

NASA's GreenLab Research Facility: A Guide for a Self-Sustainable Renewable Energy Ecosystem

*B.M. McDowell Bomani and R.C. Hendricks
Glenn Research Center, Cleveland, Ohio*

*Malik Elbuluk
The University of Akron, Akron, Ohio*

*Monica Okon
Glenn Research Center, Cleveland, Ohio*

*Eric Lee
Ohio Aerospace Institute, Brook Park, Ohio*

*Bethany Gigante
Glenn Research Center, Cleveland, Ohio*

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA STI Help Desk at 443-757-5803
- Telephone the NASA STI Help Desk at 443-757-5802
- Write to:
NASA Center for AeroSpace Information (CASI)
7115 Standard Drive
Hanover, MD 21076-1320



NASA's GreenLab Research Facility: A Guide for a Self-Sustainable Renewable Energy Ecosystem

*B.M. McDowell Bomani and R.C. Hendricks
Glenn Research Center, Cleveland, Ohio*

*Malik Elbuluk
The University of Akron, Akron, Ohio*

*Monica Okon
Glenn Research Center, Cleveland, Ohio*

*Eric Lee
Ohio Aerospace Institute, Brook Park, Ohio*

*Bethany Gigante
Glenn Research Center, Cleveland, Ohio*

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

This work was sponsored by the Fundamental Aeronautics Program
at the NASA Glenn Research Center.

Level of Review: This material has been technically reviewed by expert reviewer(s).

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076-1320

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

Available electronically at <http://www.sti.nasa.gov>

NASA's GreenLab Research Facility: A Guide for a Self-Sustainable Renewable Energy Ecosystem

B.M. McDowell Bomani and R.C. Hendricks
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Malik Elbuluk
The University of Akron
Akron, Ohio 44325

Monica Okon^{*}
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Eric Lee
Ohio Aerospace Institute
Brook Park, Ohio 44142

Bethany Gigante^{*}
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Summary

There is a large gap between the production and demand for energy from alternative fuel and alternative renewable energy sources. The sustainability of humanity, as we know it, directly depends on the ability to secure affordable fuel, food, and freshwater. NASA Glenn Research Center has initiated a laboratory pilot study on using biofuels as viable alternative fuel resources for the field of aviation, as well as utilizing wind and solar technology as alternative renewable energy resources.

The GreenLab Research Facility focuses on optimizing biomass feedstock using algae and halophytes as the next generation of renewable aviation fuels. The unique approach in this facility helps achieve optimal biomass feedstock through climatic adaptation of balanced ecosystems that do not use freshwater, compete with food crops, or use arable land. In addition, the GreenLab Research Facility is powered, in part, by alternative and renewable energy sources, reducing the major environmental impact of present electricity sources. The ultimate goal is to have a 100 percent clean energy laboratory that, when combined with biomass feedstock research, has the framework in place for a self-sustainable renewable energy ecosystem that can be duplicated anywhere in the world and can potentially be used to mitigate the shortage of food, fuel, and water.

This paper describes the GreenLab Research Facility at Glenn and its power and energy sources and provides recommendations for worldwide expansion and adoption of the facility's concept.

1.0 Introduction

It is widely accepted that green solutions are needed throughout the world. The three primary human needs are freshwater, food, and fuel. However, the word "green" is often misused when describing many technologies, processes, and products. To be truly labeled a green solution, three conditions must be met. The solution must be alternative, renewable, and sustainable. An alternative solution is one that is not in mainstream use today and has no undesired consequences when compared to conventional solutions. A renewable solution is derived from sources that are naturally replenished. A sustainable solution refers to the ability to maintain ecological processes, functions, biodiversity, and productivity into the future. For any technology, technique, or method to be considered green, all three conditions (alternative, renewable, and sustainable) must be met inclusively.

At the GreenLab Research Facility at the NASA Glenn Research Center, we are concentrating on green solutions for aviation fuels as well as green energy solutions. Approximately 97 percent of the world's water is considered saline, and less than 1 percent is freshwater that is directly accessible for human use. We have developed a green solution for aviation fuels that utilize what we call the "Big 3" at Glenn. The Big 3 can be an algae,

^{*}NASA Lewis' Educational and Research Collaborative Internship Project (LERCIP) Intern

plant, weed, or bacteria that (1) does not use freshwater, (2) does not compete with food crops, and (3) does not use arable land. We have combined our GreenLab biofuels effort, which focuses on biomass optimization with viable alternative energy technologies, to establish the framework for our concept of having a self-sustainable renewable energy ecosystem.

The primary plant species being researched in the GreenLab are halophytes. Halophytes are salt-tolerant plants that are found all around the world in saline or brackish environments such as mangrove swamps, salt marshes, mud flats, and coastal environments. In the GreenLab we use climatic adaptation techniques (i.e., freshwater to seawater acclimation and vice versa) with halophytes to ensure that they will be adaptable to a wide range of ecosystems around the world. In addition, we are adapting microalgae and macroalgae with climatic adaptation techniques with the goal of identifying optimal algae species that can adapt to real-world conditions. In theory, our GreenLab concept can be applied to satisfy fuel, food, and freshwater needs when halophytes and algae are utilized as the primary plant biomass source.

What follows is a description of alternative fuels and alternative energy distributive sources, a description of our indoor biofuels lab and our GreenLab Research Facility, and lastly, our ideas for global adoption of our concept.

1.1 Alternative Fuels

By 2026, the world's liquid fuel demand is projected to grow by 20 to 25 percent, implying an increased U.S. demand from over 20 million bbl/day (2007) to 24 million bbl/day (Ref. 1). To meet that demand with alternative fuels, even if one could grow algae on the open seas fed by continent-sized nutrient streams under the most opportune of conditions and convert it to oils, the equivalent volume demand would require nearly half the Gulf of Mexico or 0.8 million km². This assumes equivalency between refined barrels of plant oil and petroleum algae production using the following estimates (from Ref. 2):

Estimate 1: $(0.8 \times 10^{12} \text{ m}^2)(0.02 \text{ kg-biomass/m}^2\text{-day})$
 $(3/10 \text{ gal/kg})(1/42 \text{ bbl/gal})(20\% \text{ bio-oil/biomass})$

Estimate 2: $(0.8 \times 10^{12} \text{ m}^2)(4.2 \times 10^3 \text{ gal bio-oil/ha-yr})$
 $(10^{-4} \text{ ha/m}^2)(1/365 \text{ yr/day})(1/42 \text{ bbl/gal})$

Also, by 2026, the world's jet fuel consumption is projected to grow from 95 billion gal (2007) to around 221 billion gal (836 billion liters) per year (Ref. 3). Replacing 10 percent with a renewable jet fuel would be similar in scale to current worldwide liquid biofuels (ethanol and biodiesel) production. The 2026 fuel burn goal for future aircraft calls for a 70 percent reduction (Ref. 3). Even if that goal is met, 66 billion gal (250 billion liters) annually would still be required. It would take at least 10 years for the technology to be injected into the fleet and require a biomass-fuel area equivalent of about one-third of the Gulf of Mexico.

The need for replacement fueling and the effects of biofuels on both legacy and future aircraft performance and design has

been established in prior publications (Refs. 2, 4, and 5). These publications illustrate conflicts between fuel types and the crops and crop land necessary for alternate aircraft fueling. The aviation industry requires specific mobility fuels that meet jet fuel specifications, and one cannot just replace jet fuel with current renewable fuels (ethanol, higher alcohols, pyro-oils, biodiesel, or hydrogen electricity). Industry is now pursuing new, large-scale, secure, sustainable biofuels within several "do no harm" restraints: (1) not competing with arable land or freshwater resources needed for food/feed production, (2) low carbon footprints that do not lead to deforestation, and (3) not engendering adverse environmental or social impacts.

