between the cultural and craft based significance of being (Feenberg, nd. a, para. 20).

Now that we have explicitly gone through a way that society shapes the formation of techné, I would like to propose an alternative for how this ontology goes the other way. How does the way we define technology impact us as a society? Obviously, technology does not birth humans literally; there is no craft supporting the makeup of a person. However, the four causes can be seen as a model for how technology shapes the human experience and therefore society. The formal cause is the framework technology builds to shape social interactions. Ways of communicating are now directly tied to a technological and data driven infrastructure. Modes of sharing information have been greatly impacted by networks and the security that keeps the information protected. Thus, this digital and material infrastructure has changed the way humans interact with one another and will continue to. The material cause can be abstracted to be more related to human psychology. We have already discussed the impacts of technology on mental health, and I argue that psychology governs who a person is and what they will do, making it the ‘tangible’ basis of behavior. The efficient cause can be seen as the ways technology is used as a tool to change or maintain larger political systems. Technology can be

seen as a marker of informal social control by creating specific modes of living centered around the production, development, and interaction with technology. Herbert Marcuse notes that this prevailing rationality will persist as long as social groups continue to subscribe to the dogmas of industry (Marcuse, 1941, p. 149). On a more personal scale, one could view the efficient cause using Winner’s idea of political character, (the inherent nature of an artifact as a marker to be used to shape the experiences of a person). The childhood of someone who grew up in a segregated and class stratified society will produce a vastly different frame of reference than someone who grew up in a socialist commune. The final cause is thus a gathering of these other three causes to produce what we know as broader societal change and influence. An exercise in directionality, such as this, provides us with a richer definition of the entanglement of humans and machines. It also makes us question how we reconcile such extremely different viewpoints like constructivism and Ellulian thought, if they both appear to have weight in their arguments.

While this falls somewhat in between both camps with regards to the social dynamic of technology, our definition is more dynamic. The simultaneousness of influence for both society and technology allows us to situate technology as the defining characteristic of progress. Back to the question of our “central domain,” it would appear that this entanglement itself is what we call progress toward modernity. The more deeply intertwined society and technology become in their development is what allows us to view our problems more concretely as technical ones. The trajectory of a society’s progress is therefore contingent on the modes of governance and control not only of its people, but its central “dogma,”⁸ technology, as well. Looking at such a feedback loop calls upon the theory of cybernetics in order to get a handle on questions surrounding climate technologies and their social impacts as we work towards a green future.

3.3 Cybernetics as Metaphor and the Realization of Being

We spent the last section identifying the balance between social influences on technological development and vice versa, and determined that technology is simultaneously influenced

⁸Term taken from Schmitt’s “Age of Neutralizations and Depoliticizations” (1929/2007)

by, and an influencer of, man. The ontic characteristic of technology is based on principles of physics, biology, and chemistry. Beyond the ontic, the ontologies of technology lie in the meanings prescribed by humans. Reconciling the ontic and the ontologies of technology is a distinct tension and release in the search for technological meaning. New technological artifacts are created for use by the public where they will have some character that shapes the experience of the user. Meanwhile, the interaction of the human with the artifact usually leads to a remodeling of the technology itself, generally for the sake of profit. The user experience is quantified as a tool to shape technology. Stripped of its political value, technology can continue to develop in such a system purely for the reason of production and profit. Thus, the mediator of the human-technology relationship is capitalism.

The underlying motive of profit adds a political layer that makes the technosphere itself non-neutral or political. What a piece of technology is capable of in the scientific sense, is skewed by what it actually gets used for and who gets access to it in the system of capitalism. This becomes a constant struggle between what the object is in reality and what it ‘wants’ to be (Feenberg, n.d. b, para. 27-28). This sentiment is most applicable to climate technologies. The scientific characteristics that underlie the functionality of any given artifact are researched for their use as purely scientific. The political structures it is subsequently placed within, controls its development and how it gets implemented. As we will see in the next section, oil companies research biofuels only to patent and shelve them in order to keep selling petroleum (Goldenberg, 2016). Consequently, the prospect of a green future may be delayed by corporate greed or political agendas.

We can call what happens to technology outside of scientific research its user potential. The user potential is always unstable because any political or economic decision can change the trajectory of how or if it is employed. Another example of this phenomenon is when renewable energy systems like wind power, where wind farms are often rejected due to aesthetic unfavorability. In my home town of Wells, Maine, there is currently a strong campaign to stop a solar farm project because of its effect on property values. Thus, “realized potential” is what

the artifact could become in its best sense based on the ontic nature of its scientific basis, and is unrealistic in any society. The basic idea Herbert Marcuse had is that humans pervert technology from its purest state of being into something political, but only through humans can we help the object realize its fullest potential (Feenberg, n.d. b, pp. 36-37). In the context of green infrastructure, this argument suggests that the factor of initial investment and aesthetic cost vs. cost of future damage due to climate change should be more heavily considered in a capitalist economy. One would hope that the well-being of people and the planet would be placed above profit margins and political power, but so far this hope has gone unanswered. So, we must ask: how should humans approach governing technology then? Is it really ever possible to get close to reaching the maxima of realized potential in a non-utopian society? Is there a level we need to shoot for to realistically get the most of our innovations in whatever economy we implement them? To answer these questions involves the guiding principles of cybernetics, and applying them in a semi-metaphorical way, in order to better understand humanity's role in the real world application of climate technology.

What we have identified is a feedback system of development, where, in its best sense, it can help to create a more egalitarian technosphere in the fight against climate change. My aim is simple, to illustrate how this system works in reality, and the barriers in place that deviate this feedback from being more utopian. Cybernetics, as coined by Norbert Wiener, defines a system of complex entities that feedback from a balance of communication and control (Wiener, 1948, p. 1). Control is the applied version of control theory which deals with constraint and power dynamics within systems. Generally, this way of thinking would lead to an understanding of the parallel and intersectional relationships between humans and machines. The ways we have already viewed the role of technology on the control of humans and humans on the control of technological development, seem on par to what cybernetics hopes to explain. Cybernetics leans on the establishment of a governor or governing body in order to keep things in check. The set of rules in computational mathematics, or the mechanism by which a system runs and is regulated (like the governor of a steam engine), are basic properties by which complex systems function.

In the social constructivist view of STS, and basic technological artifacts alike, the governing body is seen as humankind. There is a direct hierarchy of power in place in which people create objects and give them meaning, taking on the role as the governing authority of both the ontic and ontological in the Heideggerian sense. However, we also saw how technology exerts influence on humankind through the inversion of the four causes as well as viewing technology as Jacques Ellul did. In the Ellulian formalism, technology was the governing body over people, constantly controlling the ways we behave and think. When looking at climate technology in this way, the limits of technology and the science that goes into them can change how humans behave environmentally. For example, as smart solar grids become more common for the household, people may become more aware of their personal electricity consumption. Similarly, this effect may cause people to seek out more renewable energy options as they appear more favorable in the public eye, in terms of lowering one's carbon footprint (DiChristopher, 2018, para. 5). In this paper, we have argued that both the social constructivist and Ellulian views of technology appear true. As we develop more efficient and complex climate technologies and they become more ubiquitous, there is an oscillatory effect between how we influence the climate technology market as consumers and how the market influences our choices. More abstractly, this can be described as cybernetic development, a constant tension and release between the governance of these two systems.

There was another important characteristic that we noted in the ontology of technological artifacts which was the possibility of non neutrality in their inception. This is especially important to see, as the level of neutrality can drastically affect the trajectory of such a cybernetic system. A technology that starts off with some politicization has a predetermined maxima in its user potential (the question of *how* it will function). A climate artifact like a wind farm, if used to disturb and disrupt a community more so than to generate clean energy, then it will face problems in the public sphere. As we have seen, the development of artifacts hinges on the development of society alongside it. The starting point of the political character of an object thus shapes the developmental path it takes toward what I will define as its fundamental potential:

the limit of user potential where an object has moved toward its basic mode of politicization in society. For climate technology, the constraints of time and money influence a fundamental potential limiting how it is perceived within society. Unless there is a paradigm shift regarding the constraints themselves, or the technology is updated, it will stop developing further in this social context. In short, the inherent political character of an object is going to immediately shape how society views and uses it. This principle places great importance in how we view the non technical factors that go into creating climate technology. It is important that we create more efficient technology, but it is also paramount that we focus on the societal constraints we place on it which limit its effectiveness in the real world. An artifact is only as good as we allow it to be.

With this in mind, there is still an interesting note we need to recognize: the idea that technology, and particularly climate technology, encompasses a secular religion. There is a faith placed in technology that it will one day surpass our ability to problematize it, and all of the world's ills will be solved. Many technologists see this future as messianic. Langdon Winner likens this to “fantasies of immaculate technological conception” wherein our culture envisions a “futurist tableaux” which links technology with the creation of “personal identities, social ideals, private and public values, as well as spiritual attachments” (Winner, 2004, pp. 40,46). The ideas of the natural philosophers, who thought of the world as some large mechanism controlled by God, has transitioned into a belief that technology will continue to reproduce itself for our benefit. No amount of futuristic technology will get rid of the fundamental inequities in our society without us collectively thinking about these issues and using technology as a tool in that framework, not as the only solution. This exercise of thinking of technology as a social instrument is reflective of what Maria Puig de la Bellacasa notes as “matters of care” (de la Bellacasa, 2011). What Bellacasa suggests is that we need to consciously account for the conditions that we place technology in, and have the foresight to imagine what that piece of technology is capable of in that setting. Arendt also sums this up in the *Human Condition* (1955): “What I propose, therefore, is very simple: it is nothing more than to think what we are doing” (Arendt, 1955, as

cited in Sacasas, 2014, para. 4). It is therefore imperative that a variety of fields gain real world technical knowledge, and that scientists and engineers gain practice in sociological analysis. Through an interdisciplinary approach we can navigate a more complex technological future, where environmental and ethical conditions are built into the artifacts themselves.

So far, we have seen that the logics that produce capitalism and global conquest are the same ones that continue to produce technology. The entanglement of industrialism, technological development, and capitalism is so tightly bound, that to think of them each in a vacuum is naive and dangerous. The social conditions produced by capitalism and colonialism are reinforced by every technological development put in place to save the natural order, the status quo. In this way, it appears as though technology is a tool to save capitalism. The current logic goes like this: if we continue to innovate our way to a better future, we do not have to address the inequities that have become fundamental to our society. Not to mention, these are the same behaviors that contributed to the climate crisis in the first place—consumption, excess, and extraction. Technology can treat the symptoms of climate change as it has done up to this point, or we can use it to help us identify and change behaviors that are not conducive to an environmentally friendly future. The latter is obviously the more sustainable option.

4

It's Not Easy Being Green

4.1 Case Studies in a Green Future

The current discourse surrounding climate technology is similar to that of a biblical prophecy. Technology is the savior that will someday reach a level of complexity where it will be able to solve the world's ills before they can even arise. We may not know how we will get to that point, but we can entrust the scientific community to get us there one way or another. While this feeling is somewhat logical, it postpones addressing critical issues into a future that has the capability of solving them. It instills a mindset that there will always be another tomorrow. The problem is that even though technology may become more complex, the social conditions we continue to reproduce are static. Therefore, as addressed in the last chapter, technology can only do so much to create a green future. Climate technology would have to improve scientifically *and* be utilized in a new social structure in order to meet the global demand for carbon neutral or net positive energy production.

It is from this vein that climate scientists and policymakers have proposed plans that treat carbon reduction like Moore's law: an exponential change in the amount of CO₂ sequestered from the atmosphere (Carrington, 2017, para. 1-5). The hope is that both the efficiency of these technologies, and the amount we invest and produce, will double each year, eventually offsetting carbon emissions as this sector continues to grow. While the trends suggest

that this is possible, there is a fair amount of pressure from both the business sector and the environmental sector to accelerate this pace even further (Winston, 2009, para. 4), essentially putting it in our hands instead of the hand of natural progress.

The issue of climate trajectory and the use of technology has become strongly political, yet businesses and lawmakers alike have resorted to performative actions and even more blind faith in the capabilities of a technological future. Specifically, the rise of green capitalism and subsequent greenwashing has permeated the industrial sector, leaning on technologies to make practices that were once rife with carbon emissions *appear* greener. On the other side, the Green New Deal proposed by democratic lawmakers makes good on the intentions of cleaning up the planet, while placing most of their faith in the development of cheaper climate technologies. In both instances, the idea of green appears to be a band-aid put over a wound in order to make the status quo more compliant with a future imaginary, rather than changing the current ways of living for the amelioration of society. Rather than changing fundamental practices of industry it is our duty to develop technologies that will make them more presentable and palatable to the public.

Here I will highlight the concept of green capitalism and its failings. “Green capitalism is an approach that says we can use the levers of the market to fix the broken environment—that’s its fundamental reasoning” (Rogers, 2009, para. 2). Essentially, there is a twofold effect in using fewer resources: (1) eventually the planet will run low on non-renewable energy supply and companies will be forced to figure out how to cope with a low supply of energy commodities in order to function. (2) The idea of more conservative usage in business’ usage leads to more profit in the long run, because they are figuring out how to make more with less (Rogers, 2009, para. 3-6). The only problem with the “greening of capitalism” is that fundamentally, the practice of corporate business does not align with social ideals of environmental sustainability (R. Smith, 2011, 49). The idea that companies can reduce waste and produce, ship, advertise, and pay workers in a green way is a pipe dream. “CEOs and corporate boards

are not responsible to society, they're responsible to private shareholders. CEOs can embrace environmentalism so long as this increases profits" (R. Smith, 2011, 49).

Even if the managers of the world's worst polluters were willing to pursue rapid decarbonisation, their shareholders would resist. For decades, the gospel of shareholder-value maximisation has reigned supreme, and managers have known that if they deviate from the orthodoxy they will be sued for violating their fiduciary duties (Pistor, 2021, para. 7).

The idea that one can retain profit just from being more environmentally conscious is one example of placing blind faith in technology; somehow, a cheap version of technology will be produced that will allow one to continue on the current trajectory and business practice, but will limit waste and emissions. Modeling economic practice off of this "new" technology will inevitably lead companies to greenwash in the meantime.

'Greenwashing' is a common marketing ploy designed to make products seem more sustainable than they are. It's essentially a way to convince customers that a company is making positive environmental choices, often through eco-conscious verbiage designed to convince shoppers that the product is more natural, wholesome, or free of toxins than competitors (Noyes, 2021, para. 3).

Greenwashing takes shape mostly in advertising, but can also appear in the statements of the goals of the company, or in the research it is doing to become more sustainable. Tesla provides an interesting dilemma for consumers and techno-scientists alike: is the company really green? Like all electric car companies, the idea of reducing fossil fuel emissions on the roads is the goal, and a venerable one at that. However, the level of displacement from the user to the emission process is what helps electric vehicle companies appear greener. According to the United States Energy Information Administration, electricity production still largely burns coal or natural gas in order to power the grid (US EIA, 2021i). The grid will have to keep up with the rise of electric vehicles and burn more coal as a result, yet the emissions are out of

sight, out of mind. In Tesla's case, the battery used in the car is made of lithium which is mined in poorer areas of the globe. Mining companies like Cypress Development Corp. make deals with Tesla at the expense of the surrounding landscape (B. Smith 2020, para. 3-4; Ajemian et al. 2020). Additionally, the newest patents Tesla has filed in order to extract more lithium from clay deposits (a potentially cleaner way of mining) relies on technology that has not yet been tested at the scale needed to be feasible. Yet, that did not stop press releases and stock options from soaring at the news that Tesla had potentially developed a better, more profitable way to exploit the land. In any sense, the materials needed to create these advanced technologies require practices that damage the Earth in other ways, usually in the parts most affected by climate change in the first place. It becomes tough to distinguish whether or not green technologies can be produced in a green way, or whether farther upstream, they offset the good being done by their employment. In any case, the green nature of the technology lies in the public's belief that they have made the right decision by using it.

In a more blatant act of greenwashing, BP came out with the 'Keep Advancing' and 'Possibilities Everywhere' ad campaigns. BP being an oil giant provides a not so subtle irony in the act of trying to convince the public that they are a company on the rise toward being environmentally conscious. ClientEarth Communications, a scientific policy and law think tank, notes that even if they invested in new technologies to move towards a green future, currently 96% of their investment is in oil and other fossil fuels (CE, 2020). But it was not just BP that tried to trick the public into believing that they were trending in the right direction. Exxon, Aramco, Shell and the American Petroleum Institute were also sued by the City of New York for lying to consumers (Gilmer, Van Voris, Bloomberg, 2021). The most blatant of the group came from Saudi Arabia's Aramco who stated:

that it conducted business 'in a way that addresses the climate challenge' yet it is the world's largest corporate greenhouse gas emitter and plans to continue exploring for more oil and gas, despite having reserves greater than those of Exxon, Chevron, Shell, BP and Total combined (CE as cited in Carrington, 2021, para. 7).

Green capitalism functions on making the consumer believe ethical practices are being used. Most of the time, it is a performative act that uses technology as a way to advance their message. Exxon claimed that they were studying algae for potential use in a carbon neutral energy future (Carrington, 2021, para. 6). While this is useful and scientifically true, it does not offset their current work as an oil company. Climate technology, in this way, functions as an easy get out of jail free card in the court of public opinion. If the public believes you are working on something that is technologically out of reach for the average citizen, you can make your company seem like it is part of the new climate technology future; that you are part of the solution. But just as Paul Hawken notes in his assessment of a green business award he had received was that

What we had done was scratch the surface of the problem... but in the end the impact on the environment was only marginally different than if we had done nothing at all. The recycled toner cartridges, the sustainably harvested woods, the replanted trees, the soy-based inks, and the monetary gifts to nonprofits were all well and good, but basically we were in the junk mail business, selling products by catalogue. All the recycling in the world would not change the fact that [this] is an energy intensive endeavor that gulps down resources (R. Smith, 2011, 52).

Climate technology is just a mask used to hide the true business practices that go on behind the scenes.

While Green capitalism deals with the question of technology as more or less a performative art, the Green New Deal uses technology as a potential vector for success with little to no technological specifics. Green capitalism obviously functions within the regime of a capitalist economy, while the Green New Deal is seen by many as a push towards a more socialist governance. The Green New Deal is revolutionary in that it is a truly comprehensive economic analysis of climate control and deadline targeting, which in the process should provide new green energy jobs on the scale of FDR's New Deal from a little over three quarters of a century ago.

For starters, the most common phrase in hRes109, the bill proposal to Congress for the Green New Deal, is “as technologically feasible” (Ocasio-Cortez, Markey et al., 2019). In the proposal, they speak on technology that has and will be feasible in their use value, but the real feasibility they are after is how economically competitive they will be. At the same time, it correctly supposes a more technologically advanced future, yet calls for an overhaul of today’s infrastructure with the technology available to us at this moment. This does not allow for easy integration of new technologies, as they come out, if we are creating another monolithic and hard to change energy regime. It does not account for transitional technologies. Granted, one cannot create something that is beyond technological feasibility, but the issue with the verbiage is that it is just vague enough to place all hope in the advancement of technology of an unspecified kind, making the proposal itself an economic plan rather than a more interdisciplinary approach to environmental governance. On top of that, other analyses of the Green New Deal point to the fact that it speaks to “no nukes” and “no biomass” in its clean energy future (Stein, 2016). This analysis of clean energy neglects the carbon neutrality of more localized biomass production through photobioreactors as a means of producing carbon neutral biodiesel. Additionally, the loss of nuclear power would cut half of the clean electricity production; (clean electricity comprises 40% of the overall electricity production (US EIA, 2021i). Yes, the radioactive material produced by nuclear power plants is a danger to both human and environmental health, but on a larger scale the closure of nuclear power plants eliminates a source of electricity that does not emit excess carbon into the atmosphere, which addresses the immediate problem at hand. This fact makes nuclear power vital in the transition away from fossil fuels, and as time passes, it will itself becomes obsolete.

Likewise, the language that appears to be one of the largest gray areas of the GND is infrastructure. One proposition is “to invest in the infrastructure and industry of the United States to sustainably meet the challenges of the 21st century” (Ocasio-Cortez, Markey et al., 2019). While such a plan is necessary, in order to meet the standards of production to meet such infrastructure within the time frame required, would require a large expansion of industry

that is currently unsustainable. Obviously this is the point, but also the paradox. The modes of production in the current capitalist model are themselves large producers of emissions, and we would have to leverage this system in order to meet the demand of clean energy and urban infrastructure in the future, which could itself produce massive amounts of emissions. Therefore, a more specific phasing out of fossil fuels needs to be spelled out in order to give explicit direction as to how to proceed with the infrastructure goals of the GND.

The majority of the conclusion of the GND speaks to the economic requirements placed on the US government in terms of land grants, job security and training, and trade (Ocasio-Cortez et al., 2019). According to the authors, lawmakers will have to rely on partnerships with academia in order to fulfill this demand both economically and scientifically. While this proposition seems obvious, as lawmakers most likely do not possess the technical expertise required to engineer a new future, the faith that science will get it done is what unravels the other valuable parts of this project. The inclusion of land rights, indigenous voices, addressing systemic injustice, among other things embedded in the language of the plan is partially undone by the question of technology. How will this get done if the systems of oppression are reproduced? Are we supposed to just trust that things will work themselves out if we base everything on market value? Are the main questions asked by opponents to such a bill because the scope of the plan excludes more specific technological frameworks? While this is perfectly fine to use in an economic proposal it is apparent that it makes the project sound more like a pipe dream than a plan, and has been labeled as such by conservative pundits. Due to the lack of explicit technological plans, goals like “promoting the international exchange of technology, expertise, products, funding, and services, with the aim of making the United States the international leader on climate action, and to help other countries achieve a Green New Deal” (Ocasio-Cortez et al., 2019) echo the lofty sentiments of technological utopianism without changing any of the realities of everyday life.

Recently, the COP26 summit in Glasgow invited experts from all over the world to discuss the plan for global environmental regulations and goals for carbon neutrality in the

next few years. Specifically looking at the built environment, architects have proposed green technologies for building, mostly in a performative way. The architecture firm Skidmore, Owings & Merrill (SOM) made headlines for their “Urban Sequoia” proposal which would “transform buildings into solutions” (SOM, 2021). The idea is that buildings would not strive for carbon neutrality, but rather create a new type of built environment around carbon sequestration. Not only does it claim to be able to function at any building scale, at any city around the world, and could, in a more urban environment, “sequester as much as 1,000 tons of carbon...equivalent to 48,500 trees” (SOM, 2021). While the effort may be applauded for their consideration of a myriad of carbon capturing techniques, technologies, and a reorganization of urban landscapes, the proposal itself relies on “the latest innovations and emerging technologies” and applying them “at the scale of the building.” The language appears to be a euphemism for technology that has not yet been developed or remotely tested at the scale SOM attempts to use it at. One day, the proposal may come to fruition when the technology fully presents itself, but for now it seems to be more of a publicity stunt.

SOM is not alone however, as architects have begun greenwashing in an attempt to build a brand and make new designs appear eco-chic. Joel Makower notes that “some firms are overselling in an attempt to tout their green credentials. ‘What I see ... is an epidemic of vagueness. There are a lot of companies using claims that either don’t mean anything, sound too good to be true, or both’” (Makower as cited in Lee, 2008). Project designs in sustainability have become more about how you present them than the actual content of their design. UL Laboratories (formerly Terra Choice) calls these false promises the “Six Sins of Greenwashing” which are:

1. Sin of the Hidden Trade-Off
2. Sin of No Proof
3. Sin of Vagueness
4. Sin of Irrelevance

5. Sin of Fibbing

6. Sin of Lesser of Two Evils (ULL, 2007)

Looking at architecture proposals and analyzing their language through this lens, reveals that most firms fall into one or more of the six when discussing project ideas, with the hope of boosting their own public image.

Looking at the Green New Deal, Green capitalism, and their intersection through greenwashing as well as through their respective economic frameworks emphasizes the idea that climate technology is political. Just as it is used to promote ideas of one side of the political spectrum, the lack of specificity or enhanced performative action leads to denunciation from the other side. These artifacts are used not just for their purposes as sustainability machines, but also as tools of economic and political influence. The politicization of the first kind that Winner noted, is exemplified in the exploitation of technology as a means of masking the true intentions of corporate America. The inherent politicization of the second kind is emphasized by the perspective change of what technology really means in its given context.

The GND is by all means the future framework for which we must strive to achieve, vague in its language or not. The scientific facts presented within it and the economic feasibility of the plan itself appear well researched and certainly possible with the right amount of ingenuity and mobilization. However, we must go one step further if we are to achieve the goals outlined in the plan and get them fast tracked in a divisive political climate. We must think of technology in a new way, addressing both the socio economic ramifications they present and the political uses they may inherently possess along with the actual technical knowledge to make them feasible. At its best, technology has the capability to change society not only through technological rationalism, but also through its ability to restructure and reshape the way we view society. With new technology comes new ways of constructing coexistence. From the days of natural philosophy to the movement of Green capitalism, technology has functioned more as a tool to repair capitalism and restore society to its status quo. Very rarely is a paradigm shift recorded in the field of technology that undoes the extensive economic and political system through its

use to full capability. Climate technology must then not be a tool to save capitalism, because under the current system it has failed to create equitable human coexistence with each other and with the planet. Climate technology would need to be thought of through these principles in order to create truly meaningful change: (1) Scale (different from scalability in the sense that technology requires a determined scale where it can be most efficient and effective). (2) Localization: not every problem is the same nor is every spatiality. Individualizing solutions is tedious but produces the richest outcomes. (3) Viability: in what economic or political system does this produce the social results it intends to achieve? (4) Political character: what inherent politicization does this artifact possess? (5) Temporality: the timescale with which we need to act. While this may reduce the overall effectiveness, it is better to have a viable product than none at all. Obviously, we would always want to optimize climate solutions to their “realized potential,” but the constraint of time is not something that can be avoided when engineering them.

In any sense, climate technology must be created not entirely within the confines of a single field of thought, but rather through the consultation of a multitude of thinkers. The liberal arts model of technological production would help to view climate technology from different disciplines as it is employed for public usage. Additionally, climate technology must either carve out spaces within the current political and economic systems in order to realize its true potential as a social force, or those spaces must be carved out for its utilization. Whether this is a socio economic or political space we have encountered before, or a new one that can only be realized through the study of the technological system itself, begs to be seen. The rest of this project seeks to grapple with the social and technical decisions of a specific technology: the algae photobioreactor. The hope is that, in the end, a comprehensive look at the social and technological implications of this artifact can be leveraged to help realize a mode of living that best suits it, and that it is the key for this way of living to exist.

4.2 What Do We Mean By Climate Technology?

Thus far we have used the term 'climate technology' to describe tools for a green future. I would like to explicitly dive into what climate technology is and is not based on what we have identified more abstractly in the previous chapters. When I say climate technology I am referencing artifacts like solar panels, wind turbines, hydroelectric generators, hydrogen fuel cells, photobioreactors, and electric vehicles. More generally, I am referring to any human engineered artifact that in some way mediates an environmental issue and/or changes the social organization centered around consumption, extraction, and waste. The latter is what we have come to know as sustainability. While the ones above are more specifically about energy production, wastewater treatment and emission reducing devices also fall into the category of green technology. For the sake of this paper, we are focusing on energy production, as that is more contextually grounded in the extraction and consumption economy that has grown over the last 500 years or so. According to climate physicist Beate Liepert, the most prominent factor warming our planet is the emission of greenhouse gasses and other aerosols into the atmosphere, due to their ability to scatter solar radiation and drastically disrupt the water cycle (Liepert, personal communication, Apr. 22, 2022). Therefore, clean power and electricity generation are going to be fundamental problems to solve if we are to continue to work towards mitigating the warming of the planet.