When burned, 2 tons of jet fuel generates over 1.6 tons of carbon and over 2.5 tons of water. Globally, aviation fuel has been growing at about 4 percent per year despite a 1 percent per year improvement in airplane fuel efficiencies. The resulting high-altitude cloud formations and carbon footprint (CO₂ emissions) are of increasing concern to the commercial aviation industry, which has set a goal that future growth in the industry should be carbon neutral. Thus, renewable jet fuels are a critical need for this industry. The Commercial Aviation Alternative Fuels Initiative (CAAFI) and commercial aviation industry have set a goal of certifying a blended renewable jet fuel between the 2009 to 2012 timeframe. To reach this ambitious goal, a program is underway to establish the technical feasibility, environmental sustainability, and eventual commercial viability of renewable biojet fuels. The basic technical feasibility of synthetic paraffinic kerosene (SPK) jet fuels produced from coal or natural gas or of hydrogen-treated renewable jet fuels (HRJ) produced from vegetable oils or similar sources having the same properties as conventional jet fuels has already been proven through several flight demonstrations by the U.S. Air Force, commercial airline partners, and four aircraft engine original equipment manufacturers (OEMs). The next stage is to develop secure scalable, sustainable, and economically viable feedstock for biojet fuels that satisfy the aircraft industry's "do no harm" constraints and reduce their reliance on petroleum-based fuels.

Our society heavily relies on hydrocarbon-energy-generating sources but needs to rely on biomass to reduce CO₂, NO_x, nanoparticulate, and emissions to minimize health and climate hazards. The challenge is to make our fuel resources secure, sustainable, economically viable, and sufficiently available. We must use Earth's most abundant natural resources, which are biomass, solar energy, arid land (43 percent), seawater (97 percent) with nutrients (80 percent), plus brackish waters and recovered nutrients to resolve the environmental triangle of conflicts between energy, food, and freshwater; also, we must mitigate ultrafine particulate hazards. Accomplishing this resolution requires a paradigm shift. We must develop and use solar power for energy (in the form of virtually any renewable fossil fuel replacement resource: photovoltaic (PV), thermal, wind, and drilled geothermal); biomass for aviation; and hybrid-electric-compressed air mobility fueling with transition to hydrogen and electric or extended range hybrid-electric in the long term (Refs. 2, 5, 6, and 7).

1.2 Alternative and Renewable Energy Sources

Presently, most of the world's energy supply comes from fossil and nuclear sources. Despite the increasing resource limitation and environmental pollution, these sources continue to be important for providing energy for the next few generations. Global demand for increased energy and for decreased environmental pollution have prompted the need for alternative or clean energy sources, which do not depend on fossil fuels, and have a tolerable environmental impact. Alternative or renewable energy sources such as solar PV, wind, wave, tidal, geothermal, and hydroelectric energies seem to meet the requirement for clean energy. Figure 1 shows a sample of some renewable energy sources. Although the energy potentially generated by these sources exceeds that generated by fossil fuels, they have not yet become a major part of the electrical power system grid. Figure 2 shows the alternative energy sources contributing 7 percent of the world's total electricity generation. The projection is to double this contribution within the next decade. What follows is our solution and recommendations for integrating alternative fuels and alternative energy concepts into a self-sustainable

renewable energy ecosystem that can be replicated anywhere. Our approach presents a truly green solution, meaning that it is alternative, renewable, and most importantly, sustainable.

2.0 Indoor Biofuels Laboratory

We needed to develop a way to conduct high-throughput screening of potential algae and plants that can be used for alternative fuels. This is achieved by having a controlled indoor laboratory that will enable efficient germination of potential plant and algae crops. Our indoor biofuels laboratory is set up to facilitate the climatic adaptation of seeds that can potentially meet our goals of not relying on freshwater, not using arable land, and not competing with food crops.

There are six 40-gal plant control tanks labeled IBF1 to IBF6 ranging in true specific gravity from 1.000 (freshwater) to 1.025 (natural seawater) in increments of 0.005 (see Figure 3). Climatic adaptation is the specific ability to salinize a plant and algae species as well as desalinitize algae and plants species for use in varying soil and salinity conditions (see Table I). We also have two 40-gal (151-L) control tanks consisting of a marine ecosystem (1.025 true specific gravity) that also doubles as a mangrove nursery

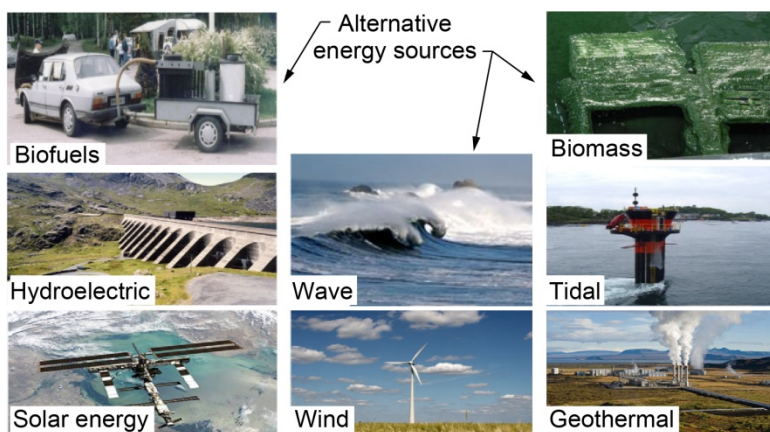


Figure 1.—Sample of renewable energy sources (Refs. 8 to 13).

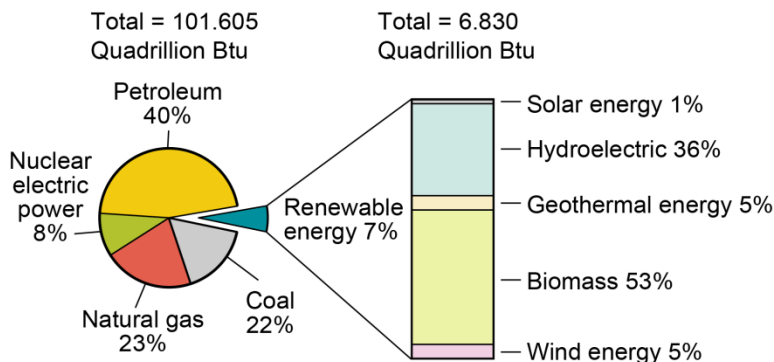


Figure 2.—Contribution of renewable energy sources to generation of electricity. Sum of components may not equal 100 percent due to independent rounding (Ref. 14).



Figure 3.—Left side of indoor biofuels laboratory.

(see Figure 4). In addition, we have two 100-gal (379-liter) marine ecosystems that are utilized for microalgae and macroalgae experiments. One of these ecosystems is connected to a CO₂ injection system, and the other is maintained as a control ecosystem. It should be noted that all of our control tanks are made of glass material to maximize light penetration and provide for easy maintenance. This laboratory is a climate-controlled laboratory with an average temperature of 72 °F (22.2 °C) and relative humidity of less than 50 percent. These ranges are necessary for us to operate because this laboratory is connected to other laboratories, and our laboratory controls the entire floor.

2.1 Conditions of a Successful Ecosystem

To have a successful ecosystem, four conditions must be satisfied: (1) sufficient water supply, (2) adequate soil, (3) optimum lighting, and (4) nutrition source. In addition to these four conditions, life cycle analysis must be taken into account for large-scale implementation of the expansion of the indoor biofuels laboratory.

2.1.1 Water Supply

The initial water supply was achieved by utilizing reverse osmosis combined with deionization (RO/DI) water to provide for an ultrapure water source. RO/DI water was placed in all tanks and the salinity of each tank was achieved by utilizing a high-quality sea salt mixture. Synthetic sea salt was used instead of natural seawater to provide ideal laboratory conditions as well as to minimize undesirable organisms that are present in natural seawater that may negatively affect the ecosystems of our algae and plant life.

2.1.2 Soil

The soil used in the indoor biofuels lab was prewashed ocean floor reef sand. It was used because it contained no artificial fertilizers or additives and is adaptable to varying salinity levels that are present in the laboratory. The diameter grain size of our sand ranged from 0.049 to 0.077 in. (1.25 to



Figure 4.—Right side of indoor biofuels laboratory.

1.95 mm) to facilitate seed growth, pH stabilization, and water penetration. We initially mixed a sand additive to our ocean reef sand composed of an 80 percent oceanic mud-sand mix combined with a 20 percent formulation of minerals and trace elements to provide initial nutrients for the plants species. The depth of the sand in the indoor biofuels lab was 4 in. (102 mm).

2.1.3 Lighting

The most challenging part of our ecosystem was lighting. Based on what is currently used in the plant industry, we chose to use metal halide lights for their high light output and efficiency over fluorescent lights. The first major challenge when using these bulbs was choosing the light wattage and spectrum. We settled on using 400-W bulbs because of the size and application of our laboratory. The 250-W bulbs proved not intense enough, and 100-W bulbs were much too bright and generated a considerable amount of heat. To determine the optimal light spectrum, we initially tried 20,000-K bulbs, but they turned out to be too blue and did not maximize the growth of our seedlings. We next tried 10,000-K bulbs but they turned out to be too white in color. We then settled on 6500-K bulbs because they are the most closely aligned with the spectrum of the Sun, which is approximately 5500 K. The higher kelvin bulbs were chosen for the intense light, but this did not translate into increased growth rate. We have had great success with using 6500-K bulbs and recommend that they be utilized when growing plants and algae in a controlled indoor biofuels lab. They are considered a yellow bulb (between red-orange and green-blue spectra), but have worked out well for our applications.

The next task was to determine the optimal photo period. We experimented with photo periods ranging from 2 to 8 hr per day and settled on a 6-hr photo period. A 6-hr photo period based on a 3-month testing period was chosen because it maximized the growth of our seedlings in the laboratory. Another issue with lighting was the height of the lights above the tanks. We conducted experiments with the distance and settled on a distance of 18 in. (457 mm) above the tanks. At this height, we did not experience sunburn on the plants or

seedlings. Again, there was a trial-and-error period to determine the height distance above the tanks. We also had to determine the number of lights to use. We initially settled on three because that is what would fit over our plant systems, but this proved to be too much light and caused undesirable algae to grow in our tank systems. We then settled on using two bulbs with an interesting application. We used light movers. We attached our lights to a light mover system and had the lights move back and forth traversing the tanks while they were on. Doing this allows us to have consistent, full coverage over all of our tanks while maximizing light exposure as well as simulating direct and indirect sunlight that plants are exposed to on a daily basis.

2.1.4 Nutrition

Providing adequate nutrition for our plants and algae is paramount to long-term growth and stability and is the main reason to find a fertilizer source that would be sustainable and safe for the environment. We decided that we would not use any artificial fertilizers in our systems, and based on our plant research, nitrogen and phosphorus are the two most important nutrients needed to optimize plant growth. The artificial addition of nitrogen and phosphorus could lead to the degradation of our ecosystems by way of unintended algae blooms such as cyanobacteria. We settled on using fish waste as our natural fertilizer in our ecosystems. Where would we get the fish was the next question. Using our experience in climatic adaptation, we acclimatized freshwater mollies (*Mollienesia* species) to thrive in each of our ecosystems. This process enables us to have several breeding pairs of mollies in each one of our plant tanks. Mollies are prolific breeders and efficient waste producers. They are also one of the few species of fish that can be subjected to climatic adaptation without any ill effects. We started each tank with 10 mollies, and prolific breeding populations were established within 1 month and are still intact. It should be noted that mollies are excellent algae eaters and have thrived on eating diatoms and filamentous algae that grows on the sides of the glass ecosystems in our laboratory.



Figure 5.—Microalgae and macroalgae experiments.

Once we optimized the four conditions for a healthy ecosystem, we began to conduct experiments using halophytes, weeds, and algae. To date, we have investigated over 19 different plant and algae species in the indoor biofuels laboratory with the goal of being able to transfer the most viable plant and algae species to our GreenLab Research Facility. Figure 5 to Figure 9 some of the plant and algae species we have studied. Table I is a list of the species that we have tried to grow in our lab along with general comments on our findings.



Figure 6.—*Salicornia virginica* species.



Figure 7.—*Salicornia europaea* species.



Figure 8.—*Kosteletzkya virginica* species.



Figure 9.—*Salicornia bigelovii* and *Salicornia virginica* seedlings.

TABLE I.—PLANT SPECIES INVESTIGATED IN THE INDOOR BIOFUELS LABORATORY

Plant name (Common name)	Comments
<i>Salicornia virginica</i> (Pickleweed)	This plant species is the best overall plant that had a consistent lipid yield over all salinity levels. The germination was 7 to 25 days.
<i>Salicornia europaea</i> (Common glasswort)	This plant was by far the largest plant and had adequate lipid content. The germination was 3 to 15 days.
<i>Salicornia bigelovii</i> (Dwarf glasswort)	This plant was the shortest plant but had the highest lipid yield. The germination was 7 to 15 days.
<i>Salicornia subterminalis</i> (Parish's pickleweed)	This plant is currently being investigated. Our primary analysis is that this plant is similar to <i>Salicornia virginica</i> . The germination was 15 to 25 days.
<i>Kosteletzkya virginica</i> (Seashore mallow)	The freshwater weed is a good candidate for climatic adaptation. The germination was 5 to 10 days.
<i>Rhizophora mangle</i> (Red mangrove)	Used primarily for CO ₂ abatement and water filtration.
<i>Avicennia germinans</i> (Black mangrove)	Used primarily for CO ₂ abatement and water filtration.
<i>Lena camelina</i>	The freshwater plant is the fastest plant to grow and seed in our lab. It also had the highest lipid yield. The germination was 2 to 5 days.
<i>Moringa oleifera</i>	This plant is very difficult to grow but we have had limited success in our freshwater system. The germination is 15 to 30 days.
<i>Pueraria lobata</i> Kudzu sp.	This plant was actually a surprise since it died off quickly when we exposed it to climatic adaptation in the lab. It does not like salt, which may be helpful eradicating this plant in the United States.
<i>Sesuvium portulacastrum</i> (sea purslane)	This is a co-plant that grows along <i>Salicornia</i> and while it thrived in all salinity levels, its lipid content was quite low.
<i>Suaeda maritima</i> (Sea blite)	This is a co-plant that grows along with <i>Salicornia</i> but has a low lipid yield.
<i>Chaetomorpha</i> sp.	This is an excellent macroalgae species that is used as a filter for our tanks but absorbing excess nutrients and CO ₂ .
Sea grass	This is a co-plant that grows alongside <i>Salicornia</i> in the wild and has the potential to be used for usable biofuels via pyrolysis.

2.2 Monitoring and Maintaining Ecosystem Parameters

To establish a stable ecosystem, regular maintenance is required. Because we are in a closed indoor facility, it is important to replicate nature as closely as possible, meaning we need to have an efficient and effective biological filtration system, chemical filtration system, and mechanical filtration system to ensure long-term stability. Optimal biological filtration is achieved by using the reef sand as a biological filter. Because the sand is partially submerged in water, beneficial bacteria will

establish in the sand bed over time and this will result in optimal biological filtration since there will be an efficient conversion of ammonia, which is the result of fish waste and other decomposing organic matter into nitrates, which are used as a beneficial fertilizer for plants and algae. No additional biological filtration methods are used in the indoor biofuels laboratory besides sand, and our systems have been up and running since mid-2008. Mechanical filtration is achieved by way of utilizing a power filter that has a sponge filter attached to it that efficiently removes particulate matter from the ecosystem. Water is pulled through the filter by a siphon tube and into a chamber that has a

sponge filter inside, trapping the particles and the water is returned to the ecosystem by way of a waterfall, which enriches the ecosystem with oxygen by way of surface agitation. Rinsing the sponge filter frequently should be a part of normal maintenance. Chemical filtration is achieved by the use of activated carbon, which eliminates dissolved wastes that accumulate in any ecosystem. Healthy plants can also extract dissolved chemical wastes from water through their roots, which is one of the reasons we chose to use mangrove plants. Replacing the activated carbon at regular intervals will be required to maintain sufficient chemical filtration. Lastly, we use submerged power heads to ensure adequate circulation inside of our ecosystems. The placement of the power heads is not critical because water movement is the ultimate goal, which increases oxygen levels in a closed ecosystem. Nature's equivalent would be the tides coming in and out during the day along the coastline. However, hypoxic zones can occur in tank corners and bottom edges. This is why it is very important to monitor ecosystem parameters (see next section) in multiple locations in each ecosystem. We use a spray bottle to mist the indoor plants once a day to minimize salt buildup that can occur due to the lack of rain. This is crucial to a closed saltwater ecosystem because without rain, salt would build up on the leaves of the plants, causing stress and potentially leading to the plants demise.