It is also important to make the distinction of what climate technology is not. The definition posed above is also meant to fall in line, even more broadly, with the social and political markers of technology that we had defined above. An example of a gray area that we are coming to define as not an artifact of climate technology is the use of bacteria to clean waste from rivers and lakes. "At the Berkeley Pit, a Superfund site filled with acidic and metal-laden contaminated waste from copper mining in Butte, Montana, microbes have learned how to digest toxic waste" (Hird & Yusoff, 2021, p. 49). The idea scientists had was to utilize the gut microbes of Canadian geese to help clean the reservoir in Butte. The only difference is that this was a natural occurrence that humans are attempting to leverage for their advantage. I will admit that the logic used for this project, trying to utilize a biological adaptation for the gain

of humanity, is a “green technology” in the most abstract sense. However, it also includes the control and domination ethics we saw in the development of modern science. “Ecomodernisation, the ‘good’ Anthropocene, biomimicry, rewilding and geoengineering all seek to reinscribe control within environments gone awry. Even in the shit, it seems that the God complex is as robust as ever.” (Hird & Yussof, 2021, 52). While the sentiment of trying to get the planet to work for us is political in nature, the project misses the same social development and political character of technologies that are developed by humans. We cannot solely rely on the planet to fix the problems we have created (like over mining the area of Butte).

There have been other proposals that follow a similar train of thought, but go to the extreme end: trying to develop technologies to condition the planet to deal with our waste. I would also not define this as climate technology. If we can train animals, bacteria, and viruses to accommodate our way of living, we can continue to consume more and more while caring less and less. We have already pointed out that climate change is also a social and political issue, and to try and exploit the land and resources to work for us only reinforces the same social conditions that brought about the climate crisis in the first place. This way of thinking would actually be more detrimental because it permanently shifts responsibility away from humanity and onto the planet to fix itself.

Lastly, space colonization is not a climate technology as much as billionaires want to believe that it is. The space race itself pays no mind to the destruction of the atmosphere. “When rockets launch into space, they require a huge amount of propellant to make it out of the Earth’s atmosphere... Emissions from rockets are emitted right into the upper atmosphere, which means they stay there for a long time: two to three years” (Gammon, 2021). The space colonization plan is obviously very much in line with the colonial logics, as it does not even try to hide from the word in its title. The principles of the new space race are centered around a defeatist attitude toward climate change, where the planet is doomed and we must therefore defer resources into moving somewhere else. When the colonization of the Americas occurred in the 16th through the 18th century, the European model of conservation was to move all of the

existing industrial infrastructure to the New World. The reason: because they had deforested most of Europe and realized they could have more resources elsewhere (Merchant, 1980, 240). Thus, the idea of shipping our way of life somewhere else does not constitute green engineering. In short, not all ‘solutions’, technological or otherwise, are climate technologies.

4.3 Photobioreactor

For this paper, we are going to focus specifically on algae photobioreactors as our artifact of choice. This first section will address what a photobioreactor is and how it works, and the next section will deal with why we are choosing it for our precedent. So, what is a photobioreactor? A photobioreactor, PBR, is a type of enclosed environment that is used in the process of cultivating microalgal biomass (Ugwu et al., 2008); (it should also be noted that this technology can be used to cultivate other hydroponic feedstocks like macroalgae). The specification of an enclosure is an important distinction because of the existence of open air cultivation systems that predate the closed type PBR. Open systems, like the raceway pond, are seen as a separate classification within the PBR family as they yield the same result, yet require different considerations for their construction and maintenance (Narala et al., 2016, Ugwu et al., 2008). Until recently, open raceway ponds were seen as the only feasible option for large scale microalgae production, but research into improving the design of closed PBRs has led to growth potentials far greater than the open system can achieve (Orfield, Keoleian, Love, 2014).

Algae biomass was originally cultivated for draft animals to be used as a nutrition supplement (Zabochnicka-Świątek, 2010). Its nutritional value is due in large part to the high content of lipids, proteins, and carbohydrates (Senroy & Ral, 2014). It happens to be that harnessing these compounds raw from the plants themselves, proves to have enormous benefits in the field of energy. In terms of its lipid content, oil from algae can be synthesized into a third generation biofuel similar to diesel, and hence gets the name biodiesel (R.N. Singh & Sharma, 2012). Different strains of microalgae contain different oil percentages of their dry weight, leaving some to be most viable as a biodiesel feedstock. The biodiesel produced by these

PBRs is chemically and physically compatible with regular diesel and can burn in diesel engines without significant modifications (Nautiyal et al., 2014). Owing to the low content of sulfur and high ratio of oxygen, biodiesel can cut the rate of sulfur and CO emissions by 30% and 10% respectively when used in current diesel engines (Ma et al., 2016; Huang et al., 2014). Other types of biodiesel can be made from rapeseed oil, vegetable oils, and waste cooking oil, with the term most generally applied to any fatty acid methyl ester or ethyl ester from plants or animal fats that can be burned in a diesel engine (Lapuerta et al., 2008).

The emissions produced can be less chemically detrimental than regular petroleum diesel based on a number of factors, the two biggest being the quality of biodiesel and the engine type (Lapuerta et al., 2008). Any biofuel that draws more carbon from the atmosphere than it emits in the burning process, can be considered a carbon negative biofuel (J.A. Mathews, 2008). Algae cultivation provides a greater advantage in the attempt to achieve carbon neutrality because of its strong ability to sequester carbon dioxide from the atmosphere. Their photosynthetic efficiency is about 10 times higher than terrestrial plants, and therefore draws in more carbon dioxide and at faster rates during the growing process (U.B. Singh & Ahluwalia, 2013). Microalgae need just CO₂, sunlight, water, and minerals to grow (Pires et al., 2017). It is also important to note that microalgae can be used for wastewater treatment, based on their ability to utilize phosphorus and nitrogen in their photosynthetic processes (Mohsenpour et al., 2021).

In terms of design, PBRs come in five main types: bubble column photobioreactor, airlift photobioreactor, flat panel bioreactor, horizontal tubular photobioreactor, and stirred tank photobioreactor (U.B. Singh & Ahluwalia, 2013). Each has its own benefits in different areas of cultivation which include: pH, CO₂ and O₂ concentration, light exposure, nutrient density, temperature regulation, and mixing. The total growth and resulting oil contents of the plants themselves are affected differently by variations in each of these factors. PBRs themselves are a way to control the growth process more directly than open cultivation systems (R.N Singh & Sharma). Specifically, temperature regulation and CO₂ concentration are too variable to

be reliable in an open pond set up, capping their potential for large-scale bio-oil production. Closed systems have also shown to produce higher oil contents and faster growth rates among most microalgal strains due to advancements in cultivation techniques that are not possible with the way raceway ponds are constructed. Thus, a step towards an environmentally sustainable future would be to invest in PBR technology in order to improve the photosynthetic efficiency of microalgae through more reliable cultivation.

4.4 Why Choose PBRs As Our Artifact?

As you can see, PBRs have the technical capability to be a force in the future of green energy production. But why have we chosen PBRs as the precedent for our green technology research? Why not wind turbines or hydroelectric generators? The reason lies precisely in the logic of the first two chapters. We determined that two of the fundamental logics of technology are scalability and standardization. PBRs are unique in that they depend on a number of different physical factors in order to run at peak efficiency. Because those physical factors are different based on location, PBRs are a non standardized solution. A PBR that depends on solar radiation rather than LED light would not be a viable solution to producing biodiesel for communities that have long, dark winter months. The irradiance alone would make the project obsolete and not worth the time, energy investment, or constant human labor to maintain. Additionally, temperature is more easily controllable in a closed environment like a PBR, yet locations with large temperature swings from night to day and season to season might make the regulation of temperature very difficult for a PBR. Some PBRs rely on flue gasses in order to operate because of their high concentration of carbon dioxide (Yadav et al., 2015). Areas that have relatively low flue gas concentration in the air would have to work with a different PBR design that does not incorporate the same engineering as would an in situ column PBR (Yadav et al., 2015). As we are beginning to notice, not every model of PBR works in every location, and not every location can even support a PBR if the benefits are so meager. Therefore, the standardization principle fails in two ways. The first is that no standard type of PBR can exist

as a solution because the world does not have a homogenous climate. The second is that PBRs cannot be the only means of climate technology intervention for a community. In places where it is not worth the time, labor, energy, or monetary cost to cultivate algae, another supplemental solution may be needed, or a different solution entirely. In order to power certain mechanized parts of the model, photovoltaics have been suggested as a supplement to power the design (Nwoba et al., 2020). The PBR exposes the need to think critically about a site when choosing a technological option that fits the needs of that community, as they are still dependent on and affected by natural phenomena.

The second technological principle is scalability. When a new climate technology is discovered, it is oftentimes regarded as the new solution. When researchers first started studying PBRs, there was a rush to start using them in architecture. The architecture/engineering firm, Arup's, SolarLeaf project is a good example. In 2013, the firm installed a façade of flat panel PBRs on the BIQ house in Hamburg, Germany with the hopes of using them to retain heat for the building and produce energy (Arup, 2013). The light saturation provides more algal blooms and thus more shade to keep the building more temperature regulated, based on the outside conditions. However, the aspect of energy production is still up in the air. "The bio-responsive façade aims to create synergies by linking different systems for building services, energy and heat distribution, diverse water systems and combustion processes... What is most needed is an understanding and view of the systems' benefits for the user, the building and the environment" (Arup, 2013). They recognize more research would need to go into this before algae cultivation for biodiesel or other combustion processes could appear feasible at that scale.

The specific question of oil yield is one that has sparked a lot of interest and debate with regard to how practical PBRs could be. "We have yet to see any full-scale algae farms because three issues have yet to be addressed: 1) An efficient process to harvest the algae has not been demonstrated. 2) An efficient process to separate the natural oil from the algae has not been created. 3) The economic viability of algae farms at realistic prices has not been proven" (Richardson, Outlaw, Allison, 2010). Obviously, a massive amount of space, labor, time, and

money poured into a project that barely produces enough oil to get a car down the street, would be a waste of resources.

However, the last part of the quote from Richardson et al. is thematically counter to our first two chapters entirely. When studying the feasibility of a piece of technology like the algae PBR, one can analyze the use value as well as the exchange value. What we are attempting to do is analyze the former without need for the latter. Why do we not care about the exchange value? Trying to build a sustainable future means solving environmental issues as well as social ones. We have previously identified the capitalist underpinnings of technological production, and this principle is heightened in the energy industry. As I noted in Chapter One, technology has been used to reproduce capital and has been used as a bandaid rather than a medicine as it has been so prescribed. Thus, we should care more about how well a piece of technology can do its job, rather than how it can compete economically with larger industries. It is through this analysis that we are able to fairly judge and usher in a new age of technology, one that can help us to produce new socio-spatial arrangements that will have a more lasting impact on how we interact with our planet.

It is also through this lens that we can safely classify a PBR as a transition technology. A transition technology is one that will allow us to usher in this new age by reconfiguring our social and spatial conditions without overhauling the infrastructure of the present. Diesel engines are a ubiquitous part of our society, used for transport and electricity production. By engineering something like a PBR, which produces a cleaner fuel that is also compatible with this infrastructure, we can begin to employ it without radically constructing something new. Even biodiesel itself is a transition fuel. The hope is that we can produce energy at a carbon negative level by 2050 at the latest, so being carbon neutral will not be helpful at that time. However, in the fight to get away from petroleum and coal, solutions that can wean us off of fossil fuels are necessary as we start to overhaul our energy infrastructure. According to the US Energy Information Administration biofuels accounted for 17 percent of overall renewable energy and roughly 43.6 percent of all biomass produced energy in 2020 (US EIA, 2020). Even

as the market for biofuels continues to see the prospect of expansion according to studies done by the International Energy Agency (IEA), wind, hydro, and solar are cleaner and more viable alternatives to fossil fuels, and will continue to be far into the future. Thus, biofuels are at a perfect renewable energy sector share to be a transition solution, as they are meant to be a more temporary and local option.

The analysis of a PBR can even extend the transition label further, as we still must consider operating costs and initial investments of capital and labor in order to employ it. The idea is that technology such as a PBR can help us to see a post-capitalist future, at least in terms of energy production. The hope is that someday, people will not have to rely on corporations, failing networks of grid infrastructure, and the fossil fuel industry in order to survive. However, in order to take a step toward a more personalized energy future, solutions must work within the current economic and political framework in order to get off the ground.

4.5 The Social Rearrangement of Transition Technologies

Transition technologies are also transitory in their social configurations. In trying to produce a new way of living, or at least propose one, we can easily leverage new technology to allow that to happen. This principle is central to the philosophy of rationality. Boiled down, the theory can be described as there is the status quo until we have a new status quo. It is hard for us to imagine new futures, but it is becoming easier to do so when we consider the capabilities of new technology. We can easily leverage this phenomenon to imagine new ways of building community and cohabitation that are centered around technological innovation. For example: what would happen in the spaces gas stations currently occupy if gas becomes obsolete? How would communities use shared spaces if they had to produce their own energy? Does the idea of community engagement and conservation change when you are more reliant on your neighbors in order to survive? Asking questions like these become more common as we identify the potential nuances of energy production and consumption at that scale, and at the temporality of the

everyday. Chapters Seven and Eight will deal with these questions and others like them more directly in the process of urban design.

Looking more specifically at our precedent, PBRs have made us think critically about the underlying assumptions we have regarding technology, while also helping us to rethink the social conditions which make them transitory. From a spatial context, the historical controversy surrounding biodiesel as a whole lies in land usage. The first argument is that in the United States, arable land used for crops would have to be used to grow vegetables solely for their oil, thus leading to the debate of food or fuel (Prasad & Ingle, 2019). The main biodiesel crops grown in the early part of the 21st century were soybeans, which saw a sudden spatial limitation on the land they could farm upon (Gallagher, 2011). Suddenly there was a need to prioritize land usage based on food production and profit. Additionally, crops like palm, soy, and *Jatropha*, which were grown on arable land, may change the carbon concentration of the soils and actually cause more greenhouse emissions and environmental degradation than they counter (Achten & Verchot, 2011). However, the discovery of algal biomass as a potential replacement for arable crops led to a new bed of research in open raceway ponds and PBRs for biodiesel production. Algae could be seen as a long term solution for clean energy production in order to save land for food production in industrialized countries (Liang, Xu, Zhang, 2013). The history of the PBR is deeply entrenched in the debate over the use value of land.

Similarly, the organization of labor in the production of biodiesel has been historically centered on agriculture. In the late 1990s, as biodiesel-diesel mixtures were becoming more common, much analysis was poured into how biodiesel production would affect the US agriculture sector (Raneses et al., 1999). Because the process of producing oil from feedstock is primarily chemical in nature, through the process of transesterification, the majority of the labor would be on farmworkers to cultivate crops. However, in an industrial setting like the SolarLeaf project in Hamburg, would the cultivation of algae feedstock still rely on traditional agriculture labor? Would there need to be a new system of labor and production in place for a non farmland based biodiesel? These questions will be addressed more directly later in the paper, but the

ideas of organization of labor surrounding energy production are important to ask here. Will PBRs fundamentally change the relationship between people and their energy? Replacement of human beings and their irrelevance to technological systems has given way to new “modes of engagement” with remarkable social, economic, and ethical implications (Ekbja & Nardi, 2014). While Ekbja and Nardi mostly speak on computer based technological systems, the same can be said of energy production systems. The abstraction of people from where their fuel comes from is a major factor in how certain modes of energy production stay or become popularized. Despite electric cars appearing to be eco-friendly, they still rely on an electric grid largely based on the burning of coal (Pirani, 2020). Additionally, the burden placed on workers in the energy production industry has been seen to increase in all prospective renewable energy projects, other than hydroelectric projects, in Malaysia, a country that is quickly increasing its overall economic and renewable energy sector growth (Takeda et al., 2019). It may be more important to increase the visibility of where our energy comes from if we are to make more conscious and sustainable choices as a people. If not more visible, we may become more involved in the process itself in order to better account for personal energy consumption and waste. Scale of production becomes a point of thought when discussing the social implementation of the PBR.

The questions we have been asking also lend themselves to the spatial reconsideration of the current standard electrical grid. The US electrical grid is largely based on Nikola Tesla’s long range AC power generation (Lombardo, 2013). According to the US Department of Energy, North America has two major and three minor AC power grid interconnections that service people with electricity (USDE, 2021). “Fossil fuel-based power plants—burning coal, oil, or natural gas—create nearly 60 percent of the nation’s power, while nuclear power accounts for about 20 percent” meaning combustion accounts for most of the electricity generation in the United States (US EIA, nd b). However, failures due to natural disasters and the potential for hacking has exposed the vulnerabilities in having such a centralized grid system. These natural disasters are only going to get worse with time as an effect of climate change.

Some more recent examples show the threat of climate disaster on the power grid. In February of 2021, a winter storm disrupted the electrical grid of Texas and caused more than 700 deaths and led to \$200 billion dollars in infrastructural damage (Heilweil, 2021; Wu et al., 2021). The age of the US power system has become a factor in its inability to perform in the extreme weather conditions we have seen recently. In Oregon in the summer of 2021, 115° Fahrenheit heat melted the power lines and caused outages for 6,000 Portland residents (Heilweil, 2021). It is a “perfect storm of extreme temperatures, more electricity consumption, and aging infrastructure” (Heilweil, 2021). Additionally, the infrastructure put in place to serve as the main energy supply has reached too big to fail status; large power plants “are expensive to build and have very long payback periods. That means the utilities are slower to adopt new technologies” (Lombardo, 2013). The US will continue to use a larger centralized power grid even amongst an aging infrastructure, because the cost would be too great to abandon it. As an alternative, microgrids have been proposed to supplement the existing grid.

Distributed generation is a type of decentralized energy production that centers on renewable energy as a failsafe for the current electricity generation system. If one node gets knocked out on the system, the whole grid will not collapse. Texas has its own independent grid, and was, therefore, not afforded the insurance of borrowing power from a different neighboring grid like that of Oklahoma (Heilweil, 2021). Even within Texan communities, those who had electricity generation through photovoltaics were spared the blackout as they were not fully reliant on the grid. As US renewable energy resources reached 21% of the energy sector in 2020, the question of how these sources would be integrated loomed large (US EIA, 2021). It would appear that because microgrids are local in their geography, and can connect to a larger system, that they would be an obvious solution to both integrate renewable energy systems and transition towards decentralized energy production (Kaundinya, Balachandra, Ravindranath, 2009; Mengelkamp et al. 2018). Eventually, stand alone grids may become more prominent, especially in remote or rural locations where connection to a larger energy production network

is not feasible (Kaundinya et al., 2009). With a hybrid of grid connected systems and stand alone grids, renewable energy can easily find a larger space within the energy sector.

PBRs themselves offer an easily integrable solution to this problem and also create a scale that itself ensures a more carbon neutral process. Firstly, the scale of algae oil production can easily be fit into the community based on the size of most bioreactors. Small-scale energy production may be possible by having generators and distribution networks for locally sourced biodiesel. Determining to what scale this would work best, and with what biodiesel yield will be examined later in this paper. Secondly, because the carbon neutrality of algae oil cultivation, processing, and combustion hinges on the process itself, localized solutions appear to be more environmentally friendly. If one were to grow crops somewhere in the midwest on a large scale and ship them to the northeast for biodiesel production, this process would itself expend oil. Not all biodiesel is created equal (Qin, Zhuang, Chen, 2012). Algae production can be localized because the reactors themselves do not require a specific central geography. The controlled environment lends them to be placed where they will be able to grow most efficiently, not just where there is abundant arable land.

Biodiesel itself can be communally stored and owned as well. Surveys of early biofuels found that biodiesel was an attractive option for rural communities because of their lack of reliance on the oil market, private energy supply corporations, and political actors (Del Greco, Rademakers, 2008). The process of producing biodiesel requires less technical knowledge and is therefore a sustainable process for communities to undertake, as well as economically feasible (Del Greco, Rademakers 2008). In Ethiopia, *Jatropha* biodiesel production led to an expansion of a greener economy based on a decarbonization of transport fuel. The biodiesel fuel blends led to a forecast of a significant decrease in emissions and a net USD \$1 billion profit for the government (Portner et al., 2014). Communally owned and produced biodiesel is advantageous as it creates energy independence, or at least semi-independence, with a greater reliability.

PBRs are also an interesting choice for a precedent because of their scrutiny in policies like the Green New Deal. In supplying energy for a green future, biodiesel appears to be

a solution to both the electricity grid infrastructure failure and renewable energy integration problem. Yet, lawmakers have excluded any combustion related sustainability solutions (Jacobson et al., 2019). While the long term for biofuels remains a research task, the ideas of scale and localization appear to demonstrate carbon neutrality at worst, and even carbon negativity at best. While it is optimal that we get rid of any emissions altogether, the short term energy transition to completely clean sources relies on a quick shift away from burning purely coal and fossil fuels. If we can produce transport fuel and electricity that is, for a moment, carbon neutral, it will be much easier to stay under the 1.5° Celsius threshold by the year 2030 (the limit for mitigating the effects of climate change).

Lastly, the spatial and temporal considerations of the PBR make them an interesting multidisciplinary puzzle. While certain modes of biofuel production lend themselves to be less sustainable, others may be a better spatial alternative. Similarly, the scale at which a cultivation effort produces the most efficient and sustainable solution is a task that requires research in the fields of urban planning and engineering. Understanding the relative yield and feasibility economically of such an endeavor requires yet more research from economists and scientists alike. The biofuel question is not one dimensional and should be considered from a myriad of fields in order to further understand its value and place within the framework of politics.

Mie Theory and Scattering Analysis

5.1 Iridocyte Structure and Scattering Effect

The feasibility of a photobioreactor lies in its ability to efficiently intake and utilize solar radiation (Holt et al., 2014; Kim et al., 2017; Zijffers et al., 2008). The fact that the photobioreactor is, in our context, intended to produce algal biomass for the transesterification process,⁹ means the question of biomass yield itself presents the first major hurdle to overcome. One of the largest determining factors of algal growth is the ability to efficiently photosynthesize. Quantum efficiency is seen as the ability for a species to produce a particular effect relative to its photon absorption rates (Wong, Bünzli, Tanner, 2020; Skillman 2008), therefore quantum photosynthetic efficiency generally refers to carbon fixation for C3 plants like green microalgae. High chlorophyll density allows for the saturation of sunlight in terrestrial plants and microalgae,¹⁰ yet this density appears much lower in submerged autotrophs like macroalgae (Frost-Christensen, Sand-Jensen, 1992). When exposed to strong levels of solar flux, the high intensity of sunlight can cause a reduction of the electron transport chain process in photosynthesis, and lead to photodamage unless non-chemical processes quench light (Kim et al., 2017; Fischer et al., 2006). In a photobioreactor, this leads algae at the surface to have small ab-

⁹Transesterification is the process by which esters are stripped from oil in order to be synthesized into ethanol and/or biodiesel. This is the step needed to go from biomass to gas (Ghaly et al., 2010).

¹⁰For this paper, we will use algae and microalgae interchangeably. For macroalgae, it will be explicitly stated.

sorption cross sections, while cells deeper in the system become light limited (Kim et al., 2017). This, in turn, leads to unequal and inefficient photosynthetic processes. Thus, external transformations of incident sunlight would be ideal for balanced incoming flux. Photobioreactor designs have often included Fresnel lenses and waveguides in order to allow for maximum capture and usage of solar radiation (Zijffers et al., 2008). While these prove effective at mediating the flux of electromagnetic radiation, there are two main problems that are still not addressed in their design. The first problem is that lensing must be calibrated to follow the trajectory of the sun in order to effectively steer light down the waveguides, or to reflect at the correct angle according to Snell’s law (so as not to oversaturate the algae). Calibration is a costly process because of the automation of lens mechanisms, and the constant surveil of the sun’s path through seasonal changes, which is widely different across locations and orientations. Secondly, the lensing itself still does little to solve the problem of wavelength selectivity in photosynthetic organisms. Blue and red light tend to lead to more photosynthetically efficient processes, and allow for more photon absorption, while green light tends to slow this process down (Holt et al., 2014). Thus, if the mechanisms could also filter out specific wavelengths of light, they might prove more valuable.

A second type of photobioreactor, that addresses the wavelength issue, utilizes LED light at specific wavelength ranges in order to avoid photodamage. This provides an interesting topic of discussion for the maintenance aspect of a photobioreactor, as it would require more construction and housing in order to support a more synthetic, controlled system than a photobioreactor already supplies. A more complex construction also makes it less accessible to the community in terms of technical knowledge and ability to cultivate and regulate their own biomass production. With this in mind, there are biological solar transformers that exist in giant clams, *Tridacna crocea* (Holt et al., 2014; Ghoshal et al., 2016). Structures called iridocytes that live on the surface of natural algal pillars create a “dose” of sunlight in usable intensities and at more efficient wavelengths. This allows for the diffusion of sugars from algae into the clam tissue to happen more effectively, creating a strong symbiotic relationship amongst the three sets of organisms (Holt et al., 2014). Iridocytes themselves possess subcellular Bragg reflectors

in their lamellae, and by having high and low index of refraction components backscatter specific wavelengths of light better than others (Ghoshal et al., 2017; Demartini et al., 2015); (in the case of algae 500-600 nm which is why they appear green). More specifically, they have proteinous 100 nm thick platelets ($n=1.55$) in an array with ≈ 100 nm thick low refractive index cytoplasm ($n=1.33$). Essentially, the combination of the ratios of the index of refraction with the thickness of each layer selectively backscatters more green light (~ 520) nm through interference, while forward scattering more red and blue wavelengths. At the same time, the spherical nature of these cells allows for a reduction of incoming flux for forward scattered light effectively acting like a natural transformer of electromagnetic radiation. What this suggests is dominant forward scattering for red and blue light in a 15° wide scattering cone. If one were to construct a synthetic version of this symbiotic organization in the context of a photobioreactor, it may prove more efficient and therefore more economically feasible in the long run in terms of total biodiesel production and consumption.

Light scattering is an important physical property for iridocytes, and one that is utilized for the advantage of the algal cell culture in their symbiotic relationship. Microalgae utilize the visible spectrum ($\approx 400nm - 700nm$) in order to photosynthesize; however, as we have previously identified, not all wavelengths within this range are necessary or useful for this process. Red and blue wavelengths of light appear at the two extremes of the 400-700nm visible spectrum. Because green light is an inhibiting factor, leaves appear green, as their cells scatter green light effectively while absorbing red and blue.

At the same time, the backscattering also reduces the overall intensity of light hitting the algal cells, which protects them from photodamage and allows them to photosynthesize more efficiently. Both of these results prove to be positive for the microalgae, and therefore their growth has become optimized on the surface of the giant clam. When trying to cultivate microalgae in a closed environment, like a PBR, it is paramount that both the incoming flux of light is not too high, and that the whole culture is being irradiated. Most feasibility studies that track the use value of closed hydroponic systems cite light exposure as the main inhibiting factor

to biomass production. If one could synthetically recreate iridocytes through less expensive materials, photosynthesis could become more efficient and photodamage less frequent for the cultures. Before attempting to engineer these structures, however, it is important to understand the distribution of scattered light off of iridocytes, and their dependence on specific cellular configurations. The next couple of sections will deal with both the derivation and numerical modeling of the scattering intensity functions that come out of Mie theory, as well as simulations of different material and structural configurations of synthetic iridocytes in order to compare their efficacy.