Several parameters can be monitored in any ecosystem, and we chose the following parameters based on the plant species and fish that we have in our ecosystem: pH, temperature, total dissolved solids, salinity, dissolved oxygen, phosphate, and nitrates. These are the parameters that were ideal to our ecosystem, and there were commercially available electronic devices capable of accurately reading these measurements. Table II lists our current readings for each of the parameters that we monitor. These parameters have been consistent over the life of the lab and have been maintained to create a stable ecosystem for our indoor biofuels laboratory. IBF1 through IBF6 are our plant tanks that are labeled by true specific gravity values (salinity). IBF7 and IBF8 are our control tanks

that have mangroves, fish, shrimps, crabs, worms, and snails. IBF9 and IBF10 are our *Chaetomorpha* macroalgae tanks with IBF9 being the control *Chaetomorpha* tank and IBF10 being the tank that is attached to a CO₂ injection system by way of a calcium reactor.

All the plants and algae species that survived for more than 6 months in the indoor biofuels laboratory were analyzed for optimal lipid content. The most promising plants and algae species from the indoor biofuels laboratory were transferred to the GreenLab Research Facility. It is our hope that others who are interested in establishing a seedling lab concentrating on halophytes will find our information useful. What follows is an explanation of the GreenLab Research Facility and the lessons learned and implemented as a result of the success and failures of our indoor biofuels laboratory.

3.0 GreenLab Research Facility

Biofuel use has been gaining popularity over the past few years due to their ability to reduce the dependence on fossil fuels. They can be a viable option for sustaining long-term energy needs if they are managed efficiently. The GreenLab at Glenn, shown in Figure 10, is a unique research facility for investigating the possible future biofuel alternatives that are currently being researched and applied around the world. The main research objective is to facilitate the development of biofuels for aviation. Our program goals are to develop viable alternative choices for aviation biofuels feedstock, enable "seed-to-fuel" analysis, optimization, and perform performance testing of biofuels. The current research focus is on third-generation biofuel candidates: macroalgae and microalgae, and selected halophyte species. A unique bench scale laboratory was developed for aviation biofuels research. The key experimental techniques are coastline equivalent halophyte beds, open pond algae systems, and photobioreactors. Figure 11 illustrates a NASA approach to producing aviation biofuels using microalgae as an energy source.

TABLE II.—ECOSYSTEM PARAMETERS THAT ARE MONITORED
IN THE INDOOR BIOFUELS LABORATORY

Tank (volume)	pH	Temperature, °C	Salinity	TDS	DO	Phosphate	Nitrate
IBF ^a 1 (40 G/151 L)	8.34	21.6	1.002	4.4	6.40	0.04	8.0
IBF 2 (40 G/151 L)	8.27	21.9	1.005	11.1	6.23	0.03	6.3
IBF 3 (40 G/151 L)	8.20	21.8	1.010	20.2	6.15	0.07	2.0
IBF 4 (40 G/151 L)	8.25	21.3	1.015	28.6	5.96	0.20	7.0
IBF 5 (40 G/151 L)	8.14	21.6	1.020	39.3	5.73	0.15	1.6
IBF 6 (40 G/151 L)	8.13	21.8	1.025	49.1	5.10	0.30	1.4
IBF 7 (40 G/151 L)	7.97	21.1	1.023	49.8	5.20	1.35	4.4
IBF 8 (40 G/151 L)	8.05	20.9	1.023	46.2	5.35	1.65	3.1
IBF 9 (300 G/379 L)	6.7	26.6	1.021	42.1	5.75	0.25	8.2
IBF 10 (300 G/379 L)	8.7	26.0	1.021	38.4	5.61	0.25	8.3

^aIBF stands for Indoor Biofuels Laboratory and the number denotes the ecosystem.



Figure 10.—The GreenLab Research Facility at NASA Glenn.

Example: optimizing microalgae/cyanobacteria biofuel properties via transport processing and analysis.

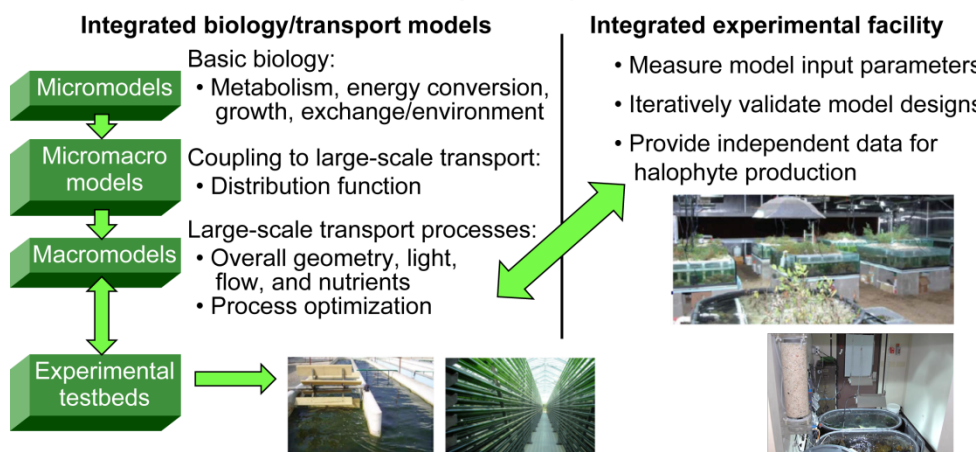


Figure 11.—Efficient NASA-unique approach to aviation biofuels.

The GreenLab enables us to take successful indoor plants and algae and subject them to real-world outdoor field trials. The GreenLab Research Facility allows us to develop efficient iterative processes utilizing modeling, experimental verification, and testing research to identify optimal algae and/or halophytes biomass candidates for aviation fuels and processes and growth parameters to improve feedstock properties and minimize complex and carbon positive refining steps to achieve greatest life cycle CO₂ reduction benefit. Specific systems that comprise the GreenLab are described below.

3.1 GreenLab Systems

3.1.1 GreenLab Ecosystems

There are six main 239-gal (905-L) plant control ecosystems labeled Tank 1 to Tank 6 ranging in true specific gravity from 1.000 (freshwater) to 1.025 (natural seawater) in increments of 0.005 (see Figure 3, GreenLab-3). These ecosystems are much larger than the indoor biofuels laboratory and give us the ability to conduct multiple experiments in each ecosystem simulta-

neously. We have a seventh ecosystem (Tank 7), a 370-gal (1401-L) ecosystem dedicated to plant growth with a deep sand bed to investigate root length and to conduct adaptive biology experiments by combining different seed mixtures with the goal of cross-pollinating plant species. We also have two 300-gal (1136-L) mangrove ecosystems (M1 and M2) in the GreenLab to maintain air quality, provide water filtration, and to abate any excess atmospheric CO₂. In addition, we have two 239-gal (905-L) microalgae ecosystems (L1 and L2) that are used to conduct open-pond microalgae experiments. We also have one 327-gal (1238-L) fish ecosystem (L3) that houses marine fish to investigate ideal parameters for a marine ecosystem. We have recently added a 561-gallon (2124-L) ecosystem (A1) attached to a 100-gal (379-L) ecosystem that is used to investigate utilizing fish waste as an optimal fertilizer for growing *Chaetomorpha* macroalgae systems. Lastly, we have a 90-gal (341-L) living reef tank that we use as a marine control tank to monitor and compare against our other ecosystems. As in the indoor biofuels laboratory, all our plant ecosystems are made of glass material to maximize light penetration and facilitate maintenance.



Figure 12.—Six main ecosystems.