5.2 Introduction to Mie Theory

Mie theory is used largely to express the scattering of electromagnetic waves on homogeneous spherical surfaces. As a plane wave hits a single scatterer, there are three things that can happen: a) light makes it through the object moving in the same direction it was incident upon, b) light gets scattered either through reflection or refraction, c) light is absorbed by the scatterer. In scenario a), even if photons get absorbed and reemitted, or light is initially scattered, any wave that is vectorially moving in the same direction as the initial plane wave is considered unscattered. Scenarios b) and c) however combine into what we call extinction. The extinction cross section of a particle tells us how much energy was removed from the incident beam by attenuation. The two main factors that influence all three scattering scenarios are the particle size and index of refraction. Particle size actually falls under three regimes of scattering that have to do with the ratio, $\chi \equiv R_s/\lambda$, of the radius of the sphere (R_s) over wavelength (λ) of the electromagnetic radiation you are studying. For $\chi > 2000$, light scattering theory falls under the regime of geometrical optics, $0.2 < \chi < 2000$ is Mie scattering, and $0.002 < \chi < 0.2$ is Rayleigh scattering. Anything below $\chi = 0.002$ is negligible scattering, and can be treated as entirely scenario a) from above when a transverse plane wave hits its surface. Iridocytes are roughly $4 - 5 \mu m$ in radius, and we are dealing with the visible light spectrum, which leaves us with a χ value of anywhere between 5.71 and 12.5, comfortably within the scope of Mie theory.

What we are after with this analysis is the intensity of scattered light as a function of angle around the particle. This can be expressed by the function:

$$I = \frac{I_0 F(\theta, \phi)}{k^2 r^2} \quad (5.2.1)$$

where I_0 is the intensity of the incident plane wave, k is the usual designation of wave number $k = \frac{2\pi}{\lambda}$, and r is the distance from the center of the scatterer to the point of measurement (which we will affectionately refer to as the 'far field' in our future simulations). The function, $F(\theta, \phi)$, is composed of two smaller complex functions, S_1 and S_2 , which help to describe the amplitude and phase of incident and scattered waves. If one looks at eqn. (5.2.1) one begins to notice the $\frac{1}{r^2}$ dependence that we expect with intensity. From the fact that we have an intensity over an area, $\frac{I_0}{r^2}$, one can begin to intuit what $\frac{F}{k^2}$ represents (hint: it's an area). You should be awestruck by the simplicity of this function in that it has the capacity to describe the intensity of light at any point in 3D after an interaction with a scatterer. Yet, be warned that this equation is very sleek, and extremely dense as we are about to find out when we unpack the definitions of S_1 and S_2 . The scattering equations we are dealing with as a part of the Mie solution are derived directly from Maxwell's theory of electrodynamics, and thus, simply stating the components of the scattering function with no physical basis would be incomplete. However, this next section will not go through a full treatment of Maxwell's equations, as in Gustav Mie's original 1908 derivation, but rather just enough to get an intuition of the math which will inform the physical nature of our problem. For a robust treatment of the Mie solution, see J.A. Stratton's *Electromagnetic Theory* (1941).¹¹

5.3 Derivation of the Scattering Equations

The next section is meant to provide a bit of conditional and mathematical context as to why the associated Legendre polynomials and Bessel functions are so prevalent in the scattering intensity functions. For resulting scattering functions and the following numerical

¹¹The following derivation utilizes pieces from Dr. Lars Gilson's derivation of Mie theory, Dr. Dennis Westra's derivation of Mie theory, and H.C. van de Hulst's 1957 work *Light Scattering By Small Particles*.

model skip to section 5.5. Maxwell's theory has provided us four fundamental equations with which to synthesize electromagnetic phenomena. They are stated without proof below:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0} \quad (5.3.1)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (5.3.2)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (5.3.3)$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \quad (5.3.4)$$

We can rewrite eqn. (5.3.3) as:

$$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t}$$

where μ is the permeability constant. Similarly we can make the substitution $\mathbf{D} = \epsilon \mathbf{E}$ in eqn. (5.3.4) where \mathbf{D} is the flux density of the wave, and ϵ is the relative permittivity. We can replace \mathbf{J} , the current density, with $\sigma \mathbf{E}$ with σ being the conductivity of the material. This gives us

$$\nabla \times \mathbf{H} = \sigma \mathbf{E} + \epsilon \frac{\partial \mathbf{E}}{\partial t}$$

Understanding that there is a time dependence on the incoming electromagnetic plane wave, the partial derivatives must act on the term $e^{-i\omega t}$, thus making eqns. (5.3.3) and (5.3.4):

$$\nabla \times \mathbf{H} = (\sigma - i\omega\epsilon)\mathbf{E} \quad (5.3.5)$$

$$\nabla \times \mathbf{E} = i\omega\mu\mathbf{H} \quad (5.3.6)$$

The Mie derivation is done for a homogenous sphere, where we can assume the charge density $\rho = 0$, making eqn. (5.3.1) equal to 0. For our purposes we will be looking at a non-conductive sphere, making $\sigma=0$. We can now rearrange eqns. (5.3.5) and (5.3.6) to get the differential relationships

$$\nabla^2 \mathbf{E} + \omega^2 \mu \epsilon \mathbf{E} = 0 \quad (5.3.7)$$

$$\nabla^2 \mathbf{H} + \omega^2 \mu \epsilon \mathbf{H} = 0 \quad (5.3.8)$$

which are solutions to the *vector* Helmholtz equations and are, more generally, our standard wave equation. We are first going to go through the derivation for scalars and then apply our solutions to the vector fields derived above. Due to the spherical symmetry of the problem, it is better to switch to spherical coordinates when solving the wave equation, making $\mathbf{E}(R, \Theta, \Phi)$ and $\mathbf{H}(R, \Theta, \Phi)$. The spherical Laplacian of $\mathbf{E}(R, \Theta, \Phi)$ and $\mathbf{H}(R, \Theta, \Phi)$ can be represented as scalars more generally in the form:

$$\nabla^2 f(r, \theta, \phi) = \frac{1}{r^2} \partial_r (r^2 \partial_r f_r) + \frac{1}{r^2 \sin \theta} \partial_\theta (\sin(\theta) \partial_\theta f_\theta) + \frac{1}{r^2 \sin^2 \theta} \partial_\phi^2 f_\phi \quad (5.3.9)$$

We can then write $f(r, \theta, \phi)$ in the form $R(r)\Theta(\theta)\Phi(\phi)$. We can plug this result back into our wave equation to get:

$$\frac{1}{r^2} \partial_r (r^2 \partial_r R) + \frac{1}{r^2 \sin \theta} \partial_\theta (\sin(\theta) \partial_\theta \Theta) + \frac{1}{r^2 \sin^2 \theta} \partial_\phi^2 \Phi + \omega^2 \mu \epsilon R(r) \Theta(\theta) \Phi(\phi) = 0 \quad (5.3.10)$$

Utilizing the fact that this is a set of partial differential equations in the scalar wave form, we can perform separation of variables to simplify. Dividing by $R(r)\Theta(\theta)\Phi(\phi)$, multiplying by $r^2 \sin \theta$, and isolating Φ , we see that we have a differential dependent on Φ alone, and the other side dependent on R and Θ :

$$\frac{1}{\Phi} \frac{d^2 \Phi}{dt^2} = r^2 \sin^2 \theta \left[\omega^2 \mu \epsilon - \frac{1}{R^2} \frac{d}{dR} (r^2) \frac{dR}{dr} - \frac{1}{\Theta r^2 \sin \theta} \frac{d}{d\theta} (\sin \theta) \frac{d\Theta}{d\theta} \right] \quad (5.3.11)$$

Thus,

$$\frac{1}{\Phi} \frac{d^2 \Phi}{dt^2} = -m^2$$

where m is a constant, giving us a second simpler wave equation which yields solution

$$\Phi(\phi) = e^{\pm im\omega t}$$

if we allow m to be both real or complex. This part of the Helmholtz solution, together with the associated Legendre polynomials, are given by spherical harmonics, the three dimensional equivalent to the circular functions that make up Fourier analysis in two dimensions. Intuitively, the inclusion of spherical harmonics for our derivation would imply the inclusion of Bessel functions in our answer, which we will see momentarily. A similar trick as the one performed

on Φ , which I will not write out at length for sake of brevity,¹² allows the radial equation to become

$$\left[\frac{d^2}{dr^2} + \frac{2}{r} \frac{d}{dr} + \omega^2 \mu \epsilon - \frac{l(l+1)}{r^2} \right] R(r) = 0 \quad (5.3.12)$$

The solutions of eqn. (5.3.12) are a linear combination of the Bessel functions and spherical Hankel functions, the latter being a complex linear combination of Bessel functions themselves. Moving onto the last part of our solution, the polar part of the Helmholtz equation becomes

$$((1 - \cos^2 \theta) \Theta')' + \left[l(l+1) - \frac{m^2}{(1 - \cos^2 \theta)} \right] \Theta = 0 \quad (5.3.13)$$

which possesses solutions in the form of associated Legendre polynomials $P_n^m(\cos \theta)$. We have just solved the pieces of our function $f(r, \theta, \phi)$, which together form the elementary solutions of the Helmholtz eqn.

$$f_{ln} = \frac{\cos(l\psi)}{\sin(l\psi)} \left\{ P_n^l(\cos(\theta)) z_n(mkr) \right\}. \quad (5.3.14)$$

These functions, the Bessel, Hankel, and associated Legendre polynomials, will become major factors in the boundary coefficients of the next section. As we just witnessed, the spherical symmetry of our problem is what allowed for such harmonic solutions to the Helmholtz equation in three dimensions. Once we begin to look at this problem as a vector and analyze the electrostatic boundary conditions, we will begin to see how these three main functions become prominent in the overall scattering equation.

5.3.1 Vector Solutions

Above we solved the Helmholtz equation for a scalar wave, using the general function $f(r, \theta, \phi)$ in spherical coordinates. Now, if we instead use a vector function $\Psi(r, \theta, \phi)$, which we will just denote as Ψ , we can see parallel solutions to the scalar case but will now be physically compatible with our electromagnetic wave. As we saw before, the scalar Helmholtz eqn. can be written simply as $\nabla^2 \Psi + k^2 m^2 \Psi = 0$. Wavefunctions, Ψ , that satisfy this relation can be used

¹²<https://www.mat.univie.ac.at/~westra/MieTheory.pdf> this provides a more in depth mathematical proof of the separation of variables for the radial and polar parts of the Helmholtz equation.

to derive a set of mutually orthogonal vectors: $\mathbf{L}, \mathbf{M}, \mathbf{N}$ which are defined as

$$\mathbf{L} = \nabla \Psi$$

$$\mathbf{M} = \nabla \times (\mathbf{r}\Psi)$$

$$\mathbf{N} = \frac{1}{k} \nabla \times \mathbf{M}$$

We can now begin to construct the electric field vector, \mathbf{E} , that satisfies our Maxwell's equations along with the magnetic field, \mathbf{H} . In our case, we care less about \mathbf{H} , but it still shows us a complete set as it relates to our scalar wave solutions. We will go through the derivation of \mathbf{E} in order to express the relationships between the fundamental vectors and the electric field, but know that they have similar properties in their relation to the magnetic field as well. Looking at the scalar Helmholtz equation, if u and v are themselves wavefunction solutions, the vectors \mathbf{M} and \mathbf{N} have components that are derived from these wavefunctions: $\mathbf{M}_u, \mathbf{N}_u, \mathbf{M}_v, \mathbf{N}_v$. Thus, our field equations are

$$\mathbf{E} = \mathbf{M}_v + i\mathbf{N}_u \quad (5.3.15)$$

$$\mathbf{H} = m(-\mathbf{M}_u + i\mathbf{N}_v) \quad (5.3.16)$$

You can also write the vector potential \mathbf{A} as a complete solution comprised of all the possible wavefunctions, with the indices corresponding to those of vector harmonics.

$$\mathbf{A} = \frac{i}{\omega} \sum_{n,m=1} (h_{nm}\mathbf{M}_{nm} + j_{nm}\mathbf{N}_{nm} + k_{nm}\mathbf{L}_{nm})$$

Mie Theory by Dr. Lars Gilsen gives a nice unpacking of the fundamental vectors from a mathematical standpoint, and from his derivation it is seen that only $m = 1$ components contribute to the incoming plane wave. I will use this fact without full proof, and along with eqn. 5.3.5 and the relationship $\mathbf{H} = \nabla \times \mathbf{A}$, we can rewrite \mathbf{E} .

$$\mathbf{E} = - \sum_{n=1} (h_{n1}\mathbf{M}_{n1} + j_{n1}\mathbf{N}_{n1}) \quad (5.3.17)$$

In our case we defined our incident plane wave as linearly polarized in Cartesian coordinates, so our incident wave is expressed as $\mathbf{E} = \mathbf{a}_y e^{-ikz + i\omega t}$ where \mathbf{a}_y is a unit vector in the y direction.

Eqn. (5.3.17) becomes

$$\mathbf{a}_y e^{-ikz+i\omega t} = - \sum_{n=1}^{\infty} (h_{n1} \mathbf{M}_{n1} + j_{n1} \mathbf{N}_{n1}) \quad (5.3.18)$$

Earlier, we stated that u and v had to be distinct wavefunction solutions to the Helmholtz equation, making them different Ψ 's. From that original relation, we were able to derive the fundamental vectors based on Ψ . I put off defining the form of these wavefunctions for inside and outside the homogeneous sphere until this point in order to get a better sense of how these functions relate to the electric field vector. Now that we have a relation, I will state without proof u and v for different cases.

Outside, incident wave:

$$u = e^{i\omega t} \cos(\phi) \sum_{n=1}^{\infty} (-i)^n \frac{2n+1}{n(n+1)} P_n^1(\cos(\theta)) j_n(kr)$$

$$v = e^{i\omega t} \sin(\phi) \sum_{n=1}^{\infty} (-i)^n \frac{2n+1}{n(n+1)} P_n^1(\cos(\theta)) j_n(kr)$$

This equation makes sense formally because it comes from the form for scalar Ψ 's that we saw previously. Here j_n is a spherical Bessel Function and unrelated to the j_{n1} that we got as a coefficient in equation (5.3.18). The fraction $(-i)^n \frac{2n+1}{n(n+1)}$ does comes from these coefficients, h_{n1} and j_{n1} , however. Exploiting the orthogonality of the fundamental vectors:

$$h_{n1} = \frac{2n+1}{n(n+1)} i^n$$

and

$$j_{n1} = -\frac{2n+1}{n(n+1)} i^{n+1}$$

Manipulating the wavefunctions for u and v with respect to our spherical coordinate system is how we get the components of our fundamental vectors.

For the fields to remain finite as r goes towards the limit of infinity, we can make the general assumption: Outside, scattered wave:

$$u = e^{i\omega t} \cos(\phi) \sum_{n=1}^{\infty} (-a_n) (-i)^n \frac{2n+1}{n(n+1)} P_n^1(\cos(\theta)) h_n^{(2)}(kr)$$

$$v = e^{i\omega t} \sin(\phi) \sum_{n=1}^{\infty} (-b_n) (-i)^n \frac{2n+1}{n(n+1)} P_n^1(\cos(\theta)) h_n^{(2)}(kr)$$

Where, above, a_n and b_n are the scattering coefficients that we are going to solve for for our overall scattering function, making them the most important piece of this part of the derivation. $h_n^{(2)}$ is derived from the spherical Bessel function of the second kind. Inside wave:

$$u = e^{i\omega t} \cos(\phi) \sum_{n=1}^{\infty} (mc_n) (-i)^n \frac{2n+1}{n(n+1)} P_n^1(\cos(\theta)) j_n(kr)$$

$$v = e^{i\omega t} \sin(\phi) \sum_{n=1}^{\infty} (md_n) (-i)^n \frac{2n+1}{n(n+1)} P_n^1(\cos(\theta)) j_n(kr)$$

Where, above, m is our index of refraction, and c_n and d_n are more scattering coefficients. Now that we have our general forms of our wavefunctions, how they relate to our fundamental vectors, and how those comprise our electric field vector, we can solve for our unknown coefficients a_n , b_n , c_n , d_n .

5.3.2 Boundary Conditions and Scattering Coefficients

We have spent the last few sections giving the basis of general wavefunction solutions to the Helmholtz equation. Our goal as we stated previously is to derive the Mie formalism, and through the mathematics of wave geometry and its combination with electromagnetism, we have been able to get a feel for how the Mie scattering function is derived. We are now at the point where we need to look at the physical set up of the problem, specifically the boundary conditions.

For a non-conductive, homogeneous sphere, we have already established that the surface charge density is zero. Looking at our classic electrostatic boundary conditions we can now pinpoint any discontinuities. There are two boundary conditions we must worry about, the tangential component and the normal component. For the normal component we have

$$E_{above}^{\perp} - E_{below}^{\perp} = \frac{\sigma}{\epsilon_0}$$

which in our case is 0 for the reason stated above. Therefore, the normal component of \mathbf{E} is continuous at the boundary. For the tangential component, we get that it is always continuous

from the solution to the integral version of Gauss' law. Another way of expressing the tangential component is

$$\mathbf{n} \times (\mathbf{H}_2 - \mathbf{H}_1) = 0$$

$$\mathbf{n} \times (\mathbf{E}_2 - \mathbf{E}_1) = 0$$

where there is a sharp boundary between the sphere and the medium it is placed within. Here, \mathbf{n} is the vector normal to \mathbf{E} and the subscripts 1 and 2 represent the fields of the corresponding media. By putting it in this notation, we are able to leverage the azimuthal and polar components of the electric and magnetic fields being equal at the boundary of the sphere and media $r = a$, where a is the radius of the sphere. The common factors, which I will state without full derivation, that appear from E_ϕ and E_σ are

$$v \quad \text{and} \quad \frac{1}{m} \frac{\partial(ru)}{\partial r}$$

and from H_ϕ and H_σ

$$mu \quad \text{and} \quad \frac{\partial(rv)}{\partial r}$$

We can now use the Riccati-Bessel functions to express the continuity between these expressions at the boundary $r = a$. The Riccati-Bessel functions are similar to the spherical Bessel functions we have encountered throughout our derivation of the Helmholtz wavefunctions, and are just off by a factor of z . Due to our use of Ψ for the previous scalar wavefunction derivations, we will abstain from using the Debye notation of the Riccati-Bessel functions (which are also seen in van de Hulst's treatment of the problem).

$$S_n(z) = z j_n(z)$$

$$C_n(z) = -z y_n(z)$$

$$\zeta_n(z) = z h_n^{(2)}(z)$$

j_n is the spherical Bessel function of the first kind, y_n is the spherical Bessel function of the second kind, and $h_n^{(2)}$ is the spherical Hankel function of the second kind which relates the two Bessel functions as such: $h_n^{(2)}(z) = j_n(z) - i y_n(z)$

The arguments which we have denoted as z , are physical in nature as they relate to the geometry of spherical harmonics:

$$x = ka = \frac{2\pi a}{\lambda}, \quad y = mka$$

where m is the refractive index, and a is still the radius of the sphere. x itself is the ratio of the circumference of the cross section of the center of the sphere to the wavelength, which is similar to the regime we found to start this problem. This similarity demonstrates the underlying importance of the size to wavelength ratios that permeate the problem.

Now the continuity equations of the expressions are:

$$\begin{aligned} [mu] : \quad & S_n(x) - a_n \zeta_n(x) = mc_n S_n(y) \\ \left[\frac{1}{m} \frac{\partial(ru)}{\partial(r)} \right] : \quad & S'_n(x) - a_n \zeta'_n(x) = c_n S'_n(y) \\ [v] : \quad & S_n(x) - b_n \zeta_n(x) = d_n S_n(y) \\ \left[\frac{\partial(rv)}{\partial(r)} \right] : \quad & S'_n(x) - b_n \zeta'_n(x) = md_n S'_n(y) \end{aligned}$$

and here we have our four unknown coefficients from earlier, and a system of equations containing four equations. We can now solve for our unknowns, a_n , b_n , c_n , d_n . When solving the system for c_n and d_n we see that they possess the same denominators and a common numerator $S'_n(x)\zeta_n(x) - S_n(x)\zeta'_n(x) = i$, which allows us to cancel them in our system. We are now just left with our final scattering coefficients, a_n and b_n .

$$\begin{aligned} a_n &= \frac{S'_n(y)S_n(x) - mS_n(y)S'_n(x)}{S'_n(y)\zeta_n(x) - mS_n(y)\zeta'_n(x)} \\ b_n &= \frac{mS'_n(y)S_n(x) - S_n(y)S'_n(x)}{mS'_n(y)\zeta_n(x) - S_n(y)\zeta'_n(x)} \end{aligned}$$

When we derive the tangential components of the electric and magnetic fields, as we had done to get the scattering coefficients, we get the relations below:

$$E_\theta = H_\phi = h_n^{(2)}(kr) \cos(\phi) \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left[b_n \frac{P_n^1(\cos(\theta))}{\sin(\theta)} + a_n \frac{dP_n^1(\cos(\theta))}{d\cos(\theta)} \right] \quad (5.3.19)$$

$$-E_\phi = H_\theta = h_n^{(2)}(kr) \sin(\phi) \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left[a_n \frac{P_n^1(\cos(\theta))}{\sin(\theta)} + b_n \frac{dP_n^1(\cos(\theta))}{d\cos(\theta)} \right] \quad (5.3.20)$$

Let's unpack these equations. They come directly from the u and v equations for scattered waves outside the sphere. From those equations we see two new additions. 1) the scattering coefficients which allow for the equality above between the electric and magnetic fields, as that was what they were solved for. 2) modified associated Legendre polynomials, which come out of the relation between the scattered wave and the polar angle outside of the sphere. These functions can actually be denoted as

$$\pi_n(\cos(\theta)) = \frac{P_n^1(\cos(\theta))}{\sin(\theta)}$$

$$\tau_n(\cos(\theta)) = \frac{dP_n^1(\cos(\theta))}{d\cos(\theta)}$$

Thus, eqns. (5.3.19) and (5.3.20) can be rewritten as

$$E_\theta = H_\phi = h_n^{(2)}(kr) \cos(\phi) \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} [b_n \pi_n(\cos(\theta)) + a_n \tau_n(\cos(\theta))] \quad (5.3.21)$$

$$-E_\phi = H_\theta = h_n^{(2)}(kr) \sin(\phi) \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} [a_n \pi_n(\cos(\theta)) + b_n \tau_n(\cos(\theta))] \quad (5.3.22)$$

What is interesting about these equation is that they can also be written in terms of matrix multiplications of incident waves. We have already noted that these equations represent the scattering effects outside the sphere. We can more generally demonstrate the scattering amplitude modification by the equation:

$$\begin{bmatrix} E_\theta \\ E_\phi \end{bmatrix} = \begin{bmatrix} S_2 & S_3 \\ S_4 & S_1 \end{bmatrix} * h_n^{(2)} \begin{bmatrix} E_{0\theta} \\ E_{0\phi} \end{bmatrix} \quad (5.3.23)$$

For our system of equations, $E_0(\theta) = \cos(\theta)$ and $E_0(\phi) = \sin(\theta)$. S_4 and S_3 are 0, while

$$S_1(\theta) = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} [a_n \pi_n(\cos(\theta)) + b_n \tau_n(\cos(\theta))] \quad (5.3.24)$$

and

$$S_2(\theta) = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} [b_n \pi_n(\cos(\theta)) + a_n \tau_n(\cos(\theta))] \quad (5.3.25)$$

making these our scattering amplitude functions. $S_1(\theta)$ and $S_2(\theta)$ having angular dependence also encodes polarization of the scattered wave, with $S_1(\theta)$ being related to perpendicular polarization, and $S_2(\theta)$ being related to parallel polarization. Their exact relation is that if we calculate the intensity

$$I_{\perp} = \frac{|S_1(\theta)|^2}{k^2 r^2} I_0$$

$$I_{\parallel} = \frac{|S_2(\theta)|^2}{k^2 r^2} I_0$$

The parallel and perpendicular subscripts correspond to the polarization of the scattering functions S_1 and S_2 . Now we can calculate our full intensity as a function of angle outside the sphere (at the far field).

$$I = \frac{\frac{1}{2}(|S_1(\theta)|^2 + |S_2(\theta)|^2)}{k^2 r^2} I_0 \quad (5.3.26)$$

Where we have found our $F(\theta, \phi)$,

$$F(\theta) = \frac{1}{2}(|S_1(\theta)|^2 + |S_2(\theta)|^2)$$

Notice how $F(\theta, \phi)$ has become $F(\theta)$ due to the scattering function being axisymmetric in spherical coordinates. We can now use this equation and its components to parse out all aspects of the scattered wave.

6

Code and Results

6.1 Mathematica

We can solve the derivation we have just completed analytically for the case of the homogeneous sphere in a medium, which we define as a silica microsphere in air. Throughout our derivation, we had chosen the specifications of surface charge and conductivity to be for a silica microsphere, as this is an accurate control approximation for the material, size, and shape of an iridocyte. The next step was to use Wolfram Mathematica to solve the Riccati-Bessel functions in three dimensions, and check the output scattering of our electromagnetic waves. Silica has a refractive index of 1.45, and we chose our sphere to have a radius of 5 micrometers in order to mimic the iridocyte. Our input intensity was done with an electric field magnitude equal to 1 V/M. For the 520 [nm] (green) wavelength, our scattering intensity as a function of angle looks like fig 6.1.1:

The characteristics of the graph are reasonable for what we would expect physically: lots of forward scattering because it is a transparent material shaped like a lens (angles $-.33$ to $.33$ radians above), but having some reflective properties due to multiple media changes resulting in a small spike in backscattering; (think of photons going from low index to high index when it passes from air to silica glass, and then high to low when it reaches the back edge of the

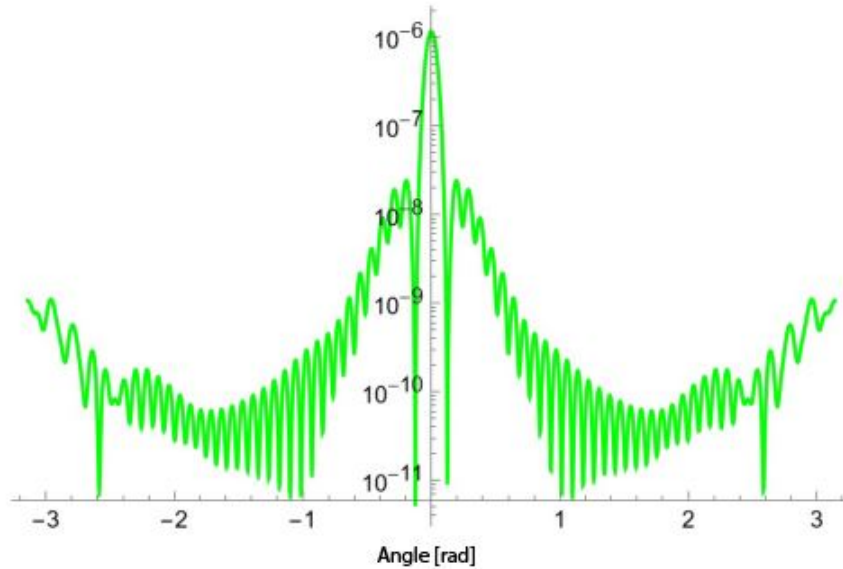


Figure 6.1.1: Mathematica plot of intensity per solid angle as a function of wavelength for 520 [nm] light on a single silica scatterer of 5 micron radius. Y axis represents intensity per solid angle and the x axis represents angle in radians.

microsphere causing a reflection). Beyond the eye test we can compare directly the data from our analytical solution to that of our two-dimensional simulation (fig 6.1.2).

As seen above the trends of both simulations is fairly constant and hover around 70-75% for forward scattering. The little discrepancy that there is between the two is most likely attributable to the difference in dimensions of each of the calculations due to their slight variance in symmetry. Thus, due to their similarity, we see that the COMSOL 2D model is a fairly accurate approximation of light scattering for a 3D object. We will use the data from our simulations in order to speak on problems of light scatter in 3 dimensions.

6.2 Methods

In order to simulate light scattering in a physical world setting (and by world I mean artificially coded world) COMSOL Multiphysics was used. The program itself solves Maxwell's equations to the specifications of the desired geometry, boundary conditions, and materials. For

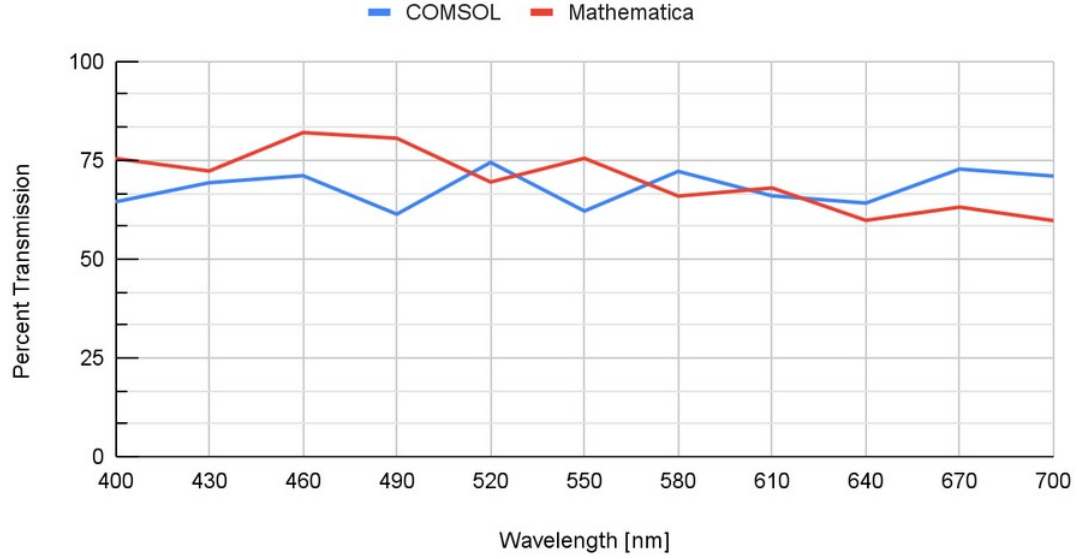


Figure 6.1.2: A comparison of the ratio of transmission for COMSOL 2D simulations and Mathematica 3D analytical solutions. Data for COMSOL sims based on control microparticle in air with radius 5 microns

our world, we attempted to model different iridocyte structures as single geometries. (See figs 6.2.1 and 6.2.2 for reference of iridocyte and Bragg stack configurations). Once the geometries were constructed, we selected materials corresponding to different parts of the microspheres. The incoming electromagnetic radiation was polarized in the y direction with a magnitude of 1 V/M. The world itself contains a perfectly matched layer (PML) which represents a nonreflecting infinite domain for which to solve Maxwell's equations. The surfaces themselves were defined as non conducting, and the sides of the world were defined as periodic in order to mimic an infinite array of the world created. The simulation itself was conducted in 2D, and therefore the geometries are created as a cross section of a 5 micrometer sphere. This set up translates to an infinite cylinder extending out of the (x,y) Cartesian plane the world exists within in the z direction. However, the cross section of a cylinder and a sphere along its diameter are identical if they have the same radius, which we have set them up to be. For our 2D results, we can extrapolate a dimension higher using the fact that a sphere is symmetric in the azimuthal direction (imagine a cross section being rotated around its central axis). For the purposes of

the rest of this paper, I will be referencing geometries in the 3D case, e.g. a nanosphere was actually represented as a nano circle.

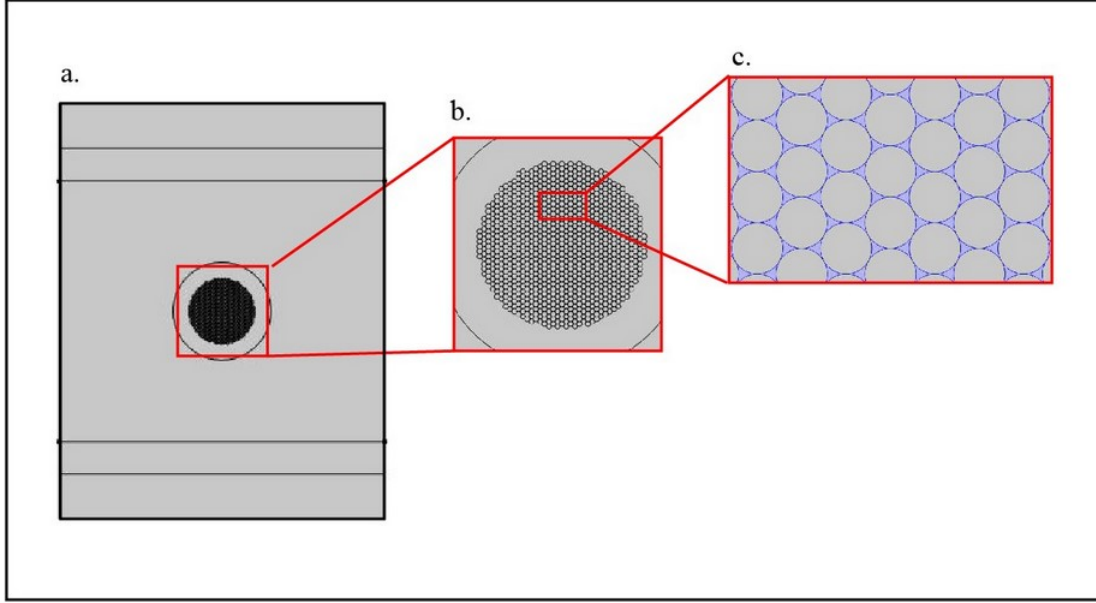


Figure 6.2.1: A,B, and C are all different scales of the synthetic iridocyte. Circles represent infinitely protruding cylinders. The highlighted space in between is specified as the medium. Control is the same 5 micron radius, that the smaller circles fill, with no medium inside.

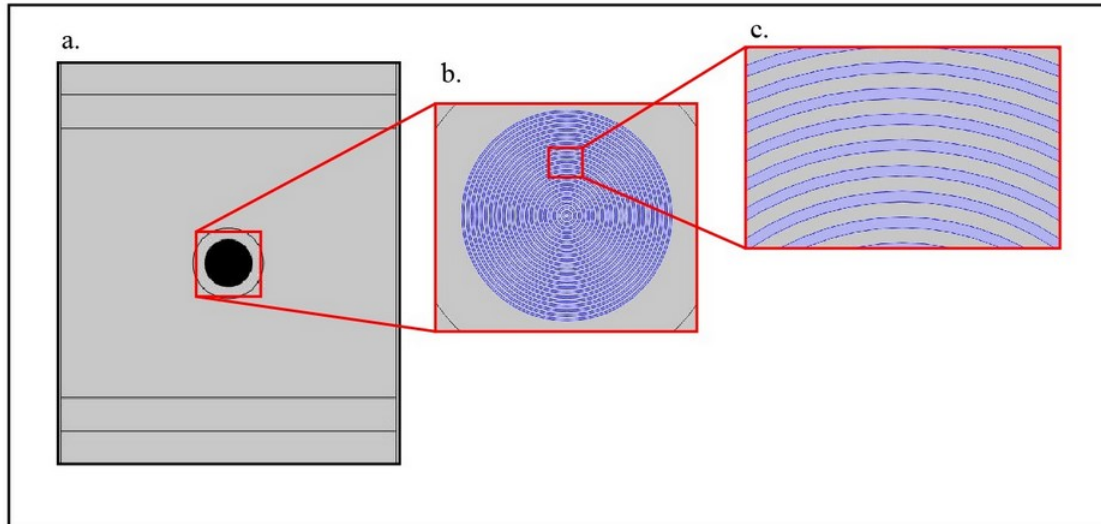


Figure 6.2.2: A,B, and C are all different scales of the Bragg stack. Each layer is quarter wavelength thickness for 520 [nm]. Control is the same 5 micron radius, that the smaller circles fill, with no medium inside.

6.3 Results

The main characteristics we were searching for were the different configurations' ability to both enhance forward scattering of incident radiation and inhibit non photosynthetically efficient wavelengths i.e. 520 [nm]. We define forward scattering similarly to Holt et al., (2014), being within a 16 degree cone on either side of the point of incidence. The models consisted of different shaped and sized geometries as well as different material interfaces for each. We utilized two different controls, a homogeneous silica microparticle in air (which we solved analytically above) and the same sphere immersed in a layer of gelatin to simulate cytoplasm in an iridocyte cell. Then we looked at creating a silica microsphere out of smaller constituent nanospheres, with the non tessellated space being air in one simulation and gelatin in the other. For the gelatin nanosphere set up, the exterior medium was also gelatin, mimicking the cytoplasm again. Lastly, we modeled synthetic Bragg stacks tuned to reflect 520 [nm] light using quarter wavelength mirroring. The alternating layers were meant to act as the platelets of an iridocyte cell, and were composed of silica and tantalum pentoxide in one and silica and gelatin in the other. Tantalum pentoxide was chosen as it is used in super polished mirrors. All simulations were conducted under the parameter of wavelength, which for our purposes spanned the visible spectrum in steps of 30 [nm] (400, 430, 460...700).

6.3.1 Control Group Simulations

For the control simulations, we wanted to see first how the medium interface affected light scattering. Choosing a standard size of 5 micron radius, we then averaged the intensity across all wavelengths to gauge how well each forward scattered light regardless of light color.

In figure 6.3.1, we see that a microparticle in gelatin film has marginally more forward scattering in the immediate 180° direction (full forward scattering) as they are around the same order of magnitude. However, as we move across the forward scattering cone, we see that the light intensity trends higher for the gelatin immersed geometry. Similarly in the backscattering direction, at 0°, there is more intensity reflected for the gelatin case, but this time along the cone

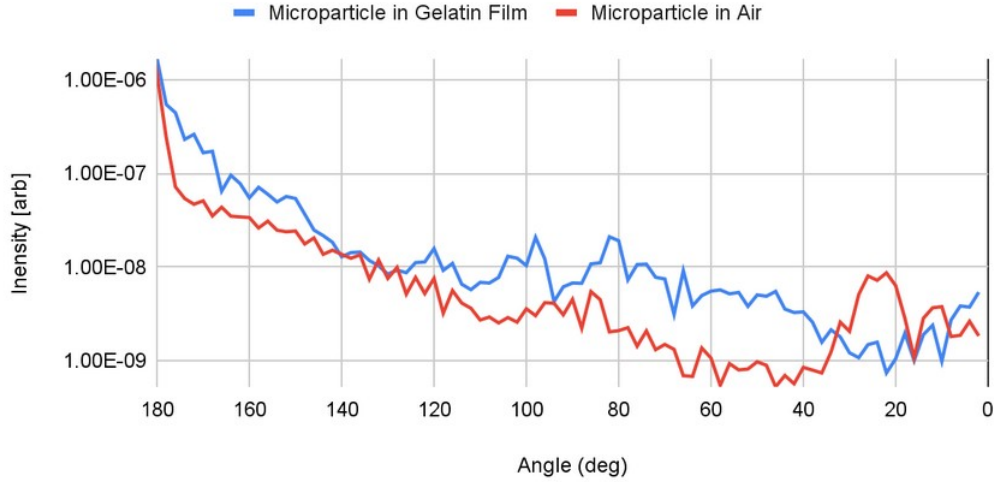


Figure 6.3.1: A comparison scattering for a 5 micron silica nanoparticle in different media. 2D representation of Mie scattering on homogeneous spheres. Intensities per solid angle averaged over all wavelengths tested (400-700 nm with a step of 30 nm) 180° represents full transmission in the forward scattering direction, and conversely, 0° is complete reflection. Plot is symmetric for the 180-360° range.

of backscattering there is overall more of a spike of reflection for the particle in air. This trend suggests fewer overall losses to backscattering for the gelatin interface, with more intensity

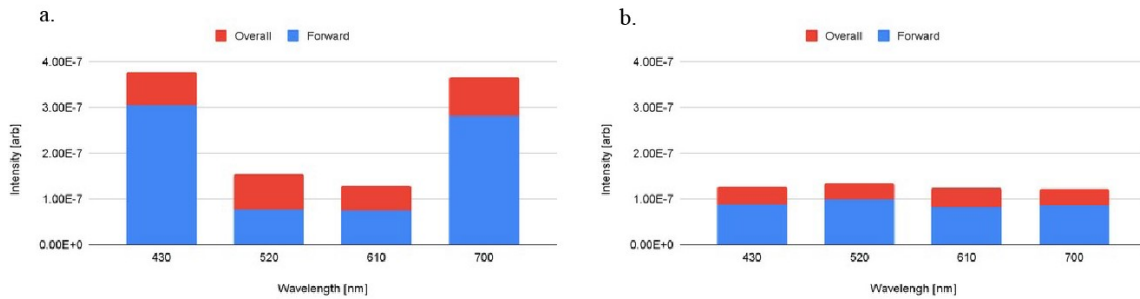


Figure 6.3.2: Comparison of transmission with respect to overall scattered intensity for microspheres embedded in different media. The blue shows forward scattering within the 16° cone (164°-196°) which represents bulk transmission of light through the scatterer. Red represents the difference between overall scatter and forward scatter. A) A 5 micron radius homogeneous silica sphere embedded in a film of gelatin. B) A 5 micron radius homogeneous silica sphere in air environment ($n \approx 1$)

going in the forward direction. It is worth noting that the gelatin case is the same one that Kim et al., (2017) use as their control for what an iridocyte would look like in its most basic cost

effective configuration. Next, we must ask what the breakdown of these scattering effects are across wavelengths to see if the models discriminate against any colors in the visible spectrum.

In figure 6.3.2 we see a noticeable increase in overall intensity for blue and red photo-synthetically efficient wavelengths, with a suppression of the intermediate wavelengths between them for the gelatin configuration. Additionally, a higher portion of the overall intensities for each of these wavelengths was sent in the forward direction in the gelatin model as compared to the air medium. This trend therefore gives some credence to the argument that the ratio of refractive indices between the media contributes to more selective scattering.

While this analysis was performed for the size 5 microns, it is also important to see if there are any trends in the size of the overall sphere and its effects on scattering. Testing one material interface, in this case gelatin, we sought trends in scattering amongst overall size. An iridocyte does not itself have a standard size, but rather grows to be within a range of 2.5-7.5 micrometers in diameter on average. Thus, different wavelengths were assessed for a range of 3-5 micrometers.

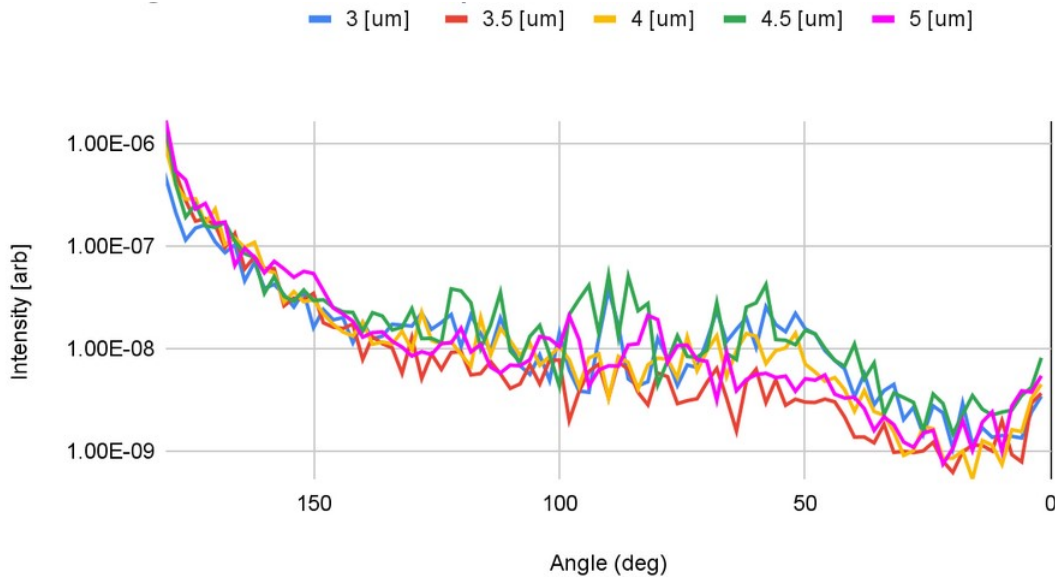


Figure 6.3.3: Size parameter of a silica microparticle in gelatin film for averaged wavelengths in the visible spectrum. Plot is symmetric along the 180° line (from 180°-360°). Vertical axis is intensity represented per solid angle. Intensity measurements for each wavelength averaged as a function of angle and plotted according to microparticle radius.

Averaging across all wavelengths of the visible spectrum, fig 6.3.3 demonstrates that aside from some noise in the side scattering direction, the forward and backscattering appear to be similar across sizes, especially 3.5-5 micrometers. The variations with respect to noise may be from the ratio of wavelength to the overall size, and the corresponding interference pattern that would arise from photons going through medium changes, however that is beyond the scope of this paper.

Breaking it down by wavelength in fig 6.3.4 we see that the character of the trend is similar for all sizes in the blue light regime, but more unpredictable in the green and red wavelengths. Specifically amongst backscattering angles for the 520 [nm] case, all sizes are fairly consistent. For the forward scattering case amongst microparticles in the gelatin interface, there is a certain randomness to the size of the particle and its ability to inhibit. This could possibly be attributed to interference at this wavelength, but this is only speculation. The red 700 [nm] wavelength seems to have larger variations in backscattering, but increase according to particle size. Forward scattering is again more random than 430 [nm] but less than 520 [nm]. Overall, the trend of the scattering for 430 and 700 [nm] appears to be very similar in that 5 [um] gelatin interface microparticles scatter more in the forward direction within the 16° cone from incident, while inhibiting more than the smaller counterparts in the 520 [nm] case. For this reason 5 microns seemed to be supported as a good size average for the rest of the synthetic iridocyte simulations.

6.3.2 *Synthetic Iridocyte*

Based on the designs of a synthetic iridocyte from Kim et al. (2017), we constructed a 2D version of the stacked constituent nanoparticle (NP) design, experimenting both with material and nanoparticle size. The first problem encountered when constructing such a model to fit within a larger 5 micrometer circle is what is known as the packing problem. Circles, like spheres, do not tessellate, leaving space in between to be filled by some other material. In our case we looked at gelatin and air as the two types of media. As a part of this packing

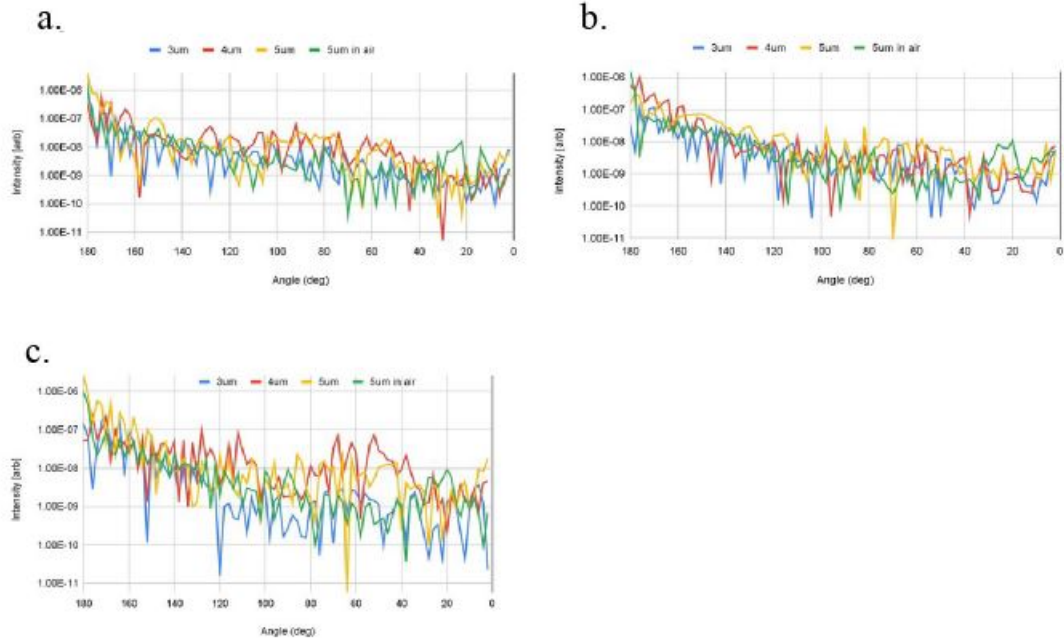


Figure 6.3.4: Scattering intensity per solid angle as a function of angle plots for different sized silica microparticles in gelatin and air. Blue, red, and yellow lines represent different sized silica microspheres in gelatin film. Green represents a silica microparticle left in air ($n=1$). A) 430 [nm], B) 520 [nm], C) 700 [nm].

problem, the shape of the circle is also discretely approximated, as the smaller constituent circles don't map perfectly smoothly to the larger surface. However, as they state in the paper, the randomness of the exterior configuration with respect to its roughness is an asset of the design as not every iridocyte is perfectly smooth and circular (spherical) in shape. Thus, the constituent NPs were trimmed to fill the 5 micrometer radius with a degree of care placed on symmetry but not on perfection and complete smoothness (see fig 6.3.5).

First, we had to identify the trends in constituent nanoparticle size in order to make a more simple iterative model for the media interfaces. We held the media type constant, in this case using gelatin as our control, and constructed each to fill the 5 micrometer radius sphere, as to have the same overall size. What was modeled was the similar NP diameter sizes as Kim et al. (2017), within the range of 150[nm]-300[nm]. What was gleaned from the data is that there is little to no difference in the forward or backward scattering directions. Constituent NP size

appeared to be far less significant than overall microparticle radius. Only at around 300 [nm] diameters did the backscattering appear to diverge, however more testing with larger constituent NPs would need to be done in future simulations to confirm the validity of divergence.

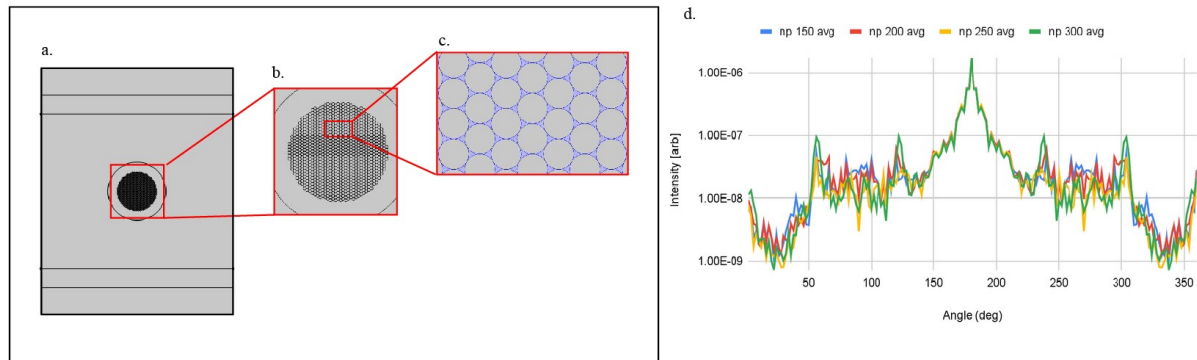


Figure 6.3.5: COMSOL model 2D synthetic iridocyte and the intensity as a function of angle for constituent nanoparticles of different diameters. A) Zoomed out interface of the synthetic iridocyte. Top and bottom horizontal lines denote perfectly matched layers, and intermediate horizontal lines denote start and end of radiation propagation. B) Synthetic iridocyte of radius 5 microns. C) Constituent silica nanoparticles. Blue space in between denotes internal media (either gelatin or air). D) Intensity per solid angle averaged over all wavelengths. 180° represents full transmission. Particle size corresponds to constituent nanoparticle diameter which was uniform for each case.

The difference in the 180° complete forward scattering transmission of light was within a 7% range for all of them, further exemplifying that they produced almost identical results. 250 [nm] had between 1.4 and 4.8 times lower reflection (backscatter) intensities than the 300 [nm] and between 1.2 and 2.4 times lower reflection than 200 [nm]. Based on its intermediate to larger size and relative efficiency in terms of lack of reflective losses (however marginal), 250 [nm] NPs were chosen as the control for the next set of simulations.

Looking at different media, we first held both synthetic microparticles at having a specific nanoparticle size for their makeup, 250 [nm] diameter. Averaging over all wavelengths, fig (6.3.6), we see that the gelatin interface yields more overall forward scattering in the 16° range, while also having fewer backscattering losses in the 16° backscatter range.

Looking specifically at the green wavelength, fig (6.3.7), we see that there is a trend when it comes to the media interface and the amount of suppression. For angles within the forward scattering cone, the gelatin interface has overall a higher transmission, with a similar

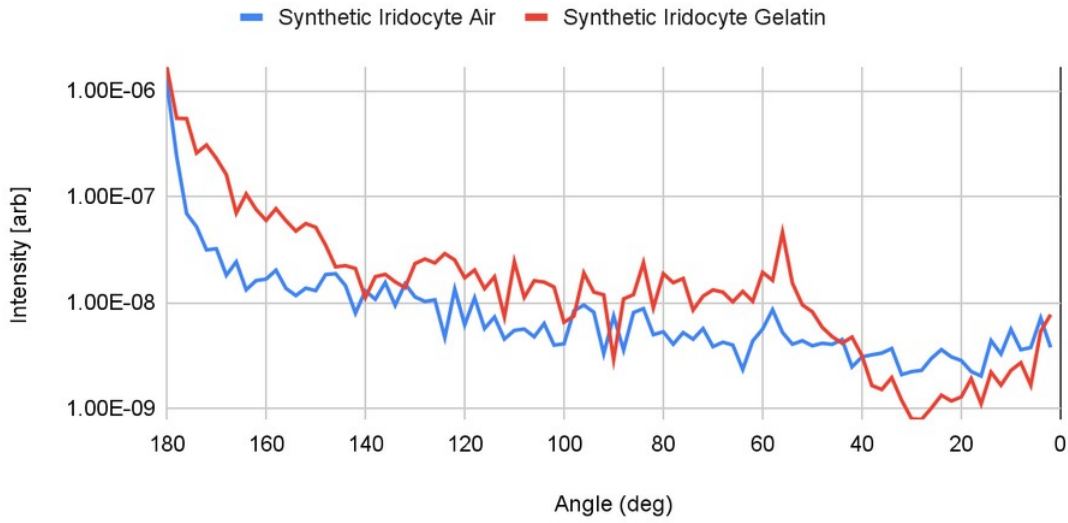


Figure 6.3.6: Scattering as a function of angle for synthetic iridocytes in different media averaged for all wavelengths.