3.1.2 Control

Unlike the indoor biofuels laboratory, which is climate controlled via the use of an air conditioning system and humidifier, the GreenLab is designed to be as environmentally friendly as possible. If we were to use an air conditioning system, we would not be able to find a feasible alternative energy solution. Our solution to the air conditioning issue is to use an evaporative cooling system, which is controlled by a low-watt recalculating pump in the rear of the GreenLab (see Figure 12). Water is constantly circulating through porous recyclable cardboard pads. However, we did install a heating system so the plants and animals will survive through the winter months. On average, the GreenLab temperature is 75 °F (24 °C) and has a relative humidity of less than 80 percent. The GreenLab is set up so that real-world temperatures and humidity levels can be achieved. This provides an environment where we can test the adaptability of the plant and animals in nonideal conditions. In addition, we have an automatic heating system in our GreenLab that is used only in the winter to account for colder temperatures.

3.2 Successful Ecosystem Conditions

As stated in the indoor biofuels section, five conditions should be met to have successful ecosystem. What follows is our implementation of these five conditions for the GreenLab Research Facility.

3.2.1 Water Supply

Just as in the indoor biofuels laboratory, the initial water supply for the GreenLab was obtained by utilizing RO/DI water to provide for an ultra-pure water source. We used the same high-quality sea salt mix to achieve the desired salinity for each of our ecosystems. Natural seawater poses several contamination issues (e.g., parasites, plankton, cyanobacteria, etc.) for a closed ecosystem so we relied on synthetic sea salt to give us relatively disease and parasite-free water source to begin our experiments.

3.2.2 Soil

We utilized two sizes of prewashed aragonite sand for our soil in the GreenLab. This was due to the increased depth of the sand in our ecosystems. The total depth of our sand bed in our plant ecosystems was 6 in. with the first 4 in. composed of 0.049 to 0.077 in. (1.25 to 1.95 mm) sand grain size and the bottom 2 in. of the sand bed composed of 0.049 to 0.077 in. (1.25 to 2.0 mm) sand grain size to avoid excessive clumping of the smaller sand sizes. We combined the sand with the same additive as used in the indoor laboratory, which was composed of an 80 percent oceanic mud-sand mix combined with a 20 percent formulation of minerals and trace elements to provide initial nutrients for the plants species. After the sand was established, there was no need for additional additives or nutrients.

3.2.3 Lighting

While the lessons learned concerning lighting was done indoors by choosing 400-W and 6500-K lights along with light movers, the optimal photo period turned out to be very different than indoors due to direct sunlight and the requirements of each type of ecosystem. Since 2009, we have settled on the following photo period for our GreenLab ecosystems:

Tanks 1 through 7 (1.000 to 1.025): 8 hr of metal halide (MH) lighting per day with the lights on from 3 to 8 p.m. Tanks M1 and M2: 6 hr of MH lighting per day (4 to 10 p.m.), which is sufficient for our mangroves nurseries. Tanks L1 and L2, which are algae tanks, received the most MH lighting and the photoperiod ranged from 12 to 16 hr per day depending on the algae species. Tank A1, which is our wastewater treatment experiment using *Chaetomorpha*, received 12 hr of MH lighting per day. Tank L3 and reef receive 8 hr of MH lighting per day with the lights coming on at noon and going off at 8 p.m. All photoperiod times were controlled by the use of digital timers that simultaneously control the light movers so that the light movers turn on when the lights turn on. The height of the lights above the ecosystems was 32 in. (813 mm). We have approximately 34 MH lights in our GreenLab compared to 6 in the indoor biofuels laboratory.

3.2.4 Nutrition

The GreenLab poses different challenges than the indoor biofuels lab because of the many different ecosystems. The indoor biofuels laboratory only had two main types of ecosystems: *Salicornia* seedling ecosystems and macroalgae ecosystems. The GreenLab has seven different types of ecosystems: *Salicornia* seedling ecosystems, adaptive biology ecosystems, mangrove ecosystems, microalgae ecosystems, wastewater treatment ecosystem, fish control ecosystem, and reef control ecosystem. Each system poses different challenges. The *Salicornia* plants systems nutritional needs re-met by maximizing the mollies in our system to provide optimal fertilizer by way of nitrogen and phosphorus. The mollies feed primarily on filamentous algae that grow on any available surface. Occasionally, they are also fed dry flake food to

minimize predation and to ensure that baby fry get additional nutrients. We have approximately 300 mollies in each of our *Salicornia* ecosystems. Our climatic adaptive biology ecosystem has both plants and fish, and the fish are fed dry pellet and flake food periodically to maintain a varied diet and reduce predation. All plants in the GreenLab get energy from natural sunlight and MH lighting as well as from fish waste. The mangrove ecosystems, which simulate a coastline environment, get nutrients through natural sunlight, MH lighting, and fish waste. The mangrove ecosystem's primary job is to be a CO₂ sponge for our GreenLab and provide a model for water filtration via its roots. The microalgae ecosystems are primarily grown on atmospheric CO₂ with its primary nutrients coming from our MH lighting and natural sunlight. Our reef ecosystem nutrients also get its primary nutrients from natural sunlight and MH lighting and minimum nutrients from dry food additions. Our fish control tank is provided with as close to natural food as possible in order for us to accurately moni-

tor our GreenLab parameters. This tank is fed a varied diet from frozen food to flake food to dried seaweed with the waste from this system going to our wastewater treatment experimental tank that has a *Chaetomorpha* filter attached to it to absorb all excess nutrients from this ecosystem. This ecosystem consists of approximately 30 large marine fish that are prolific waste producers. This ecosystem is fed the same varied diet as our fish control tank. It must be noted that all ecosystems are in the same environment and have been thriving together since 2009. We did not take very long to stabilize our ecosystems in the GreenLab due to our experience in the indoor biofuels laboratory. We did, however, investigate fewer species in the GreenLab based on the potential for long-term success. To date, we have investigated approximately 13 plant species in the GreenLab, and Table III lists the plant species grown in the GreenLab along with general comments. Figure 13 to Figure 18 show a few of the plant and algae species we have studied.

TABLE III.—PLANT SPECIES INVESTIGATED IN THE GREENLAB RESEARCH FACILITY

Plant name (Common name)	Comments
<i>Salicornia virginica</i> (Pickleweed)	<i>S. virginica</i> is the most successful plant that we have had to date. It has excellent growth, seeding, and adequate lipid production.
<i>Salicornia europaea</i> (Common glasswort)	<i>S. europaea</i> was the largest <i>Salicornia</i> plant species we have had, and it is also the fastest to germinate.
<i>Salicornia bigelovii</i> (Dwarf saltwort)	<i>S. bigelovii</i> was the shortest <i>Salicornia</i> plant species we have had, but it had the highest lipid content.
<i>Kosteletzkya virginica</i> (Seashore mallow)	We have been able to successfully use our climatic adaptation techniques to get seashore mallow to seed and grow in the first four ecosystems, which shows that a freshwater weed can be adapted to saline environments and to become a harvestable crop.
<i>Rhizophora mangle</i> (Red mangrove)	Used primarily for CO ₂ abatement and water filtration.
<i>Avicennia germinans</i> (Black mangrove)	Used primarily for CO ₂ abatement and water filtration.
<i>Laguncularia racemosa</i> (White mangrove)	Used primarily for CO ₂ abatement and water filtration.
<i>Lena camelina</i>	This freshwater plant is the fastest plant to grow and seed in the GreenLab. We have been able to successfully grow this plant in all of our ecosystems and are investigating its potential for climatic adaptation.
<i>Moringa oleifera</i>	This plant has grown successfully in at least three different salinity values and we are investigating it as both a fuel and food crop.
<i>Sesuvium portulacastrum</i> (Sea purslane)	This is a co-plant that grows along <i>Salicornia</i> and always seems to grow back. We did not find any use for this plant in the GreenLab. Investigating cellulosic extraction via pyrolysis.
<i>Suaeda maritima</i> (Sea blite)	This is a co-plant that grows along <i>Salicornia</i> and always seems to grow back. We did not find any use for this plant in the GreenLab. Investigating lipid extraction via pyrolysis.
<i>Chaetomorpha</i> sp.	This is an excellent macroalgae species that is used as a filter for our tanks but absorbing excess nutrients and CO ₂ . In the GreenLab, it is being used as a wastewater treatment experiment.
Sea grass	This is a co-plant that grows alongside <i>Salicornia</i> in the wild and has no usable biofuels value. Investigating cellulosic extraction via pyrolysis.



Figure 13.—*Salicornia europaea*.



Figure 16.—Seashore mallow flower ready for pollination.



Figure 14.—Microalgae tanks showing open-pond and hybrid photo-bioreactor system.



Figure 17.—*Salicornia bigelovii* seedlings.



Figure 15.—*Salicornia bigelovii* ready to seed.



Figure 18.—Microalgae from our open-pond system.

3.2.5 Maintenance

The maintenance required in the GreenLab is significantly more than the indoor lab due to the increased number of power filters and pumps. Daily maintenance is required for the GreenLab to remain in optimal working order. Biological filtration occurs by way of a 6-in. (152-mm) partially submerged sand bed that has an established bioload. Mechanical filtration is achieved with two large power filters, and chemical filtration is achieved by using activated carbon in the plant tanks with additional chemical filtration through phosphate absorption media in the fish control tank and reef tanks. We mist the plants in the GreenLab for 30 sec each day to minimize salt buildup. This simulates natural misting by dew or light rain, which helps the plants eliminate salt residue on its leaves. We also use two high-output submerged power heads to ensure adequate circulation inside of our ecosystems, being aware of potential hypoxic zones near tank corners and edges. Wave generators are used in our microalgae open-pond systems to maximize mixing of the algae. The biggest issue with maintenance is the frequency of cleaning the power filters and pumps. The power heads need to be cleaned at least three times a week while the power filters need to be cleaned daily to ensure optimal conditions. This is a time-consuming task but required because the failure to do so may result in less than ideal conditions for the plants and animals.

3.3 Monitoring Ecosystem Parameters

We monitor the same parameters in the GreenLab that we do in the indoor biofuels lab: pH, temperature, total dissolved solids, salinity, dissolved oxygen, phosphate, and nitrates. Table IV lists our current parameter readings that we monitor in the GreenLab. These parameters have been the most important for our ecosystem health and created a stable environment. Tanks 1 through 7 are our plant tanks that are labeled

by true specific gravity values (salinity) ranging from 1.000 to 1.025 true specific gravity. M1 and M2 are our mangroves ecosystems that have primarily mangroves, fish, snails, and crabs. A1 is our wastewater treatment ecosystem, L3 and reef are our fish control and reef control tanks. L1 and L2 are our microalgae tanks investigating potential freshwater microalgae species that can be climatically adapted.

All of the plants and algae species listed in Table I have survived in the GreenLab for more than 2 years, and we have analyzed each species for optimal lipid content using chemical extraction processes. We have been maintaining our GreenLab Research Facility since 2009 and wanted to present our findings to assist others in establishing GreenLabs around the world.

3.4 GreenLab Lessons Learned

If one is going to create a GreenLab, it is important to understand that it is not a trivial task and there are certain unique challenges that should be addressed before a climatic adaptive GreenLab is established. The first challenge is the actual environmental conditions. The GreenLab is essentially a saltwater ecosystem, and the number one problem is corrosion due to the relatively high humidity and salt spray in the lab. We have learned that the ideal material to use in the GreenLab is stainless steel 316 or higher. Failure to purchase equipment or tools not rated at this level will result in rust in a matter of days. The general rule in the GreenLab is that everything is considered disposable, and just about everything has been replaced through trial and error over the past few years. Another challenge will be electrical connections. One needs to be sure to have ground-fault interrupts on each and every receptacle to minimize any potential electrical problems. Deep covers were installed on each receptacle to minimize moisture penetration and water exposure. Another issue is the flooring. We chose to use a gravel bed contained in a PVC

TABLE IV.—ECOSYSTEM PARAMETERS THAT ARE MONITORED IN THE GREENLAB RESEARCH FACILITY

Tank (volume)	pH	Temperature, °C	Salinity	TDS	DO	Phosphate	Nitrate
Tank1 (239 G/905 L)	8.52	22.5	1.002	3.5	7.98	0.07	5.1
Tank 2 (239 G/905 L)	8.43	22.4	1.005	5.6	7.31	0.42	9.4
Tank 3 (239 G/905 L)	8.53	22.5	1.010	12.4	7.13	0.40	3.9
Tank 4 (239 G/905 L)	8.37	22.5	1.015	26.4	7.18	0.33	0.3
Tank 5 (239 G/905 L)	8.09	22.4	1.020	28.9	6.13	0.81	1.7
Tank 6 (239 G/905 L)	8.04	23.2	1.025	34.3	5.29	0.47	3.6
Tank 7 (370 G/1401 L)	8.08	24.7	1.023	42.3	5.01	2.01	30.0
M1 (300 G/1136 L)	7.88	24.2	1.022	44.9	3.83	2.50	17.8
M2 (300 G/1136 L)	7.88	25.0	1.021	39.4	4.38	2.50	15.8
A1 (561 G/2124 L)	8.06	24.6	1.022	45.7	5.04	2.50	15.3
Reef (90 G/341 L)	8.19	25.6	1.019	40.1	5.94	0.34	3.7
L3 (327 G/1238 L)	8.06	24.6	1.022	47.9	4.90	1.62	5.3

cage using a polyurethane mesh because of its ease of maintenance and relatively low cost. Be sure to get prewashed gravel because it will reduce dirt in the lab. We did not choose a cement floor because it is always wet in the GreenLab, and a cement floor would be a major slipping hazard. Air circulation is also a big concern and we went through three iterations before we found the optimal numbers of fans. We have six small fans and four large fans in the GreenLab that circulate the air to avoid dead zones. At least two sinks are needed to clean the equipment. Additional fluorescent and flood lights may have to be installed as well. Lastly, one must plan on replacing tools frequently because we have yet to find stainless steel tools that can withstand the GreenLab environment.

3.5 Making the GreenLab Energy Efficient

One of the goals of the GreenLab is to have it ultimately be a self-sustainable climatic adaptive renewable energy ecosystem, which means that we need to make sure that the GreenLab can be operated without the use of direct electricity from a power company. To that end, we have installed two wind turbines capable of up to 2.4 kW of energy each to supplement the GreenLab. We plan on adding additional wind turbines in the future. We are also connecting solar arrays to the GreenLab, which would put up as 100 percent renewable power at least 6 hr a day. What follows is an explanation of the available alternative energy sources and options for the GreenLab to reach our goal of having a working biofuels lab that produces and uses clean energy.

4.0 Alternative Energy Integration

Renewable or alternative energy sources such as solar PV and wind are clean technologies that can reduce the major environmental impact of present electricity sources. The

electricity obtained from these energy sources is normally unregulated and cannot be directly connected to the power system grids or to non-grid-connected loads. Therefore, regardless of the power ratings of the renewable energy generation unit, it has to be converted to a suitable form by utilizing power electronic converters and other controllers. When connected to the grid, the role of power electronic converters and controllers is not only to convert electricity to a suitable form, but also to ensure that the distributed generation (DG) unit connected to the grid will not create problems that can impair the quality of the power supply and the safety of all other equipment connected to the point of common coupling (PCC). Examples of these systems are discussed for solar and wind energy systems. Figure 19 shows typical power electronic converters arrangement for solar systems. The unidirectional bidirectional power converters are required to ensure that the energy storage devices (ESDs) and loads can be supplied by the grid or the PVs.

For wind systems, several possible power electronic topologies are used that can be classified into two groups: direct-in-line wind turbines and doubly fed generator wind turbines. An example of the first group that uses a squirrel cage induction generator is shown in Figure 20. The generator is mechanically coupled to the wind turbine via a mechanical gearbox. The variable frequency voltage of the generator is rectified and fed to the inverter to produce a constant frequency voltage that can be connected to the grid.