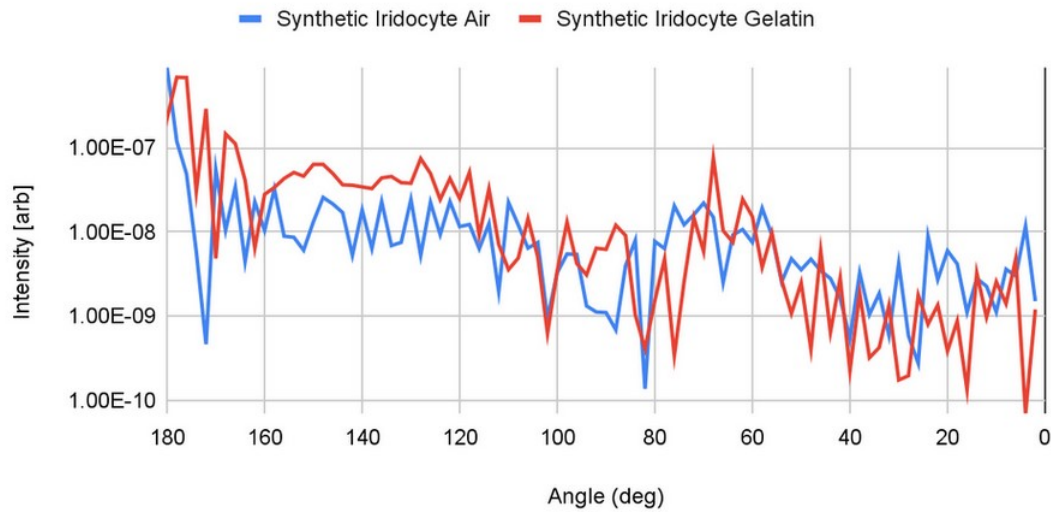


Figure 6.3.7: Scattering as a function of angle isolated for 520 [nm] wavelength. Plots above and below symmetric for range 180° to 360°.

trend overall. However, within the direct forward scattering window, 4-5°, there is a noticeable suppression of the green wavelength. It is important to note that this does not happen with the 430 [nm] nor the 700 [nm] wavelengths as seen in figures 6.3.8 and 6.3.9.

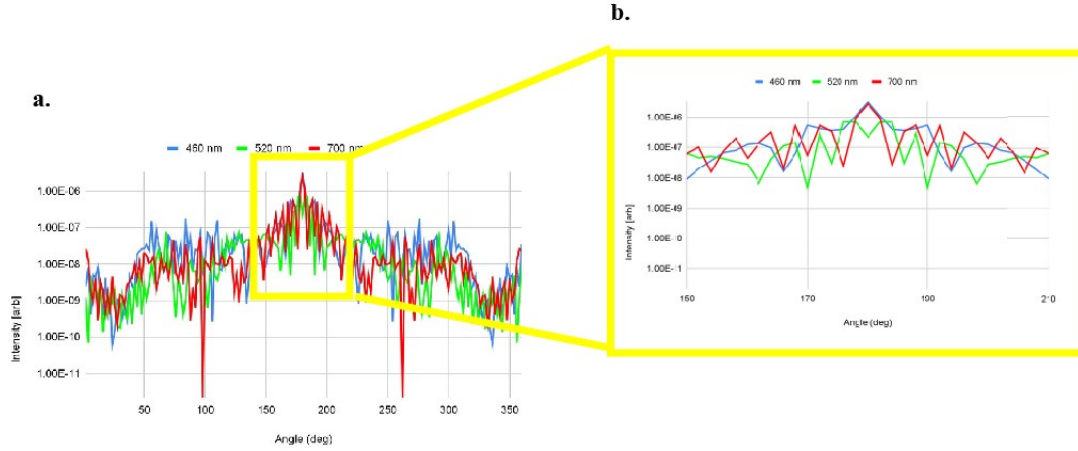


Figure 6.3.8: Scattering intensity as a function of angle for different wavelengths and media with respect to the synthetic iridocyte geometry. A) Full angle range of scattering for blue 460 [nm], green 520 [nm], and red 700 [nm] in the synthetic iridocyte gelatin configuration. Constituent nanoparticle size is 250 [nm] diameter. B) Same as plot A from range 150-210° forward scattering.

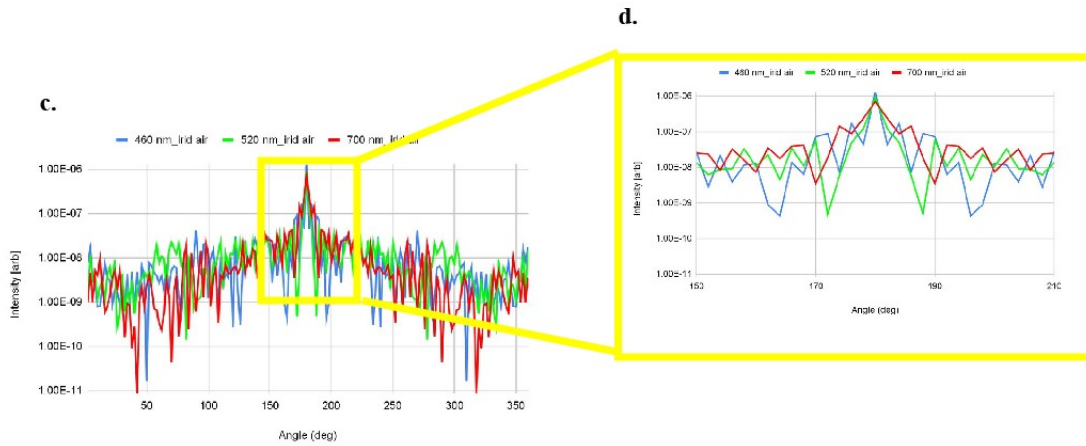


Figure 6.3.9: C) Full angle range of scattering for blue 460 [nm], green 520 [nm], and red 700 [nm] in the synthetic iridocyte air configuration. Constituent nanoparticle size is 250 [nm] diameter. D) Same as plot C from range 150-210° forward scattering.

The overall intensities for blue and red wavelengths respectively are higher in the gelatin film interface than in the air interface. This comes at a minimal loss to backscattering which suggests more optical efficiency in their ability to forward scatter. At the same time, green wavelengths are actually lower in the gelatin interface as compared to the air interface despite overall higher levels of intensity from all wavelengths. Side scattering appears comparable in

both for green wavelengths with the gelatin interface experiencing a greater intensity for blue and red. Again, the suppression patterns seem to be more pronounced overall for the correct wavelengths in the gelatin interface, rather than the air interface.

6.3.3 Bragg Stack

A Bragg mirror, also known as a distributed Bragg reflector or Bragg stack, is a mirror that is made up of alternating optical materials at set thicknesses corresponding to specific wavelengths. The most common is the quarter wavelength Bragg reflector, where the thickness is set at a quarter of the wavelength one would want to reflect. Due to the biological nature of alternating platelet and cytoplasm layers within the cell of an iridocyte, and the ability to selectively backscatter specific wavelengths of light, this model appeared to be a potentially more effective alternative to the ones proposed in Kim et al. (2017). Because you can layer optical materials on top of one another in the process of mirror making, the assembly of a Bragg mirror with the right optical interface could also be cheaper than assembling smaller nanoparticles into a microsphere (see fig 6.2.2).

First we sought to compare overall mirror size, as more layers may impact the reflectivity of the material, and each layer is set at a fixed quarter wavelength thickness of $\frac{520}{4}$ [nm]. It appears the intermediate sizes 4-4.5 μm were more efficient in their scattering efforts, while the largest size had more overall scattering. Similar to the control Silica MP, larger sizes tended to be more effective at forward scattering but at a slight cost to side scattering. Here, the intermediate sizes appear to do a better job at limiting obtuse scattering and focus light more in the forward direction.

For gelatin as the optical material, the overall difference in size appears to have minimal effect on forward or backward scattering, with 5 [μm] yielding intensities 1.2-1.4 times higher in the full transmission (180°) direction.

For a more reflective material like Tantalum Pentoxide (Ta_2O_5), which has a refractive index of 2.275, we can again see chaotic scattering along the oblique angles and reflection

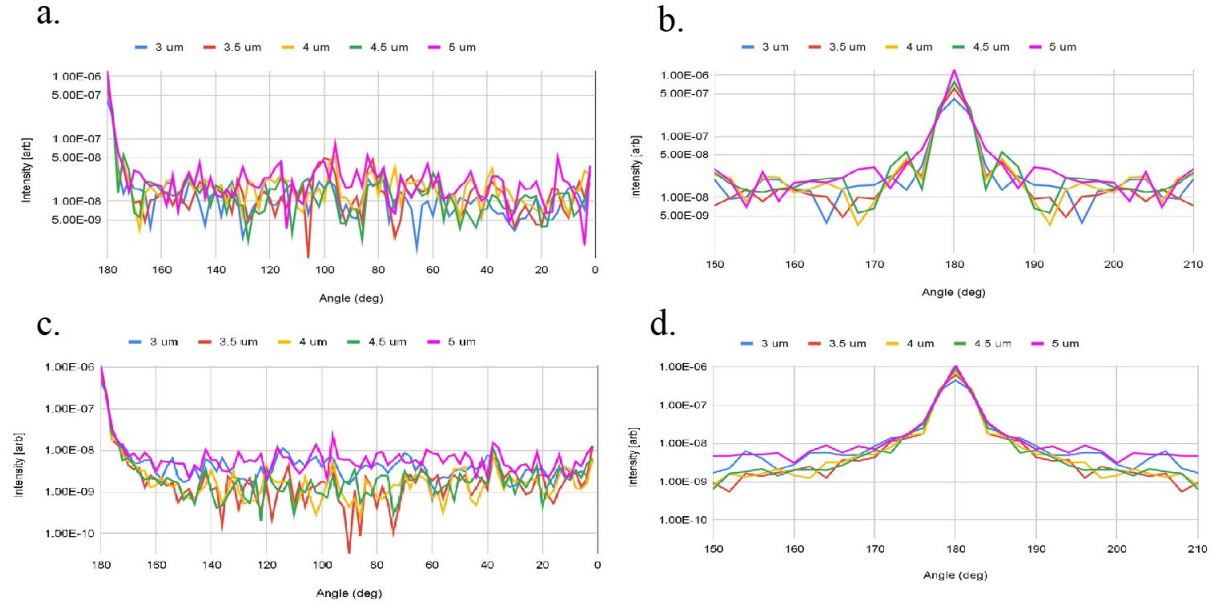


Figure 6.3.10: Size parameterized plots of intensity per solid angle as a function of wavelength for Bragg reflectors of different optical materials. A) Tantalum Pentoxide (Ta_2O_5) coated mirror ($n \approx 2.275$). Sizes represent radii of the overall scatterer. B) Same as plot A in the range 150-210°. C) Gelatin coated mirror ($n \approx 1.33$) with sizes corresponding to radii of overall scatterer. D) Same as plot C in the range 150-210°.

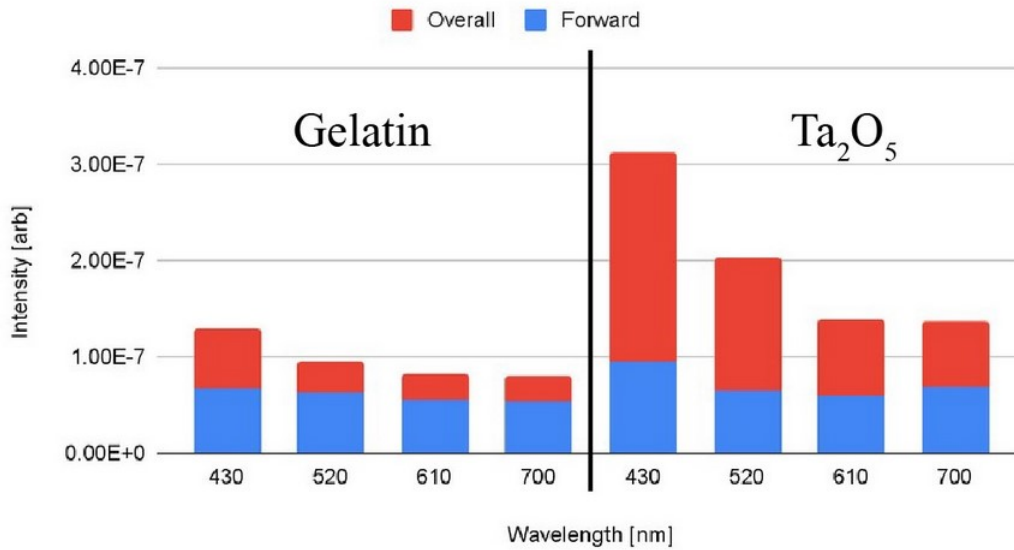


Figure 6.3.11: Forward scattered intensity for different wavelengths compared to overall scattering intensity for Bragg mirror geometries. Left) Gelatin optical coating. Right) Tantalum Pentoxide (Ta_2O_5) optical coating

angles. However, for transmission, we can see a difference of between 1.586 and 3 times as much forward scattering for 180° , with the trend going upward for larger and larger sizes.

Above, we see that the overall intensity for each wavelength is higher for the Tantalum pentoxide Bragg mirror, yet the efficiencies for forward scattering are lower for each than the gelatin case. In both configurations, the overall intensities go down as wavelength increases, with the efficiencies themselves staying relatively constant in their proportion of forward to overall scattering. There is a slight increase in both overall intensity and efficiency in the 700 [nm] case with the Tantalum Pentoxide mirror, but this itself is marginal.

6.3.4 Aggregated Comparisons

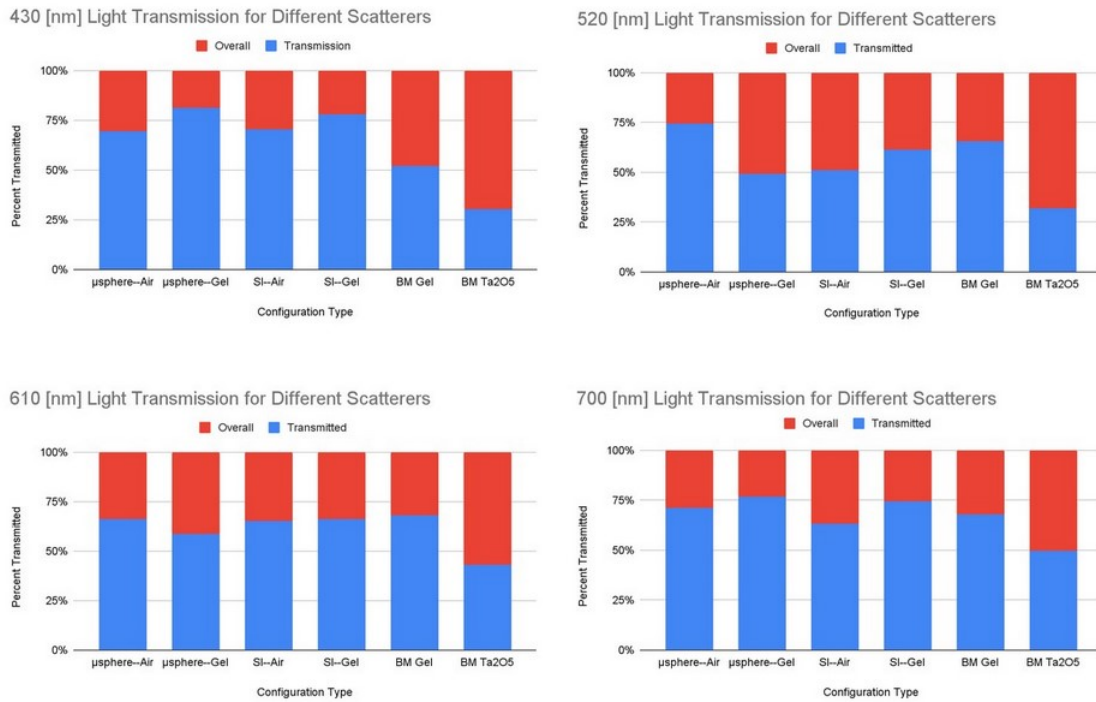


Figure 6.3.12: Light Transmission for different scatterers. Each configuration had an overall radius of 5 microns. Synthetic iridocytes both had constituent nanoparticles of diameter 250 [nm]. Both Bragg mirrors had quarter wavelength thickness corresponding to 520 [nm]

In trying to analyze a geometry and media combination that effectively forward scattered light of the wavelengths 400 and 700 [nm], it was observed that the control microsphere performed roughly the same for all wavelengths, further validating its configuration as a control,

fig (6.3.12). Changing only the interface of the control, by placing it in a film of gelatin, possessed the desired effect of inhibiting the green 520 [nm] wavelength, while still allowing the other wavelengths to transmit at around the same level as the control. This suggests that the ratio of the indices of refraction at the boundary plays an important role in the scattering effects of specific wavelengths, in this case $\frac{1.33}{1.45} = \frac{\text{gelatin}}{\text{silica}}$.

Moving to more complex geometries, the 2D version of the synthetic iridocyte that Kim et al. (2017) had identified, trended similarly despite the different media. The synthetic iridocyte, with a silica/air interface, remained rather stagnate in its transmission percentage across wavelengths that were not 520 [nm], staying between 63-70.4%. However, the transmission for 520 [nm] dropped to a low of 51.2% of the overall light scatter. The two highest transmissions were for the 430 and 610 [nm] wavelengths at 70.4% and 65.4% respectively. For the gelatin/air interface synthetic iridocyte, there was slightly more variation within the non 520 [nm] wavelengths, ranging from 66.2-78%, showing more transmission overall. Along this line, there was more transmission for the 520 [nm] wavelength, yielding 61.4%. The two highest transmission percentages were for the advantageous 430 and 700 [nm] wavelengths with 78% and 74.3% respectively. Despite more transmission overall, the gelatin configuration showed more differential between advantageous and non advantageous wavelengths.

The Bragg mirrors both displayed trends of increasing transmission with wavelength. The Tantalum pentoxide mirror reflects more for each wavelength, due to the large difference of refractive index between media. The overall transmission for Ta_2O_5 lies in the range 30.5-49.6%, with 520 [nm] being the lowest transmission out of all six configurations at 32%. The Bragg gelatin mirror transmits in the range 52.2-68.2%, with the difference between 700 and 610 [nm] being -0.2%. Both were effective at inhibiting lower wavelengths but fail to adequately transmit wavelengths lower than 520 [nm]. The geometry of each was set to specifically reflect 520 [nm], and therefore, all other wavelengths are a product of the thickness of the constituent layers in terms of interference.

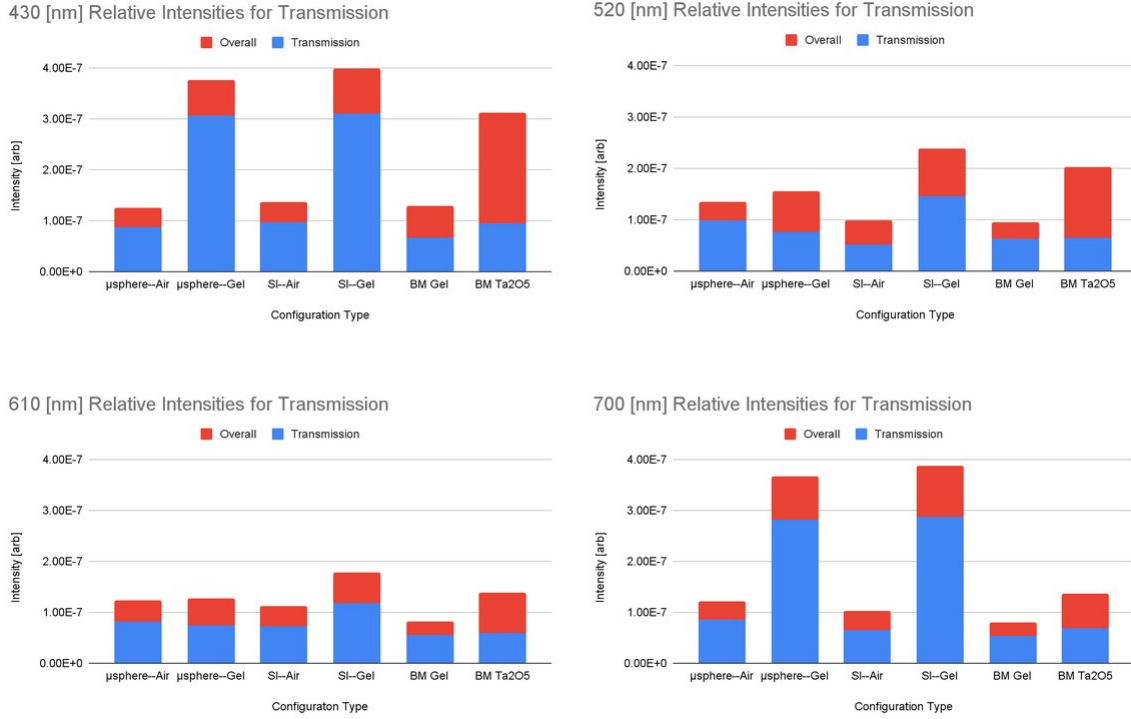


Figure 6.3.13: Relative intensities of overall and forward scattering for different scatterers. Intensity represents intensity per solid angle integrated over all angles. Transmission is within angle range 164-196°. Each configuration had an overall radius of 5 microns. Synthetic iridocytes both had constituent nanoparticles of diameter 250 [nm]. Both Bragg mirrors had quarter wavelength thickness corresponding to 520 [nm].

In terms of overall intensity of light scattered, the synthetic iridocyte gelatin medium and microsphere gelatin medium scatter the most radiation along with transmitting the most for almost all of the wavelengths. The microsphere gelatin configuration actually performs best in terms of intensity inhibition over all angles for 520 [nm] with respect to its overall scattering of other wavelengths (a 58.8% decrease in intensity with respect to 430 [nm])—which it transmitted the best. For transmission alone (16° forward scattering cone), it has a decrease of 75% between these two wavelengths. The synthetic iridocyte in gelatin showed a 55.3% decrease in intensity over all angles from 430 [nm] to 520 [nm]. In terms of transmission alone, this configuration saw a decrease of 52.6% from 430 [nm] to 520 [nm] and 62.1% from 430 [nm] to 610 [nm] (the most inhibited). For 430 [nm] and 700 [nm], the microsphere in gelatin was 98.71% and 97.91% as effective as the synthetic iridocyte in gelatin. For the 520 [nm] and 610 [nm] wavelengths, the

microsphere in gelatin was 47.96% and 37.61% more effective at inhibiting than the synthetic iridocyte in gelatin. The only configuration that inhibited the 520 and 610 [nm] wavelengths less than the control, was the synthetic iridocyte in gelatin.

As stated before, backscattering losses present a loss of radiation for the culture. Side scatter, while not direct transmission, can reach the algae and interfere to reduce/increase saturation as long as it is less than 270° and greater than 90° . Fig 6.3.14 shows the backscatter along the 16° reflection cone, the same range as we took for the forward scattering direction.



Figure 6.3.14: Reflective losses due to backscattering. Backscattering is considered within the $344\text{--}16^\circ$ range. Plot colors organized by corresponding visible wavelength. Each configuration had an overall radius of 5 microns. Synthetic iridocytes both had constituent nanoparticles of diameter 250 [nm]. Both Bragg mirrors had quarter wavelength thickness corresponding to 520 [nm].

As shown above, the Bragg mirrors do the best job at direct backscattering of radiation, producing the highest intensities for most wavelengths. The tantalum pentoxide mirror scattered the most at every wavelength, with the most scattering coming from the 430 [nm] wavelength. The control microsphere in air backscatters more at the wavelengths that should

be inhibited, 520 [nm] and 610 [nm]. At every wavelength but 700 [nm], the synthetic iridocyte in air did a better job reflecting light than the synthetic iridocyte in gelatin. For the three scatterers that were not the control or the Bragg mirrors, less 520 [nm] radiation was inhibited with respect to the other wavelengths except for the microsphere in gelatin for the 610 [nm] case and the synthetic iridocyte in air 700 [nm] case.

6.3.5 Discussion

When analyzing the effectiveness of these different configurations in terms of performing the function of the iridocyte for the giant clam, one must take into account: how much and what type of light is lost to backscatter, how much green light was inhibited, how much red and blue was transmitted, and whether or not the overall flux was lessened. In all cases, because there was scattering of some kind, there was an extinction cross section. This suggests that all of them performed the task of lessening the incident radiation that would normally saturate the surface of the algae. When looking at the extinction cross section, there are two components: absorption cross section and scattering cross section. We are looking at intensity or intensity per solid angle across all possible angles, so if there was no absorption of light for any of these configurations, they would all have the same scattering cross section. The data above shows that when comparing relative intensities, like in figure 6.3.13, this is untrue, suggesting that some do absorb more light than others.

The question becomes what type of geometry utilizes this lessening effect of the overall intensity on the right wavelengths. As seen by the control (silica microsphere in air), the geometry alone does little to influence wavelengths that get inhibited or transmitted. This is exacerbated by the fact that there was little variation from wavelength to wavelength for the synthetic iridocyte in air. As noted in Kim et al. (2017), the reason that gelatin was chosen, along with silica, is that the ratio of their refractive indices closely resembles that of the cytoplasm and platelets of the iridocyte cell. We see that of the three different geometries,

only the gelatin coated Bragg mirror remained fairly stagnant across all wavelengths, in terms of overall intensity and transmission intensity.

Both Bragg mirrors served their main purpose of reflecting light, however, they became wavelength dependent based on their geometry. In terms of the light they both transmitted, both performed poorly at overall transmission and selectivity of wavelength. The Bragg stack may have the potential to be improved upon if it was made non circular (nonspherical in 3D), resembling something more like an iridocyte cell.

The two best performing configurations for selective inhibition were the homogeneous silica microparticle in gelatin and the synthetic iridocyte in gelatin. Both displayed strong selectivity to the green 520 [nm] wavelength as compared to the other wavelengths. In terms of backscattering, the two performed similarly, with the synthetic iridocyte exhibiting slightly more backscattering for all wavelengths except 520 [nm]. The synthetic iridocyte, did however, provide more overall intensity for every wavelength, which suggests that it is a solar transformer that still maintains strong levels of flux, which is important for not oversaturating, while also not under-radiating the culture. If the culture does not get enough light, it will similarly not be as photosynthetically efficient, and will yield less biomass.

This is all to say that those two configurations performed similarly, with the silica microparticle in gelatin appearing to utilize photosynthetically active wavelengths as a higher percentage of overall transmitted light. The general characteristics of these simulations that confirmed findings by Kim et al. (2017) and Holt et al. (2014) were size, shape, and material, along with constituent nanoparticle size. Due to this being a 2D simulation rather than 3D, it cannot be confirmed which configuration was better between the two gelatin geometries we highlighted above (despite our confidence in the simulation's ability to approximate). However, in the 2D case, the silica microparticle in gelatin performed best at transmitting advantageous wavelengths while inhibiting others, and the synthetic iridocyte appears to have great promise in performing these tasks. More testing would need to be done in the 3D case in order to confirm

the most beneficial geometries, as well testing engineered microspheres on actual cultures in fixed growing environments.

6.3.6 Photobioreactor Design and Distributed Systems

Now that we understand the iridocyte structure to be useful in increasing the irradiance of an algal surface, we must ask the question: what is the design of such technology? When tasked with this question we must consult the literature regarding the variables most necessary to facilitate algal growth and oil concentration. The use value of the PBR depends on both of these factors first and foremost, and the variables that affect them become fundamental in our design decisions. Similar to bacterial batch cultures, algae will continue to grow exponentially unless presented with a limiting or inhibiting factor. At that time they will plateau in growth and eventually go into a death phase (Llorens, Tormo, Martinez-Garcia, 2010). At present, the variables we most care about are irradiance, nutrients, temperature, gas exchange, pH, and mixing (Cañado, Lizárraga, 2016; Huang et al., 2017; Narala et al., 2016; Posten, 2009). This next section will parse out what we want out of each of these aspects of PBR construction, and will synthesize them into a design that attempts to accommodate each.

Shape

While shape was not mentioned as a variable above, it is important to note that the biomass yield largely hinges on the type of PBR in question. While we have established we are dealing with a closed system, we need to identify which will prove most effective as we think through our design. In terms of closed system cultivation, the flat plate, bubble column, and tubular bioreactors prove to be the most common (Dunford, 2015). While there are modified types that use different materials, such as bags and hangers, they are harder to engineer with respect to the variables above, and are therefore less dynamic in their design. The tubular type may be the most studied, and its disadvantages are a combination of spatial and maintenance. Spatially they take up too much land area because they are long and slender in build. They also require more close monitoring as many of the factors listed above are hard to regulate in

a tubular design, most noticeably high gas concentrations due to tube length (Abou-shanab, 2015; Jeevanandam et al., 2020). Bubble column reactors are effective due to their high surface area to volume ratio (R.N. Singh, Sharma, 2012), but are not ideal for a synthetic iridocyte integrated design due to their shape and the fact that they are made to have a smaller overall illumination window (Abou-shanab, 2015). The flat plate cons are mostly centered around its difficulty in controlling temperature, which has been more closely researched in recent years (Abou-shanab, 2015; Polycarpou 2019). Flat plate reactors can also very easily be integrated within the landscape, as they are spatially similar to solar panels and can easily be manipulated to enhance sun exposure. They also possess short optical path lengths like the tubular system, and have very low power consumption in their cultivation and self maintenance processes (M. Chen, Y. Chen, Zhang, 2021). Therefore, the flat plate type PBR is the base design we are working with in the sections below.

Irradiance and Temperature

We have spoken at length thus far about the problem of irradiance, as irradiance is the most important factor to microalgae photosynthesis. However, beyond the solar flux problem we have been dealing with for the last few sections, there are nuances to irradiance that underlie other variables, specifically temperature (which is why I have grouped them here). We have previously established that the photosynthetically active range (PAR) of microalgae lies within the visible spectrum range 400-700 [nm]. What we have seen experimentally, is that even within this range, microalgae perform best at the ends of this spectrum. However, that trend does not extend outside of the PAR to ultraviolet and infrared wavelengths, in terms of biomass production. Physically, as we see with black body radiation, infrared wavelengths account for a large portion of thermal energy increases within materials. According to Encyclopedia Britannica, most wavelengths fall outside of the PAR, only 1-2 % of incident solar radiation is absorbed, leaving the rest to be converted into thermal energy within the culture. Therefore, in order to better regulate the temperature of a PBR as solar radiation changes throughout the day and year, blocking non-visible wavelengths appears advantageous. Additionally, electromagnetic

flux can be lowered without having to block biomass productive radiation, which aids in the problem of oversaturation.

Flat plate PBRs normally use passive evaporative cooling (PEC), which is the process of allowing the surrounding air to naturally ventilate the culture (E.G. Nwoba et al., 2020a). While this can be effective, like it is in certain building designs, it is generally unreliable to maintain feedstock productivity due to seasonal changes. Nwoba et al. (2019, 2020b) found that an infrared blocking film allowed for selective damping of solar flux at non optimal wavelengths, allowing for more ease in control over temperature. Additionally, PV insulated glass made it possible to have standalone PBR designs that used less water for cooling and helped to generate the small amount of electricity needed to power spargers or other mechanical components (Nwoba et al., 2019).

Nutrients

Nutrients are linked with an algal strains' ability to survive and produce biomass through classic cultivation techniques. However, this variable is linked strongly with the type of strain used, so first we must identify our strain of microalgae and then we can determine its nutrient recipe. When assessing the oil content and productivity of different algal strains, the two prominent *Nannochloropsis* varieties, *sp.* and *oculata*, were found to have oil contents higher than most other strains, and can be easily manipulated to produce more oil than their counterparts, exceeding 60% oil content for *Nannochloropsis sp.* (which we will get into with the other variables) (Rodolfi et al., 2008; Ma et al. 2016). They are also easily maintained in terms of pH and carbon dioxide concentrations. For their lipid potential alone, we have selected *Nannochloropsis sp.* as our strain of choice.

The two main substances we deal with, in terms of nutrients, are nitrogenous compounds and phosphorus. It has been seen that lipid production increases in *Nannochloropsis sp.* when they are placed in a condition of nitrogen deprivation. Similarly, phosphorus deprivation boosts triacylglycerol in *Nannochloropsis* strains, including *Nannochloropsis sp.* by stimulating pathways associated with carbon fixation. In both cases, algae biomass growth is lessened when

the lipid content increases, but less so in phosphorus deprivation (Shi et al., 2020; Martin et al., 2014; Yaakob et al., 2021). This effect is negligible when balanced with the amount of oil produced, which is the end goal. Therefore, a phosphorus deprived environment may be more optimal in our design for a PBR.

pH and Gas Exchange

Different strains of algae require different pHs to grow effectively. In the case of *Nannochloropsis sp.*, a pH ≈ 8 has been confirmed to be productive. In terms of engineering, this is in large part maintained by the carbon concentration of the fluid the algae resides within. CO₂ dissolves within water, hydrogen ions are released making carbonic acid, which lowers the pH below neutral 7. Temperature is also a large factor in balancing pH, and through greater temperature regulation strategies mentioned above, pH should be more easily maintained under stable conditions. Organic matter, which can release carbonic compounds in water when dissolved, are kept out by the closed system design of a PBR, making them easier to maintain than an open raceway pond in this regard. Therefore, carbon regulation techniques, such as sparging, can allow for a more well balanced pH across the fluid medium. At the same time, sparging also reduces oxygenation of the algae, something that inhibits oil productivity. During photosynthesis, as algae take in carbon dioxide and produce oxygen, the ratio of these gasses is thrown off if left unregulated. In a closed system, like a PBR, the oxygen can easily build up and oversaturate the media. In this process, the increase in oxygen can starve the algal cells and inhibit growth.

Mixing

Mixing is a process that serves multiple purposes, most of which we have mentioned above. Mixing of the culture allows for greater gas exchange, better cooling, balanced nutrient concentration, and even photon distribution. Even photon distribution not only means the spreading of photons across the surface, but allowing for adequate light and dark phases of photosynthesis in the cultures to optimize efficiency in biomass production. The geometry of

the flat plate panels themselves are good at keeping the optical path length short, as mentioned above, as well as having a large surface area to volume ratio, which is important for our synthetic iridocyte sub layer. Mixing itself however cannot be too strong as to shear cells and kill them (J. Huang et al., 2014). Sparging, or pump based mixing, tends to produce excess force along the middle column and not enough on the edges, creating an imbalance in the culture. Novel designs, proposed by J. Huang et al., (2014), suggest that trapezoidal cells built into the panel can help to regulate fluid velocity and control the mixing of the culture. We are now able to begin designing a flat plate photobioreactor based on the specifications above (see fig 6.3.15).

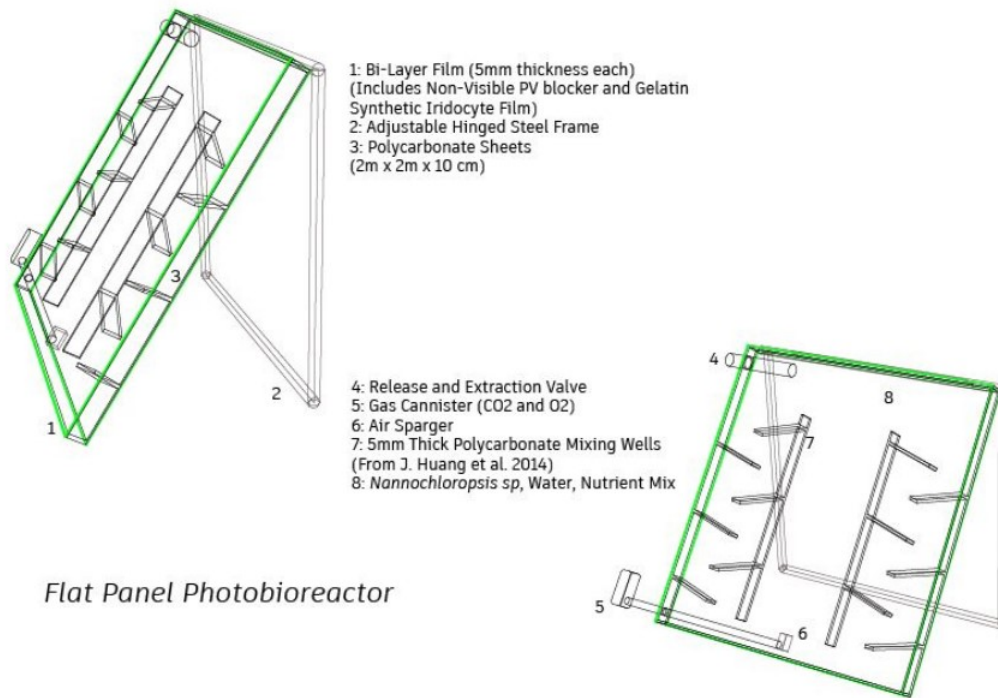


Figure 6.3.15: Schematic of flat plate airlift photobioreactor based on the specifications listed in the above subsections.

7

Social and Spatial Reorganization

7.1 On Decentralization

As we have already discussed in earlier chapters, the US energy grid is in dire need of upgrading if it is to function in the 21st century. As harsher climate change related weather events occur more frequently, and more facets of daily life become electric, the grid needs to be able to both transmit massive amounts of electricity and be resilient. This section deals with the notion of decentralization as a strategy for improving energy security and efficiency. As the US attempts to become carbon neutral by 2050, infrastructures compatible with the realities of renewable energy production and storage are necessary, and must be established locally in order to develop more stable networks.

The ethos of decentralization is what is most enticing to those looking to create more confidence in energy. As Peter Galison notes, while decentralization and deconstruction have existed as concepts in a myriad of contexts, it was during the second world war that the notion of dispersion took hold as a war strategy. Under the US Air Force, “‘Operations Analysts’ were essentially a methodological theoretical reconstruction of the interconnections that held together the German economy and war machine and asked how it could be blown apart” (Galison, 2001, p. 4). The point was that you could dominate the war effort by attacking nodes upstream in the economy centered around the production of a ubiquitous item, in the case of Germany it was ball

bearings. The US could then survey how centrally something as important as the ball bearing would be manufactured and then bomb it, destroying the capability of the German military to produce weapons. When the US dropped the atomic bombs on Hiroshima and Nagasaki, the question became larger in scope: how would the destruction of a single city affect the distribution of knowledge, utilities, communication etc?

This question prompted the United States to look back at home and survey the potential harm that could be done to the US economy and infrastructure as a whole if they were targeted in a similar manner. Suddenly, the dispersion of industry became a point of conversation in the field of urban planning. How much could the US space out its auxiliary production points, while still having them be reasonably located near the point of service? In the 1960s, other utilities began to be surveyed in a similar fashion, specifically telecommunications. It was found that redundancy would serve to protect US communications better, because it allowed for there to be connections from one end to another, even if part of the overall network were compromised. As a result, three types of grids were identified by RAND researcher Paul Baran: centralized (the least stable), decentralized (more stable), and distributed (the most stable) (Galison, 2001).

While the overall network of power plants and transmission lines is itself decentralized, the nodes that comprise the grid are so large in spatial orientation and service that they operate as a bunch of centralized grids locked together. According to the American Society of Civil Engineers (ASCE) and the US Energy Information Administration (EIA), there are 600,000 transmission lines with 5.5 million miles of local distribution (Meyer, 2021) and “11,070 utility-scale electric power plants” (USDE, nd). Most of this infrastructure is at least 50 years old, with most of it even older. Just due to age, the grid appears to be close to failing, while also not incorporating modern strategies of transmission, distribution, and storage. The current grid cannot sustain two way traffic (Alliance to Save Energy, 2021), meaning it cannot send unused electricity back within the grid to be used in areas of excess consumption.

Distributed energy resources and microgrids combat these problems in two main ways: 1) they themselves create a more distributed network of transmission which increases resilience in the face of disaster, and 2) it allows for a distribution in the types of energy used within the grid. A microgrid can be defined as “a local energy grid with control capability, which means it can disconnect from the traditional grid and operate autonomously” (US Dept Energy, 2014). The key work in that definition is disconnect. The microgrid can normally function as its own node attached to the larger central grid, but has the ability to become its own “island” by disconnecting at a common coupling point (USDE, 2014). A microgrid generally functions as a node of distributed energy resources (DERs), a combination of renewable and non-renewable energy sources. Distributed systems “refer to electric power generation resources that are directly connected to medium voltage or low voltage distribution systems, rather than bulk transmission systems (Akorede, Hizam, Pouresmaeil, 2010). DERs encompass both technologies that generate and store energy, which allows for more efficient use and fewer power losses. According to Akorede et al. (2010), the three largest environmental benefits of DERs, and specifically generating technologies, are: 1) higher energy efficiencies due to the location of their set up, and therefore, a lack of transmission loss over great distances. 2) Reduction in greenhouse gas emissions, due to their potential to save energy and decrease the cost of upgrading the existing grid. The latter reason allows for the integration of renewable energy more seamlessly into the daily lives of people within a community. 3) Space minimization. The ability to utilize urban landscapes like rooftops and building facades to generate energy decreases the footprint of the grid in the natural landscape. This factor, coupled with the lack of space needed for long transmission lines, helps to keep ecosystems intact, specifically in rural areas.

The other advantage of microgrids is that because they utilize multiple types of renewable energy resources, they are malleable to fit the region into which they are designed. As we have discussed when it comes to choosing sites for specific technologies, most locations are either not feasible, or actually carbon net positive when factoring in maintenance with their production. Additionally, because they are an infrastructural upgrade to the current grid, smart

technologies can convert nodes into what are known as smart grids. Real time monitoring of electricity consumption and production can allow for rerouting of such utilities in order to meet the needs of the people. The ability to sense an influx or decline in usage will allow for more regulation of power flow and reduce the amount of strain placed on the grid in peak hours. In order to maximize this practice from a social perspective, the commoning of energy will be necessary for electricity to be easily shared between nodes, distributing the surplus to whoever needs it (which is made easier through the storage capacity potential of DERs). The ability to have two-way flow to send energy back, and to limit wasted power alleviates the stress on the grid while also maintaining a store of usable power.

It is therefore important not only that the DER grids function in the way they are designed to, but that the social spaces we design around them are set up to maximize their potential. For example, in China, the government took a decentralized approach to localized wind energy production. This decision allowed infrastructure to be easily laid out on a community to community basis, just as the technology was able to provide (A. Li, 2022). In the United States, centralized grid infrastructures have relied on decentralized governance which has made it a headache to develop, improve, and reorganize the electric grid. According to the American Gas Association “from 2010 to 2019, the U.S. added 107,400 miles of gas pipelines” and 0 miles of ultra-high voltage transmission lines (Meyer, 2021).

This fact is largely attributable to the fact that the government requires the approval of every state to put lines down, but only a federal approval for gas pipelines (Meyer, 2021). The issue is not solely technological, and as we move into this next decade, it becomes necessary to legislate and organize space around clean infrastructure. While the addition of new, longer transmission lines just patches up a larger problem, the issue of congressional regulations still looms large over any new progress.

However, the distributed system is not perfect, especially within the neoliberal model of renewable energy. Often when we think of renewable energy microgrids, we think about someone attaching solar panels to their house or an offshore wind farm. The idea of reducing

one's personal carbon footprint is, in the current reality, a privilege. The only way out of the unreliable, polluting infrastructure of the current grid, is to have the money to extract yourself from the system of production. Offshore wind, and other projects that have invoked strong 'not in my backyard (NIMBY)' responses, tend to be in areas that have less say over where industry places their infrastructure, namely those of lower socioeconomic status. The idea of a more socially conscious distributed or decentralized grid would allow for more participation from routinely marginalized communities on the matters of energy justice, and allow for equal access to means of renewable energy.

The overall makeup of a distributed energy system itself already trends more in the direction of equity than the current infrastructure. Areas hit hardest by climate change, known as frontline communities, tend to feel the worst effects of grid failures and energy burdens (Initiative for Energy Justice, nd). These communities are predominantly communities of color. As Hernandez and Siegel (2019) note, there is a strong link between health and energy, due to factors like cost and unreliability affecting childcare, heating, and food security (Hernandez & Siegel, 2019). The more the grid fails to be reliable with usage, climate, and age, the greater the discrepancy will be between those with and without access to affordable, clean energy. Those studying energy justice have advocated for more democracy in energy systems, allowing communities to have more of a voice in their own energy legislation and provisions. The hope is that a distributed system will leverage the communal aspect of energy sharing, and energy security, in order to decrease energy burdens on those communities hit hardest. As long as energy and capitalism are linked, the infrastructures that maintain them both physically and institutionally, will continue to reproduce plantation logics, creating a further divide between in groups who make policy, and out groups who suffer from energy injustice.

7.2 Community Land Trust Model

Most communities in the west are planned around land ownership and the spatiality of private property. While there is an abundance of literature on the subject of the economy and its

relationship to privatization, subversions of the commodification of land have started becoming more mainstream in the last half century or so, the most prominent being the community land trust. The motivation for the community land trust comes from the attempt to take land out of the speculative market. Speculation broadly deals with investors betting on the increase in value of a plot of acreage over time, with little regard for the use value or benefit of the community it rests within. Speculation, is therefore, historically in contention with housing, specifically low income housing. If the land holds more value empty and traded than used by a community, it will continue to be held vacant for its return on investment.

Utilizing the principles of the cooperative movement of the mid 19th century, cooperative housing is meant to help realize the economic and social goals of a collective community rather than accumulate profit for investors in the market. For urban communities, the co-op was a way to keep the price of housing units down within apartment buildings in order to maintain livability. The basic model is a corporation or organization that funds the purchasing of land and the construction of housing retains control of it. Citizens would be able to then purchase a unit within the complex and have ownership over that unit alone. They would then be responsible for upkeep and maintenance, but would not be able to sell it outside of the organization. A board of democratically elected directors, who live within the cooperative, would govern the space for the community. If someone wants to move, they then sell it back to the board, keeping only the profit of whatever they added to the value of the unit. Even this profit would be capped in order to maintain the affordability of the neighborhood. At the most basic level, the cooperative system allows for housing to be provided at use value and not an exchange value, which keeps land and housing out of the market (J.E. Davis, 2010).

The community land trust is an almost identical model that extends the cooperative system toward conservation, farmland preservation, and establishment of green spaces for communities (N.D. Checkoway, in person communication, Aug. 14, 2021). By designating use value for land, through easements or other legal designations, the value of communal space can be easily maintained, and not intentionally shorted or held by private organizations, until those

who own surrounding plots are forced to sell. However, the community land trust poses more potential than just housing. The collective nature of both their literal and figurative infrastructure make them viable options for projects centered around the betterment of the community.

The original nature of the utopian socialist cooperative was as a way of combining smaller cottage industry businesses into a larger pool that could be shared between the members of the collective (Pittman, 2018). By controlling different aspects of production and sale, the collective stood a chance against larger actors in the market. In the same way, the members of a community land trust can insulate themselves in terms of energy, not just land. Just as we have discussed, the use value as a predictor of technological viability, communal action to improve infrastructure and pooled resources becomes more well realized, once it is taken outside of the context of the market. Some communities that are not designated community land trusts have already begun to see the values in this model when it comes to energy consumption and conservation. The city of Colorado Springs ran a libertarian experiment where the utilities became pay on demand, meaning if you wanted a street light to be on in front of your house, it was up to you to pay for it (Kim & Carver, 2015). While this experiment takes energy as a pool that can be tapped into, the community land trust goes a step further by taking excess energy produced or unused by the community and “selling” it back to the people to be utilized at a later time. The idea of energy production through renewable infrastructure makes this idea even more possible, because now not only are you pooling energy that is unused from a centralized grid corporation, but you are essentially producing energy for the community at large.

The idea of pooling and collectivization are not new, and falls under the larger umbrella of commoning. The idea of commoning land allows for the collective upkeep of it by members of the community. The idea of commoning energy allows it to be seen not as a commodity to be tapped into and traded, but rather something that can be produced and conserved for use by the people. By viewing energy in this way, suddenly power, again both literally and figuratively, is in the hands of the community (Giotitsas et al., 2022). What comes out of commoning is also a more balanced distribution and access to energy utilities. By having

community stewardship over utilities themselves, they are taken out of the market, just as land is in the community land trust model, keeping it affordable. It additionally makes people more aware of their consumption once a resource is shared. While this form of self awareness sometimes presents conflict in the face of collectivized housing, the tension it creates is necessary if we are to be a more environmentally conscious society.

If we are to employ technologies based on their use value, it becomes necessary that we treat their functions in the same way. For a photobioreactor, a community has the ability to harvest its own energy, taking away at least a fraction of its dependence on a larger commodities market. Once we overhaul grid infrastructure and begin commoning energy, then can we begin to see how energy independence is not completely unstable, due to a shift in our perception of energy consumption and production. Once taken at use value, energy becomes a daily reality more than a reservoir that we tap into (like we have in the current energy utilities model). Thus, we begin to move away from the society that Georges Bataille identified as one based on excess. As people become involved in their own energy governance, they can more easily identify the flaws in the grid system, harm of extraction principles, lack of imagination in current technology amongst other commonalities of current western society that have permeated from the Baconian camp.

At the same time this model presents the potential for recognition of care ethics within energy justice, as suggested by Damgaard, McCauley and Reid. Based on the principles of Maria Puig de la Bellacasa, the notion of dependence outweighs the autonomy of the community from the commodification of energy (Damgaard, McCauley, Reid, 2022). By creating a stronger internal network of citizens, who themselves are directly linked to their own energy production and supply, the degrees of freedom of inequity in energy become fewer and more localized. At the same time, the relationship between people and the planet, in terms of extraction and consumption, becomes more visible. Thus the idea of transitory technology extends beyond a temporal framework. While the technology and forms of renewable energy in question are themselves not long term in scope, the exercise of employing new means of viewing energy and

commoning it, allow for a small radical change that can be completed in doses. The end goal is then to shift away from the neoliberal views of energy and commodification, in order for a more equitable and sustainable long term organization of space and resources. In this view, the algae photobioreactor allows a community centered around the goal of producing clean, reliable, and affordable energy, to do so in steps, deviating from the status quo of privatized and centralized energy systems. By then designing spaces and communities with this at the forefront of planning, the idea is that more radical steps can be taken in the long run in order to fulfill a larger goal of carbon negativity.

7.3 Photobioreactor Processes

Before moving into the design component of the project it is important to touch upon the realities of the photobioreactor again in order to understand the different infrastructures involved in the production process. Going from microalgae to fuel is a three step process most generally see Fig (7.3.1). There is the cultivating stage, the biomass harvesting and preparation stage, and the transesterification stage. As we have addressed above, there are different configurations of nutrients and gaseous mixing that yield biomass. This biomass is then extracted from the photobioreactor as wet biomass. According to the authors in Dong et al. (2016), wet and dry lipid extraction are both valid processes of obtaining oils from the microalgae, but the dry extraction method is more widely used and researched (Dong et al., 2016).

Thus, wet algae must be dried and stored after it is harvested. To produce biodiesel, which is different from bioethanol and biogas, it then must undergo the transesterification process. Essentially the lipid oil that was extracted from the crop itself is brought to a processing plant where triglycerides are mixed with alcohol and a catalyst to produce the alkyl esters which make up biodiesel (Thangarasu & Anand 2019).