There are a few possible sources of energy from which the load can obtain the power, either from the alternative energy sources, from the ESDs, from the grid, or from the combinations of these sources (Figure 21). The choice of source or combination of sources used to supply the loads has to be made carefully to ensure maximum and efficient energy utilization. This depends on several factors, such as the instantaneous power available from the sources, energy on the ESD, load

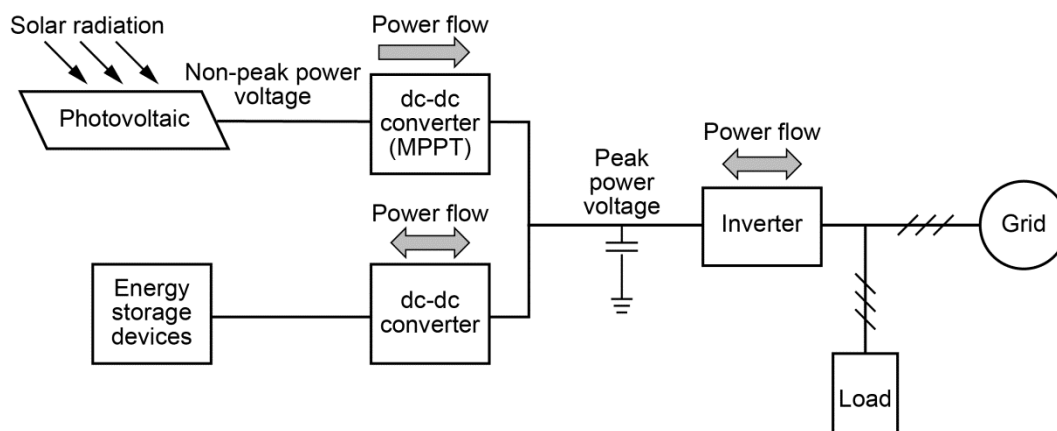


Figure 19.—Power electronic converters for photovoltaic systems.

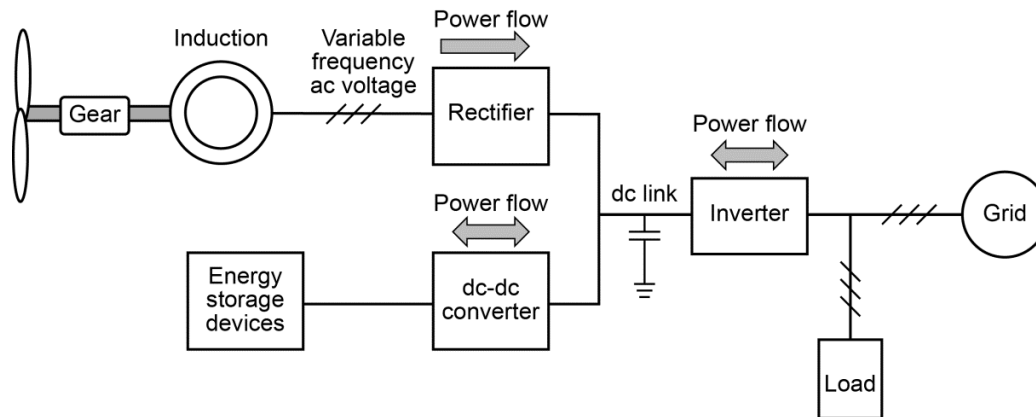


Figure 20.—Power electronic converters for wind turbine.

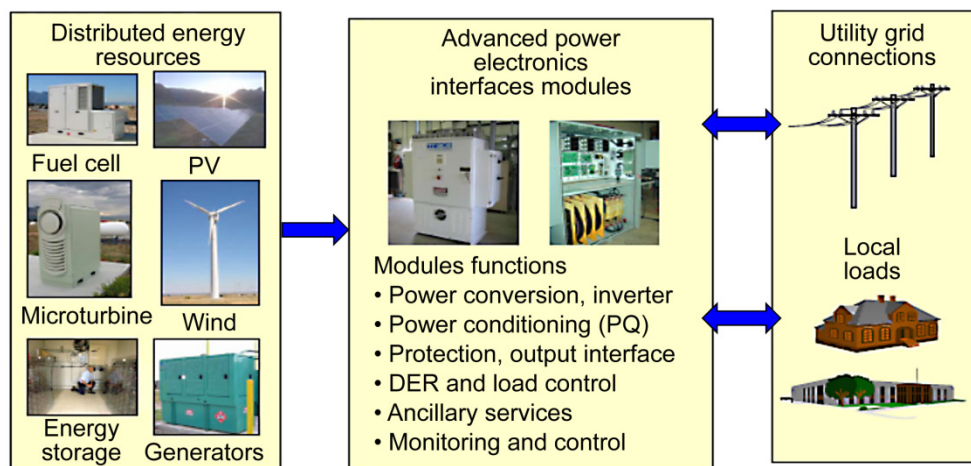


Figure 21.—Distributed energy resources (DERs) and interface with the utility grid (Ref. 8) (photovoltaics (PV)).

characteristics, price of energy from the grid at that instant, and the desired power factor. Integrating these factors with a decision tree in the power electronic interface modules for optimum energy utilization and cost constitutes the energy conversion conditioning system (ECCS). During power outage on the grid, the energy sources and the ESD supply power to the loads and fulfill instantaneous peak power demand. The ESD can be charged up either by the grid or energy sources depending on the instantaneous power available and the load demand. The sizing of the ESD has to be determined, based on the anticipated loads, outage times, and energy sources characteristics. The ESD are used to compensate the high transient power demanded by the loads that cannot be delivered by the energy sources due to their slow response.

In photosynthesis, sunlight and artificial lighting provide photon distributed energy resources (DERs). These DERs are collected in special cellular constructs termed “antenna” that function as microgrid networks (MGNs) connecting DER-photons with chlorophyll cellular energy to ECCS with the Calvin cycle where water, nutrients, CO_2 , and sunlight react to produce CH_2O (glucose) and O_2 products (with some H_2O and plants salts). These products provide energy for biomass

foliage and root mass growth with seed, salt, and root mass ESDs.

We are investigating expanding this concept to DER sources connected through MGNs to collect and store energy provide energy and power to the GreenLab as well as establish a DER-MGN-ECCS-ESD methodology. Our goal is to achieve a self-sufficient climatic adaptive GreenLab ecosystem that is transportable worldwide.

4.1 Role of Energy Storage Devices

DERs respond relatively slowly to a sudden increase in load demand. It is reported that for microturbine and fuel cell systems, the time constant for the power output can range from 5 ms to 50 s. If the DER system is not connected to the utility grid and no ESDs are installed, because of this slow response, a sudden increase in load power demand will result in a voltage reduction to achieve energy balance. There are a few types of ESDs that are being used and researched in power system applications: batteries, flywheels, ultracapacitors (or supercapacitors), superconducting magnetic energy storage systems (SMES), pumped-hydro, and mixed-salts. Battery technologies, particularly the

lead-acid batteries, are widely used in power system applications due to their low cost, high energy density and capability, and their established and mature technology. A fuel cell has energy storage similar to a battery in that an electrochemical reaction is used to create electric current. However, batteries carry a limited supply of fuel internally whereas in fuel cells, the reactants are gases (hydrogen and oxygen) that are constantly replenished; therefore, the unit will be limited by supply of gases, but may not run down like a battery. Fuel cells are suited for distributed storage (DS) due to their low emission and high efficiency. Power rating of a fuel cells system can be from 100 kW to a few MW. Heat produced from the electrochemical reaction for electricity production can be used for combined heat and power (CHP) application. The direct current (dc) voltage generated from the fuel cells may be too low for an inverter to operate efficiently; therefore, a dc-dc converter is normally used to step up the voltage to a higher level. Other ESDs such flywheel technologies are gaining popularity and have been applied in wind turbine technologies. Mixed salts are considered in solar-thermal systems. Pumped-hydro is reliable and more commonplace in electric power systems. At present, ultracapacitors or supercapacitors are mainly used for low-energy, high-peak-power applications. They have been used in drive systems to improve ride-through capability during voltage sags; their applications in DER have yet to be found. SMES are known for their fast response and high efficiency; however, compared to other energy storage systems they are presently expensive and require cryogenic support systems. In power system applications, SMES have been used for voltage sag compensation and to improve stability performance