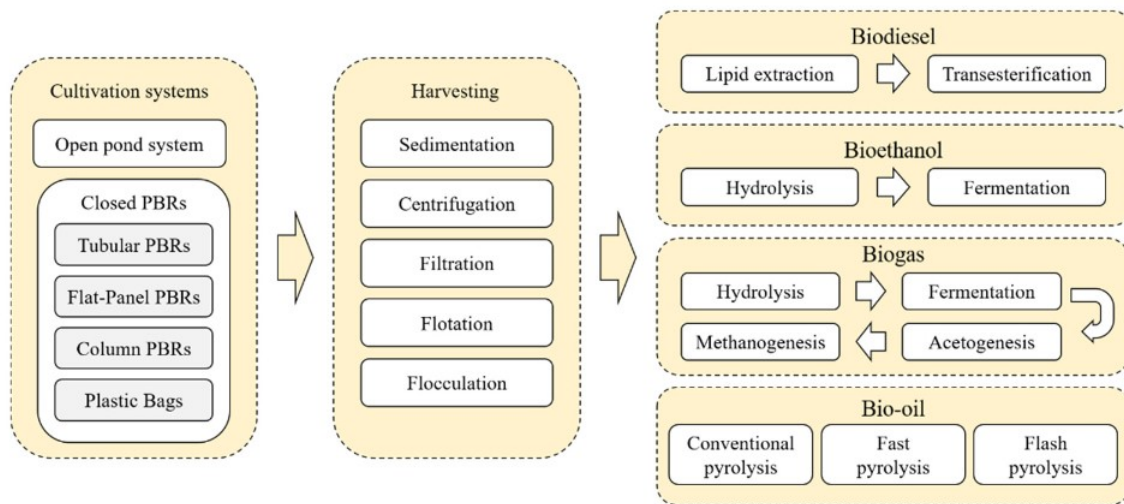
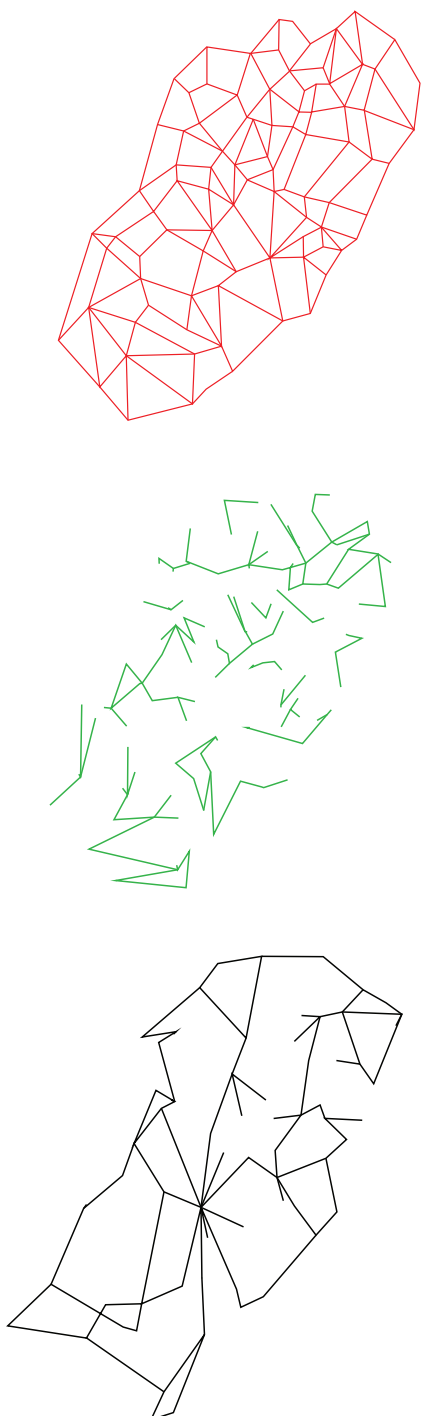
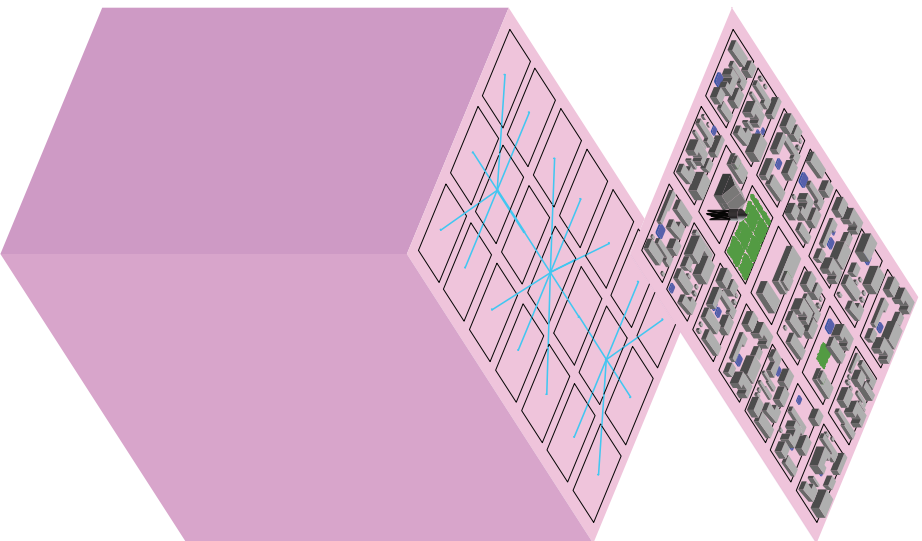


Figure 7.3.1: Algae cultivation for biodiesel process from M. Chen, Y. Chen, Q. Zhang, 2021.

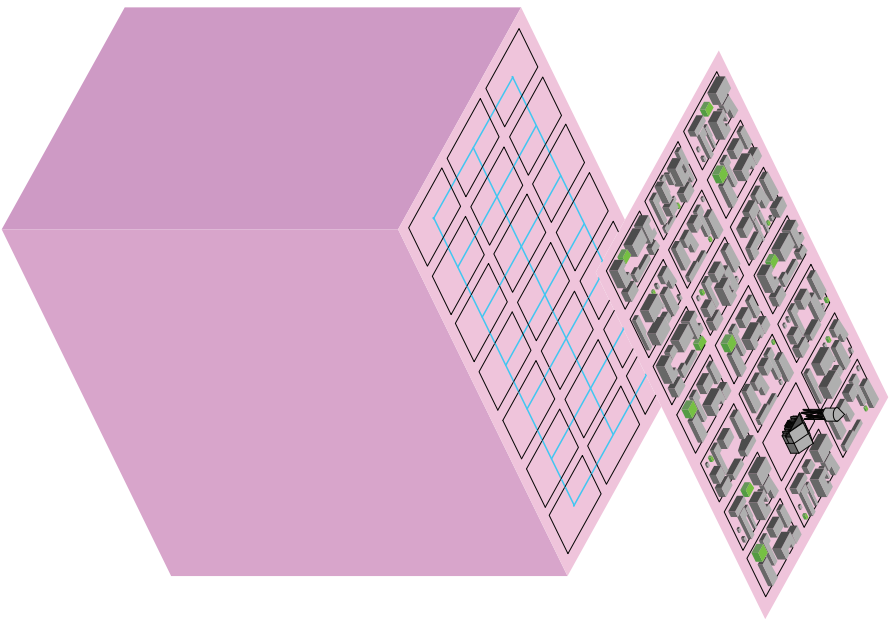
Urban Design

Sustainable Energy Futures: An Exercise in Imaginaries and Transitional Site Plans

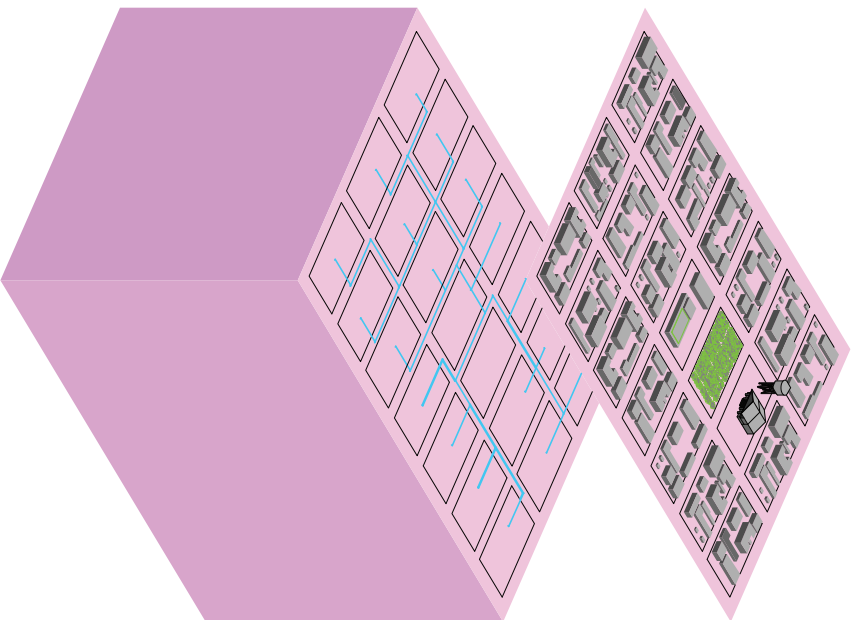




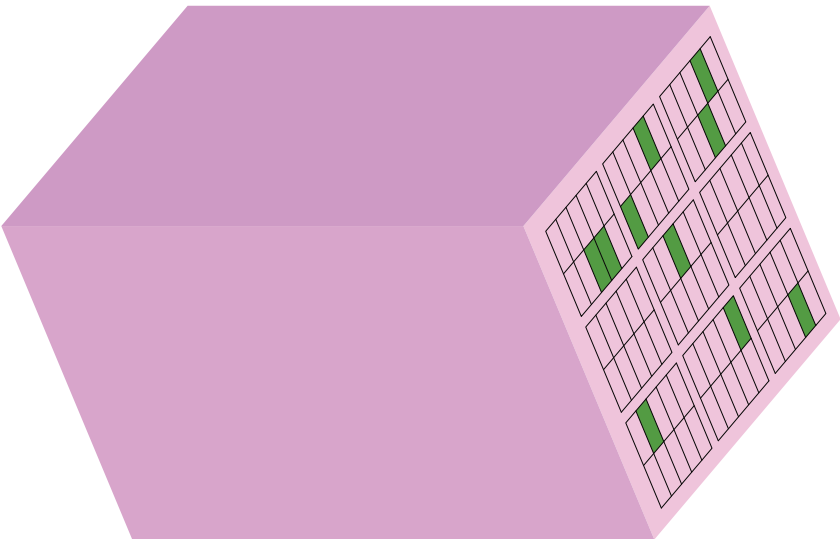
Decentralization is a more practical solution for transitioning grid infrastructures. On the scale of the city block, individual nodes allow for distribution of energy locally. An overall urban plan that contains multiple sites of production allows for security, as you can link them and pool their resources in order to provide insurance for the blocks they serve. If part of the grid were to fail, the central site of production for an individual node would be able to plug into another part of the grid. Having each node exist on the smallest scale possible, the burden placed on other nodes and other parts of the grid are minimal. If one were to design the city around energy instead of energy around the city, you would account for the estimated consumption of residential and commercial blocks and you would tailor the corresponding infrastructure to meet those demands. This way of planning creates a more distributed network of usage, therefore not overtaxing the grid in certain locations and leading to more efficient electric utilities. In areas that may be less populated or known to consume less, more electricity generation may be present as well as more biodiesel storage in order to supplement other blocks. This model then allows the internal structures of the city to support itself instead of the urban relying on surrounding hinterlands to provide a layer of energy security.



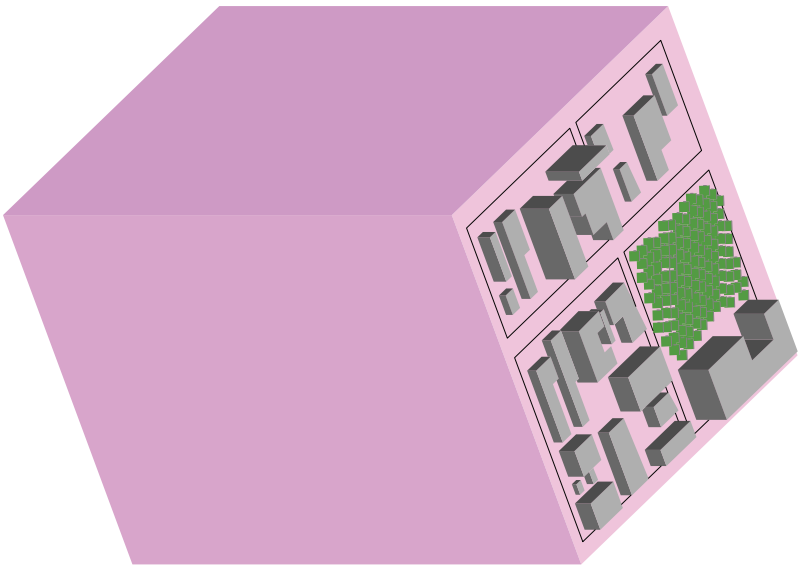
A distributed plan is one that works better when designing a city around energy rather than the reverse. Every city block would contain a site of electricity production, allowing them to be self powered. Similar to the decentralized grid, this gives great agency to those living within the node, and could easily be planned around consumption. Each node then acts as a microgrid that is laid out with respect to a more centralized one. The centralized grid acts as insurance in case the yield cannot keep up with the demand. By creating a distributed system, one can monitor the infrastructure of the individual nodes in real time with smart technology and make decisions about power allocation. By having smaller and more individual scales, it becomes easier to maintain equipment and change out old components as they become old or obsolete. Thus, the residents of the block now have more of a voice in their energy future because it is easily tailored to their needs.



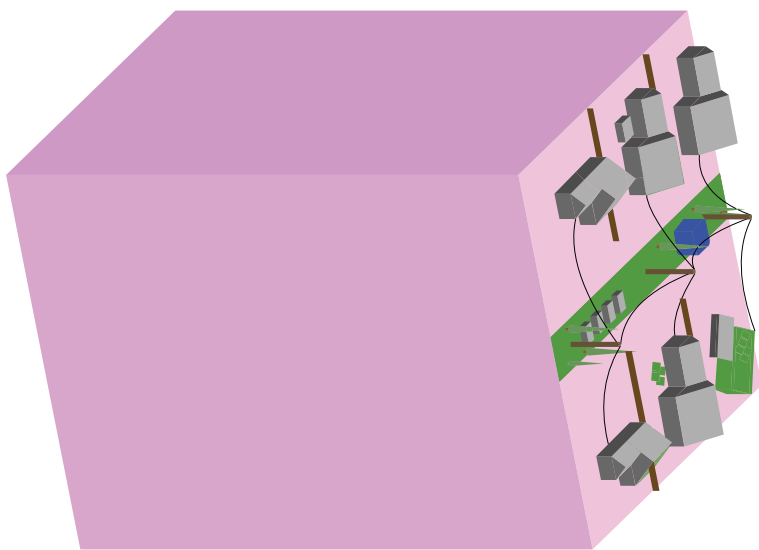
The centralized grid is based on our current infrastructure. While it remains helpful for rural locations due to its ability to connect communities far away, it is the least efficient option for an urban plan. As you can see, the connections themselves become long and too few in terms of the demand placed on them. Electricity would have to be produced on site for a photobioreactor based grid system and distributed to each block through shared lines. Real time analysis becomes more difficult because the traffic of a single line is dependent on sites of variable consumption. Additionally, shared lines don't allow for two way traffic, making it impossible to store excess electricity in a battery operated by the organization governing the energy commons.



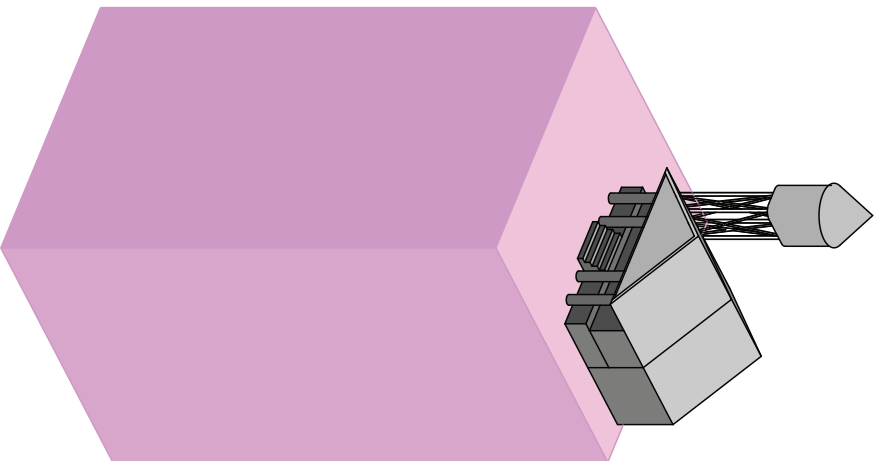
One way of creating space for algae growth is by utilizing empty plots. Planning a city around energy would avoid this step by allocating lots to cultivating a feedstock like microalgae. However, as we transition away from the current model of centralized production and distribution, locating empty plots within the urban landscape provides a spatial resource needed to produce maximal algal yield. In either case, the array of dispersed sites helps to ease the burden of production on one's own "property." This creates another form of collective behavior through farming, as it becomes commonplace to have neighbors move in on a single site to cultivate algae. There would be a need for full time farmers, a job that would be subsidized by the town/community land trust. The amount of plots and their size would be dictated by the density and overall consumption of the community in order to have a yield of biomass large enough to produce an adequate amount of biodiesel.



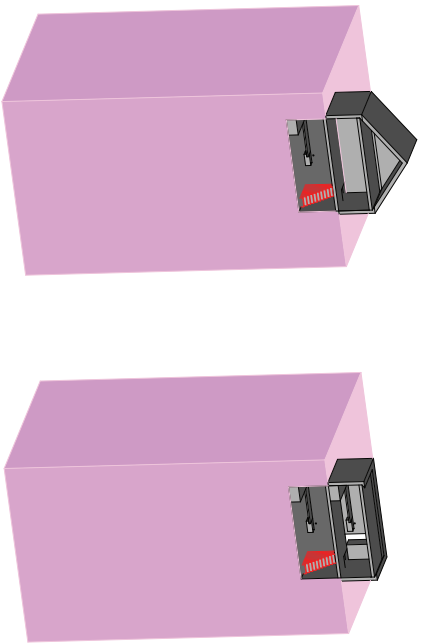
The on-site plot works as part of an urban design that cares less about density. The diagram to the left represents a larger city block being taken over by photobioreactors, but one could imagine utilizing larger swaths of non-arable land to cultivate algae biomass in a rural community. For the urban landscape, the farmlike arrangement of the panels works like a park. Their distribution would depend on the amount of blocks needed to serve the community and would need to be spaced in a way that is accessible for all to cultivate.



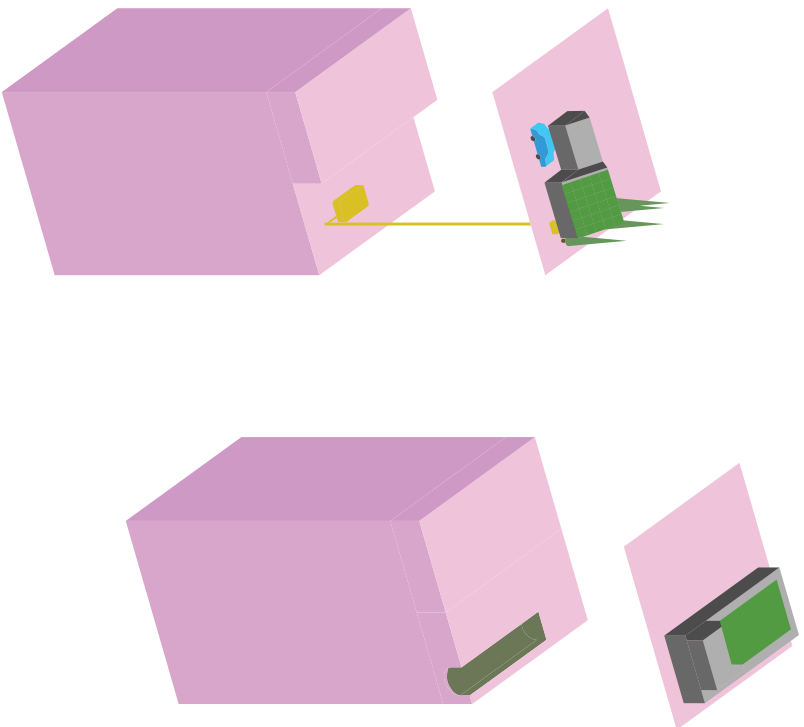
The node acts as the central part to any microgrid system. Every node contains the necessary equipment to generate its own power. In the case of the photobioreactor, a self sustaining node would be able to process biomass on site, store it, and burn the resulting biodiesel via a microturbine generator. The connections would be only a few houses or commercial buildings. The smaller grid, that centers itself around the generators and utility wires, possesses the ability to link into other smaller grids. This forms a more reliable network as repairs can be made on a node to node basis, only knocking power out for a few residences and for a shorter period of time.



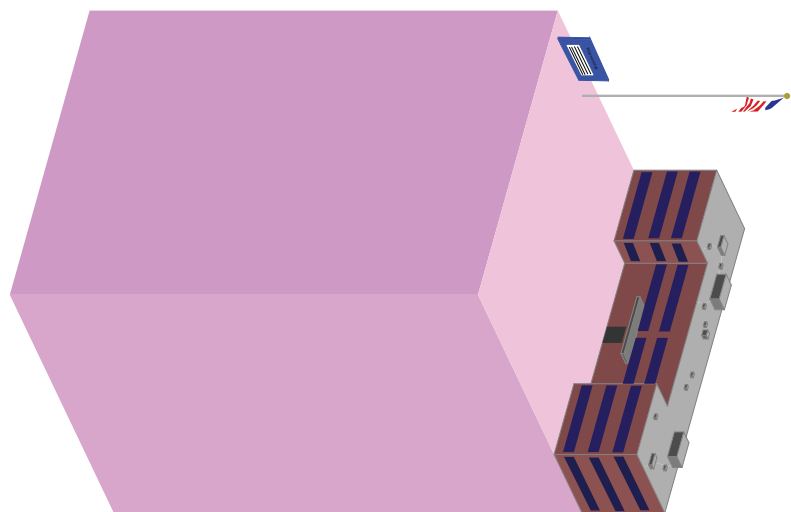
The biggest question when it comes to communal energy production is: "how do you get people to perform the necessary labor?" The easy answer, and one that is commonly used when planning a collective, is that everyone would ideally have the same mindset and goal, therefore helping to realize vision of energy independence for themselves and others. However, this is unrealistic. Similar to the recycling programs of Europe, individuals would receive credit in some form of payment beyond what is dropped from their energy utility bill. Additionally, the block would be run in a community land trust (CLT) format, except land would be taken out of the speculative market only if one agrees to house PBRS and perform necessary upkeep. One would own what lies on the property but not the property itself, and similarly the apartments would produce energy but not their own individual energy holdings. Thus, the organization in control of the land ownership is the same one that is responsible for the coming of energy. For an individual town, the organization could very well be the municipal government, and energy is distributed from the commons equitably based on production, consumption, and need. Thus, the cost of living becomes more affordable through one's labor.



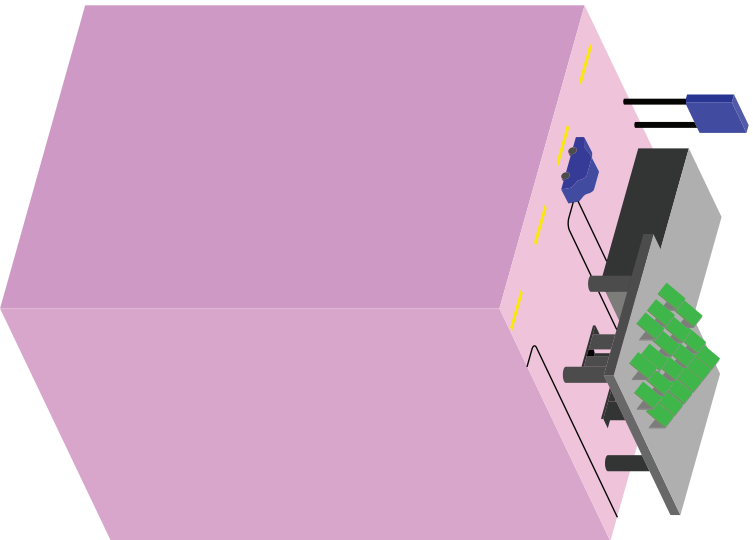
The sites of production can take two main forms: private and public. From a design standpoint, they remain similar as they both must contain the necessary components for the transesterification process. However, the notion that every home could have a room that is allocated for production is a generalization of the whole community. By assuming one has the space in their basement for a room to perform such labor, one assumes the class of the individual, their family status, and their household configuration. Essentially, the private model only works for those with the means and space to house such tasks (e.g. a middle class, two person household). By designing the spaces of labor as public, it not only gives access to everyone in the community, but also creates new daily rituals. In being able to more effectively work and communicate with neighbors regarding energy production, the community begins to work as a collective and not as individuals. Labor can more easily be split up based on work schedules and a new everyday can be rendered through this new type of 'community center.'



The idea of private and public translates to storage as well. With the idea of an energy commons comes the notion of energy equity. In an entirely distributed grid system, everyone would be their own site of production, consumption, and storage, with surplus becoming commoned. As we expressed with the production aspect, this line of thought leads to class-based assumptions as well as a re-production of green neoliberalism. The concept of a collective leverages individual production for the common good, rather than individual production to cover one's own footprint. Public storage, as seen on the right, could take form of a cistern underneath the processing plants themselves. Similarly, a water tower could be used to store the surplus, and would be controlled by the community. What becomes unseen is the labor that goes into delivering and distributing biodiesel to each node. The daily imaginary then becomes that of a milkman or a postal worker going generator to generator in order to keep the city running. Similarly, they would collect the unprocessed biomass and bring it back to the plant for treatment. And so the cycle continues...



Education becomes paramount for the employment of a new collective energy system. One needs to understand the ins and outs of photobioreactor maintenance, electrical grid infrastructure, biomass cultivation, the transesterification process, and potentially biodiesel synthesis, as well as ways to limit electricity consumption. Through green engineering programs in schools and adult education across the community, citizens can have a working collective knowledge of how to produce their own energy and how to improve their carbon footprint.

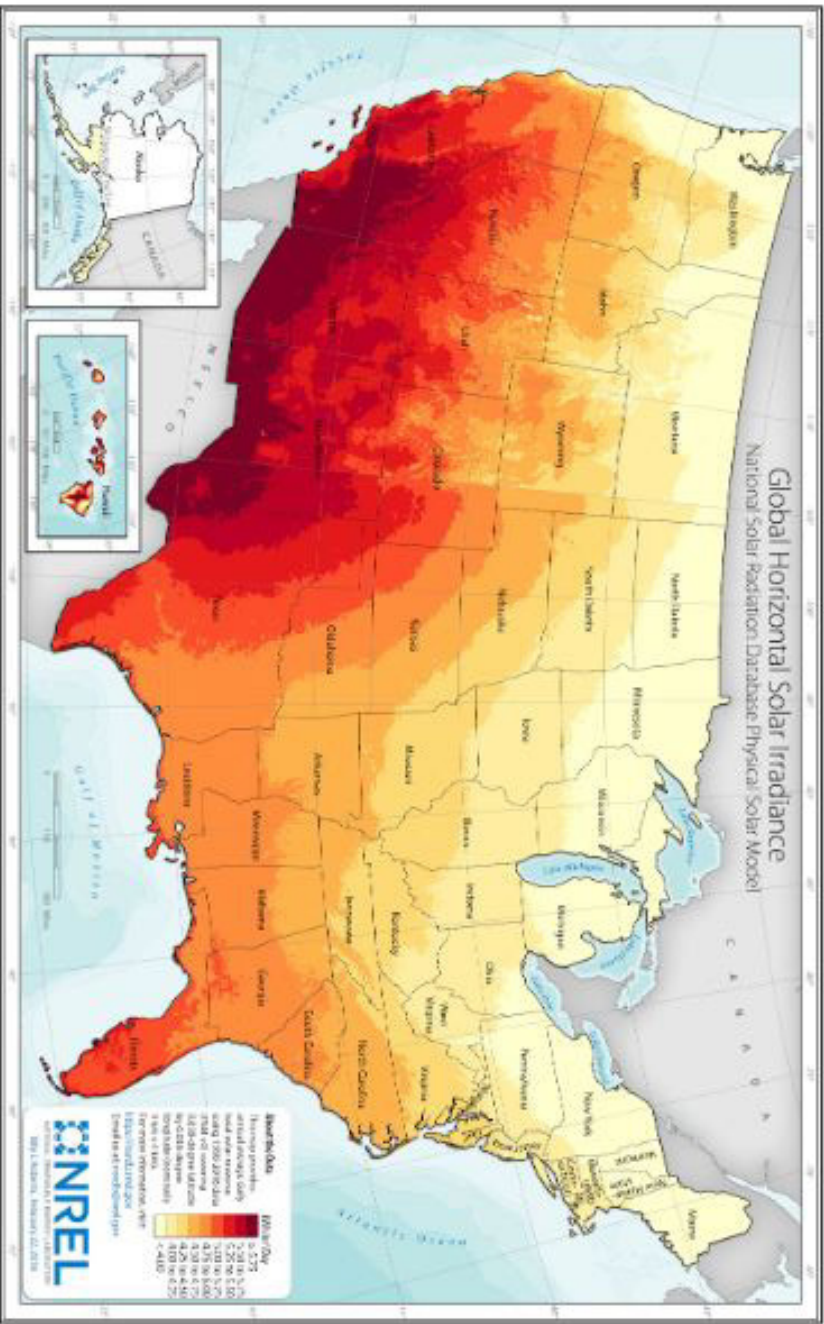


Distribution becomes a major piece of the energy puzzle. Looking toward a decentralized or distributed system in which citizens store and use the biodiesel for their respective blocks, there are two main ways to deliver biodiesel. As we have explored, a central organization that presides over the energy commons can employ distributors to collect biomass and provide biodiesel. Alternatively, gas stations can be repurposed to dispense biodiesel and can collect biomass in a similar manner as a recycling center. The transesterification plant would then be integrated into the design of the station itself. In this way, gas stations would become a site of production as well as a site of consumption.

As we have reiterated throughout the paper, site choice is an important factor in the use value of a photobioreactor. The world itself contains different climates, wind conditions, currents, etc, and therefore, renewable energy solutions need to match their locale. For the photobioreactor, the two largest variables for determining site are yearly sun exposure and temperature gradient. Yearly sun exposure is seemingly obvious, as the microalgae need direct sunlight to photosynthesize. The timescale of a year affords more weight to consistent sun exposure, not necessarily per day, but that it has a sun path that does not substantially weaken as the year goes on. An example of too much change would be a northeast US winter, where the sun remains low in the sky and the days are short. Thus, this would limit our choice to areas around the equator or where the earth's tilt sees minimal losses in direct sunlight per season.

Temperature gradient refers in our case to the change in temperature around a particular location over the course of a day/year. While the yearlong timescale is for seasonal changes in the average daily temperature, the daily gradient must also not be so extreme as to subject the microalgae to frigid temperatures overnight on a consistent basis. While the PBR is a closed environment, which can be leveraged for more temperature control, extreme cold and extreme hot still pose a problem for the culture. Most of the temperature measures taken in the engineering of the PBR are meant for cooling the cultures, and not much self regulation (internal to the system and not requiring outside energy) can be used for heating it up.

Weyer et al. (2010), tracked solar irradiance in different parts of the world, with actual measurements of irradiation being highest in the 20-35° latitude range, specifically Phoenix, Honolulu, and Tel Aviv. Part of the discrepancy between theoretical and actual yield comes from the tropical climates along the equator producing more rain, and thus more clouds. Areas with rainy seasons tend to be worse at producing consistent and direct solar radiation. A GIS model conducted by Orfield (2014), confirms this finding, where the southern third of the United States has large potential for annual algal yield (Orfield, 2014). For US locations, Phoenix and Honolulu have calculated theoretical best case yields at 53,200 and 51,700 ($L \cdot ha^{-1} \cdot year^{-1}$) respectively Weyer et al., 2010). Photon transmission efficiency, which measures how effectively photons reach the surface of a culture, either through direct or reflected radiation, was calculated to be most consistent at the lowest latitudes, with a higher proportion of direct radiation (Weyer et al., 2010). Subtropical areas of the southeastern United States produce the least variability in their algal yield potential, with Florida as a whole being the most reliable (Orfield, 2014). According to data from the National Renewable Energy Laboratory, the southwestern United States and Hawaii provide the highest levels of horizontal solar irradiance in the United States (NREL, nd., see figure 7.1). In terms of temperature, the American southwest proves to be some of the most variable due to rapid changes in elevation. Hawaii maintains consistently warmer temperatures year round, as does Florida. In terms of nighttime temperatures, areas that lack humidity like deserts and mountainous regions lack heat retention and therefore have colder nighttime temperatures on average (Baker, 2021).



However, there are other considerations having to do with social configurations and current energy infrastructure that influence decision making for biofuel production. In 2018, Hawaii ranked first in residential electricity price with 27.5 cents per kilowatt hour, more than 7 cents higher than the national number two, and more than twice the national average (US EIA, 2018). However, they ranked 5th in total residential electricity expenditures at \$1,665. This difference suggests that the population consumes less electricity on average, and is evidenced by their ranking of 44th in net consumption in 2020. According to the US Energy Information Administration, “Hawaii has the highest electricity retail price of any state and it is nearly triple the U.S. average rate, in part because the state relies on imported petroleum for 60% of its electricity generation” (US EIA, 2021a). Florida on the other hand uses natural gas to produce 75% of its electricity, while Arizona uses around 50% natural gas to produce electricity (US EIA, 2021b and 2021c). Florida is second in the nation in electricity production after Texas, and fourth in total solar generating capacity, one above Arizona, according to 2020 statistics. Arizona itself generates more energy than it consumes, and ranks second in net solar energy potential behind Nevada. Hawaii produced about 10 trillion BTU of biomass for energy consumption (up from 5 trillion BTU in 2018), while Florida produced a negligible amount, suggesting Hawaii is beginning to put infrastructure in place for biofuel production. The state also has made a commitment to 100% of electricity sales coming from renewables, and in 2020, 30% of electricity had to come from renewables. The Department of Energy for Hawaii has also bought into the idea of grid modernization and smart grids, which would optimize small scale renewable energy production. Hawaii, being a region of stable sunlight and temperature, having infrastructure compatible with petroleum electricity generation, and an investment in biofuel infrastructure suggests that they are an optimal location for algae photobioreactors. Additionally, Hawaii has a practice of community land stewardship through community land trusts like North Shore Land Trust which is dedicated to the preservation of the Kahuku coast area. Hawaii also has an inter-island land trust agreement, called the Hawaii Land Trust, with the goals of conservation, land easements, and community involvement. In their mission statement, HILT says:

Hawaii Land Trust (HILT) is Hawaii’s islands-wide land trust that is both a Hawaii’s 501(c)(3) nonprofit, and a nationally accredited land trust. We protect lands that are integral to Hawaii’s well-being and character, upholding our kuleana to these lands, and the communities they are in, through thoughtful stewardship that deepens community connection to, and builds reciprocal relationships with ‘Īnā (HILT, nd).

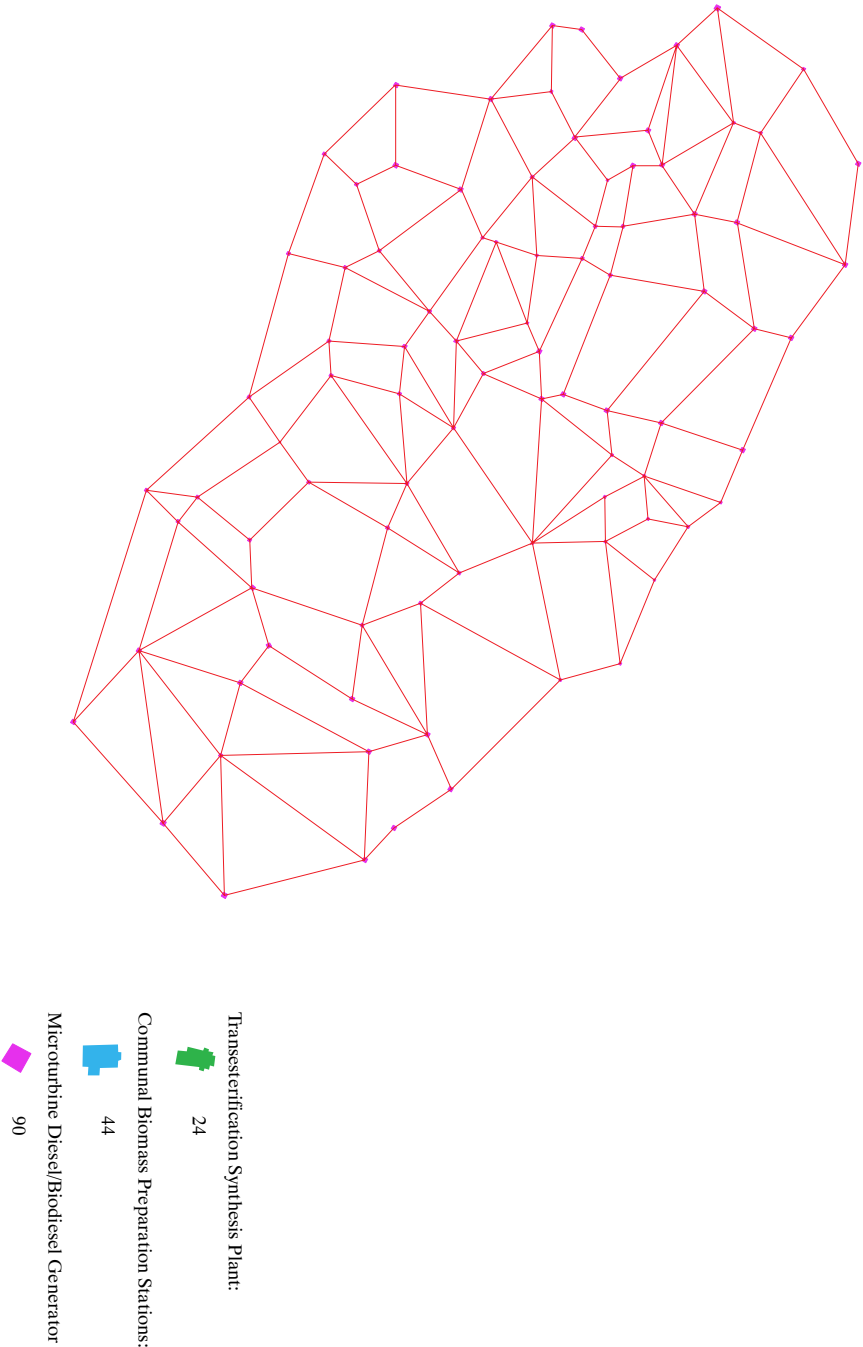
‘Īnā means love of the land, and promotes the idea of interconnectedness between land and people. The philosophy of self production of energy hinges on this idea of the dual governing relationship between human and land, recognizing nature as something humanity is a part of not on top of.

Thus, the native Hawaiian ideals of land usage and community engagement appear to match the ideals of communal clean energy production, and a commitment to improving energy welfare among members of a land trust.

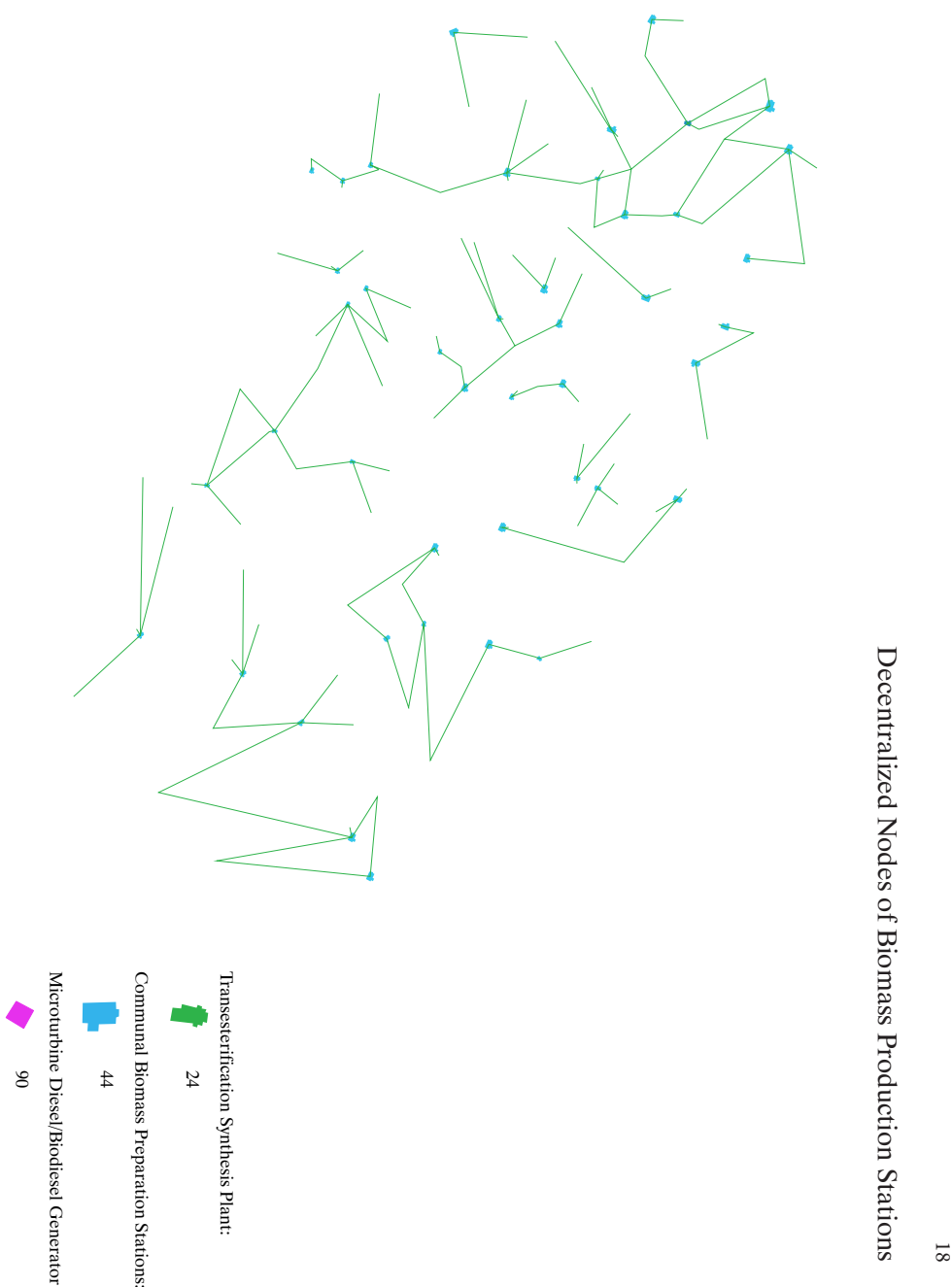
Looking at Hawaii as the state of choice for the proposal, the city of Mo'iili'i becomes a promising site due to its density, energy consumption, vacant lot space, and capacity for grid modernization. According to the Locational Value Map (LVM) of Oahu provided by the private energy corporation, Hawaiian Electric, Mo'iili'i has a hosting capacity of 50% or greater for rooftop solar installation (HEC, nd). As we propose a project that attempts to integrate photobioreactor technology onto an existing urban landscape, it becomes important to utilize rooftop space due to the lack of large plots in a city. Mo'iili'i itself is a city on the outskirts of Honolulu, rubbing right up against the college neighborhoods of the University of Hawaii. Manoa and Chaminate University of Honolulu. Mo'iili'i is generally combined with McCulley, a neighboring village, and was originally populated by mostly native Hawaiians and Chinese immigrants (Matanabe, nd). At the turn of the century, the community was heavily settled by Japanese immigrants, and to this day the majority of the population has Japanese roots (Matanabe, nd). According to the University of Hawaii at Manoa, the original draw of the town was the quarry, where former plantation workers would come to start a new life (UHM nd). Using Census collected data, Point2Homes (a real estate statistics software) shows that in the present, Mo'iili'i has become more of a white collar area, making up 86.1% of the workers, with the median household income being \$56,701. The average household income is about \$16,000 higher, suggesting a wider distribution of class throughout Mo'iili'i, with 14.2% of the population living below the poverty line (P2H, 2021). According to statistics from the Hawaiian Department of Business, Economic Development, and Tourism (DBEDT), Mo'iili'i residents pay an average of \$91.90 in electricity costs each month, below the 2019 national average of \$115 and well below the Hawaiian average for that year (\$168) (DBEDT, 2021; US EIA, 2020). This trend suggests a smaller consumption of power by the community, making it an ideal location for a site to produce its own energy. The following proposal looks at integrating PBR infrastructure into the existing fabric of the community, as well as showing the diagrammatic interconnections of the different sites of labor. A majority of the spaces used were vacant or unused lots, with some locations repurposing buildings used for electricity generation. Calculations of land space needed for PBR panels came from a combination of sources regarding biodiesel to diesel efficiency, microturbine efficiency in kWh based on 75% load, and land area of Mo'iili'i. All calculations were based on the photobioreactor panel size being 2m by 2m in surface area. Sources (Swift Equipment Solutions, 2021; Alternative Fuels Data Center US Dept Energy, 2021; McNally Institute, 2022).

Distributed Grid of Microturbine Generators

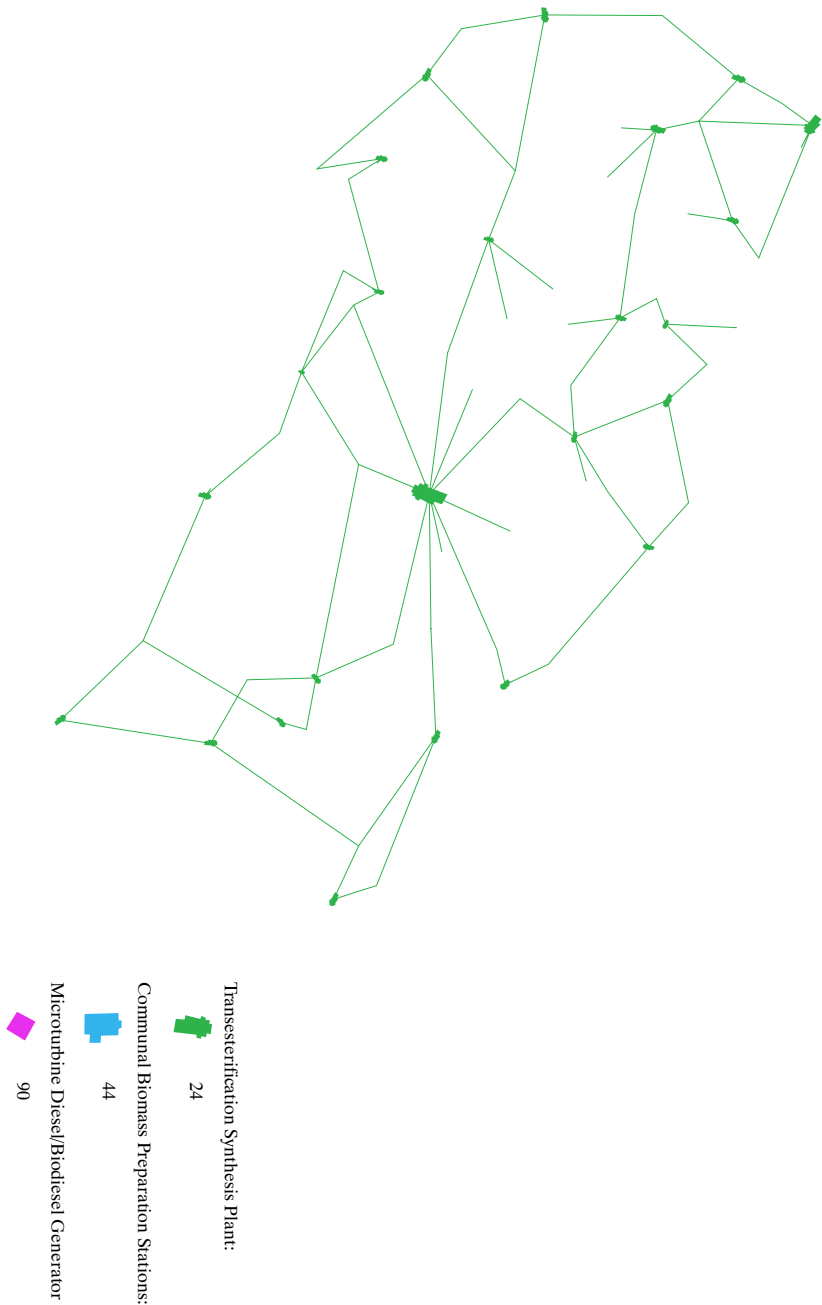
17



Decentralized Nodes of Biomass Production Stations



Centralized Grid of Transesterification Synthesis Plant



The interconnected grids try to utilize the three types of dispersion in order to organize infrastructure. The reliability of the microturbines is insured by the ability to easily tap into the other sections of that distributed grid. At the largest level, the transesterification plants can easily connect to one another in a decentralized/distributed network, but the largest production center acts as the centralized node. The majority of biodiesel would be produced here, and could easily be dispersed among the other plants for further processing. The network of biomass preparation stations make it easy to collect and process dry biomass, as they exist every couple of blocks in the city plan.



Mo'ili'i, Hawaii

Mō'ili'i, Hawaii



200 ft

Microturbine Diesel/Biodiesel Generator
90



Mō'ili'i, Hawaii

Communal Biomass Preparation Stations:

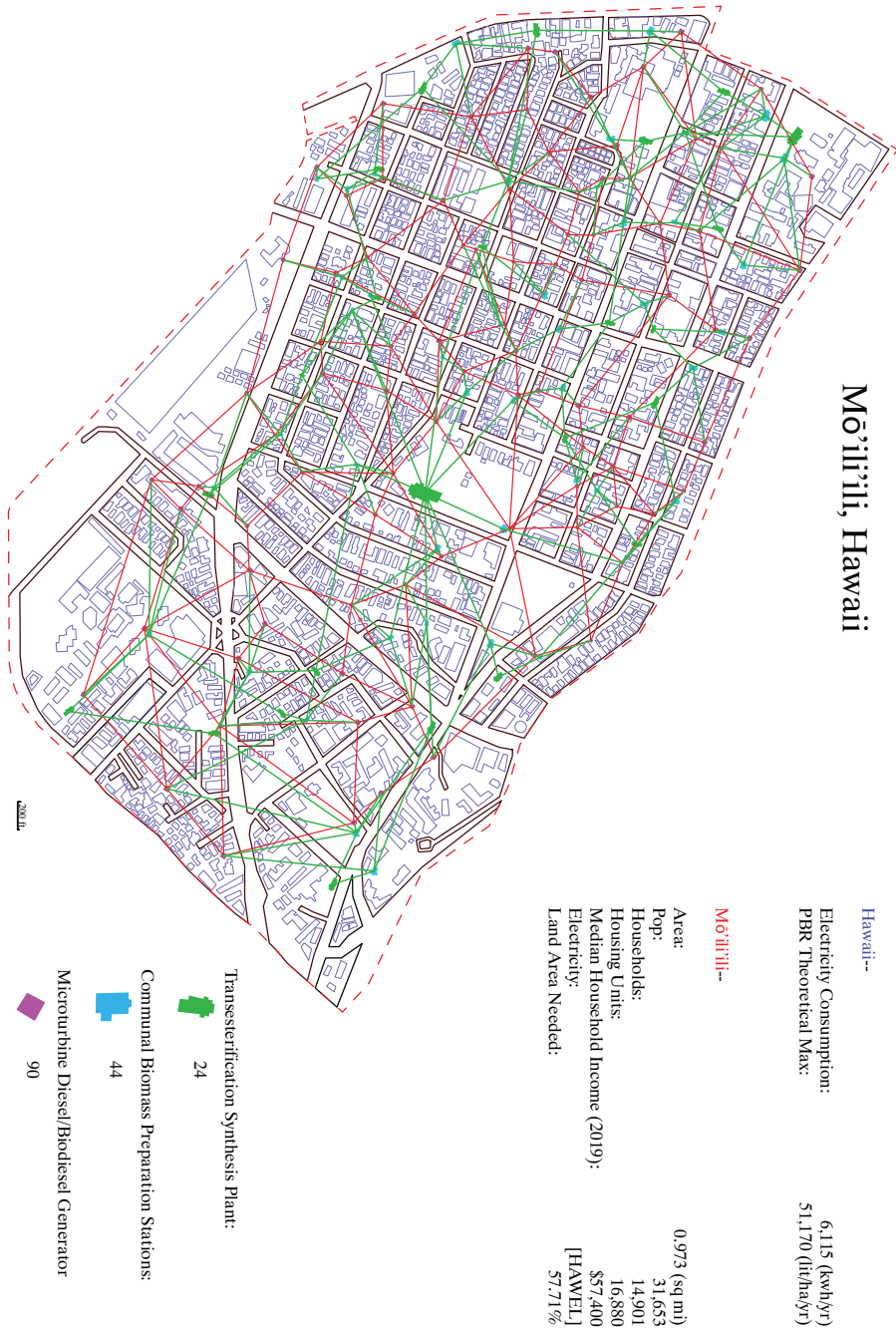


Mō'ili'i, Hawaii



Transesterification Synthesis Plant:
24

2011



9

Conclusion

The nature of the photobioreactor is that it is transitional. Climate change is a problem that exists both in the realm of the spatial and temporal, and if we are to target systems of governance and organization like capitalism, the temporal aspect could prove to be more critical than once thought. The exercise of Chapter Eight was motivated largely by spatial reconfigurations, understanding how to outright plan or repurpose space for the sake of new ways of producing energy. However, the spatial solutions themselves appear unrealistic without taking into consideration that they must occur within the realm of the present day. A complete overhaul of the norms of daily life is difficult to imagine in practice, making action almost impossible.

As stated in Chapters Two and Three, one must be able to work within the system in order to live without it in the long run. Capitalism is an ever present reality of modern life, and the pockets that try to subvert it will be easily stifled by the rest of the world due to sheer outnumbering. This is where the beauty of transitional infrastructure takes precedence. By having technology that is compatible with the modes of the everyday, we can begin to worry less about building a separate world that will overtake our own, but rather an imaginary that will ween us off of our current ways of existing.

In practice, the exercise of trying to think about how to move away from the current reality brings about more interesting questions than if one were to just envision a utopia devoid of our current problems. In the case of the photobioreactor, we begin to question how they must be spatially arranged in order to increase energy equity and access, how self sustainability can promote more conscious energy choices, and how a piece of technology can leverage its politics to combat corporate greed. In exploring the logics of different grid infrastructures we begin to see how they can perpetuate colonial ideals through their reproduction of class and race based energy inaccessibility. By viewing energy as a non-commodity we can visualize new ways of coexistence in the form of the commons and the community land trust. All of these scenarios exist in the space between the present and a sustainable future, and all pose different variations of how we can get there.

The project itself serves as a model for collaboration between disciplines more than a direct solution to any problems. The point of exploring the light scattering of a synthetic iridocyte, not only attempts to engineer a solution through the laws of physics, but also to contrast with the significance of more abstract entanglements like the ontologies of technology. First, by viewing something so small in scale and specific in scope through the lens of a completely different field, it becomes clear that not everything lives in a black box. While specialization is a must in academia, the importance of taking a step back and thinking through a problem or a solution from the perspective of a different discipline gives more depth to the work than to understand it from technical terms alone. In this way, the project gives credence to the liberal arts model—necessitating multidisciplinary solutions in confluence with specialized research. Conscious and thoughtful decision making can only come from abstract viewership. Second, exploring an abstract concept with a very real and tangible scientific one is significant when applied to the same larger issue. Both the most specific and the most broad perspective of a wicked problem serve their purpose, each taking a piece of the problem into their own hands. In Chapter Two we started with the meaning of technology, a laughably vague question that has spawned an entire field of philosophy, and worked our way all the way through Chapter

Eight, where we looked at socio spatial effects of energy autonomy, something that constitutes an entire field. However, it was the process of arriving at each of these topics that proved to be the robust discussion regarding climate solutions.

The project itself is, however, incomplete. As I have reiterated over the thesis, it takes a multitude of fields, perspectives, and lines of questioning to arrive at pragmatic solutions. More experiments must be done to prove the validity of photobioreactor theory, just as formal analysis of existing energy co-ops and distributed grid systems must be done to verify their efficacy. The question of time, though, continues to pop up. How can we ever create a sustainable energy future without succumbing to paralysis by analysis? The answer is that we must try the best we can to develop educated analyses of our problems and act on them when they become good enough to work rather than when they are perfect. The best solution is not always the perfect one, sometimes the one that gives us the best chance will do just fine.

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