4.2 Interconnections of DERs

DERs are small-scale power generation technologies, typically in the range of a few kilowatts to tens of kilowatts, used to

provide an alternative to or an enhancement of the traditional electric power system. A microgrid is a small power distribution system that includes a variety of these sources in combination with ESD and loads. When included with DG and DS, a microgrid is also referred to as a DER. Recently there has been considerable research and development on implementation of DERs, their interconnections, and the security requirements of future electric power systems, in which DERs are likely to be an essential component. DERs generate electricity from many small energy sources such as solar and wind sources. The electricity obtained from the energy sources is normally unregulated and is not in a suitable form to be directly connected to loads, as common commercial products, or to the grid. Therefore, regardless of the power ratings of a DG unit, the electricity has to be converted to a suitable form by utilizing power electronics converters (part of the ECCS). Figure 22 shows different interconnections of DERs operating in grid-connected mode with the loads connected directly or in parallel with the grid. The interconnections can be with power only drawn from the grid or with power drawn and supplied back to the grid. The interconnection is a concern to the utility provider, especially with regard to the power quality and safety of personnel or connected equipment. The grid-connected mode may or may not include ESD, with several factors that determine this choice. If the grid is intended as a backup supply to the load, ESD may not be required. Power is obtained from the grid when power from the energy sources is unavailable. With no ESD, power required for a sudden load change or during peak power demand is obtained from the grid and the alternative energy sources. However, power outage on the grid will result in the power supplied to the load being totally dependent on the energy sources. Thus, because of the slow response of the energy sources to react to an instantaneous sudden load demand, the power quality supplied to the load will be impaired. In the worst case, when the energy sources are not generating power, a power outage on the grid

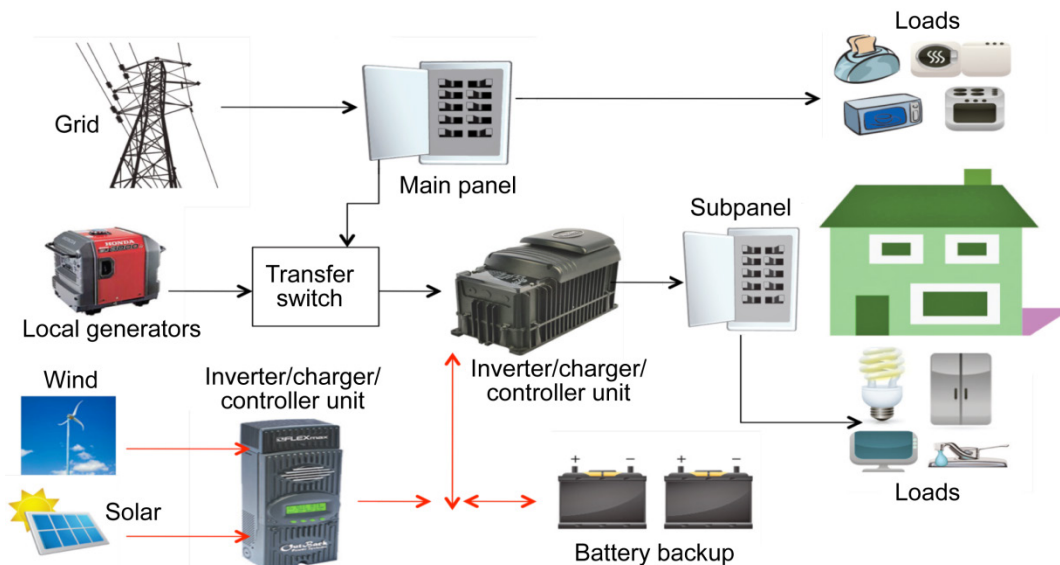


Figure 22.—Example of interconnection of distributed energy resources with the utility (Ref. 12).

will result in no power available at the load. If the energy sources are sized to supply the load only during average power usage, then during power outage on the grid, peak power demand cannot be fulfilled. Excess energy generated by the energy sources can be fed back only to the grid.

5.0 Green Laboratory Power Systems

The current power consumption of the GreenLab is about 20 kW per day. This is used by the many pumps, lights, fans,

and filters as shown in Table V. Initiated in the summer of 2011, an ongoing task will develop a structure and implement a power system architecture that will feed the electricity needs of the GreenLab from the commercially available resources of renewable energy. Emphasis is put into energy from windmills, PV, and backup power devices. Figure 23 shows the proposed grid-connected DER system architecture to supply energy from windmills and PV with battery backup systems. The dc loads are connected to the dc link via a dc-dc converter (diversion unit).

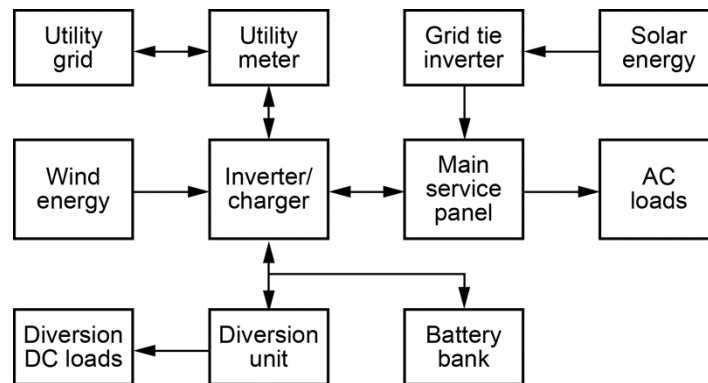


Figure 23.—Tentative green laboratory power system architecture.

TABLE V.—GREEN LABORATORY POWER REQUIREMENTS

Item	No.	Rating, W	Total power
Tunze 6205 pumps	19	55	1045
Tunze 6305 pumps	6	64	384
Tunze 6105 pumps	2	45	90
Aquaclear 500 filter	16	14	224
Dual-voltage Homer Head pump	2	246	492
Reeflo Snapper (universal motor)	4	104	416
Wave Generator Tunze 6261 pumps	6	50	300
Blue Line Aqua pump	1	390	390
Tunze Protein Skimmers pump	2	22	44
Delta Star Chiller	4	1104	4416
Ad Smith fans	2	373	746
MAG24 pump	1	237	237
Motors for moving the lights	7	6	42
Galaxy Lights	26	400	10400
Evaporative cooling	1	93	93
Total	99		19320



Figure 24.—Demonstration of commercially available wind energy. (a) NASA Johnson Childcare Center. (b) NASA Glenn GreenLab Research Facility.

Renewable energy systems are commercially available for both residential and industrial applications. Advances in power electronics and energy storage devices are helping to reduce weight and size and to increase reliability. Commercial wind power development, in which large wind turbines are connected to the electric grid and produce electricity for widespread distribution, is a relatively recent phenomenon. During the early 1980s, hundreds of commercial wind turbines were installed in three areas in California. There are several single-phase wind and solar energy systems with all of the required power electronics and battery backup energy system. Some systems are fully integrated, utility-connected wind generators designed specifically for homes and small businesses. Several single-phase wind power systems have been installed worldwide at different power levels. Figure 24 shows two examples of these systems. Figure 24(a) shows both solar and wind applications in powering a childcare center at NASA Johnson Space Center, and in Figure 24(b) a windmill is used to supply power to the GreenLab Research Facility at NASA Glenn. Currently there are two windmill systems that are partially supplying wind energy to the GreenLab facility.

6.0 Conclusions

In this report we have provided a description of the GreenLab Research Facility at NASA Glenn Research Center that is composed of two complementary components: the indoor or incubator facility and the outdoor growth facility. Each possesses a variety of climatic adaptive ecosystems, power and energy sources, and requirements. The goal is to enable worldwide expansion and adoption of the research and development facility to enable the commercialization of biomass production for energy, fuel, food, feed, and freshwater recovery.

Our primary motivation flows from the large gap between the production and demand for energy from alternative fuel and alternative renewable energy sources. The basic issues center on sustainability of humanity, as we know it, which depends directly on the ability to secure affordable energy, food, feed, and fuel with conservation of arable land and freshwater. These issues are addressed directly in the GreenLab Research Facility where focus is directed to optimize biomass feedstock utilizing primarily, but not exclusively, algae and halophytes as the next generation of renewable aviation fuels.

The unique approach is directed to the achievement of optimal biomass feedstock through climatic adaptation of balanced ecosystems that do not use freshwater, do not compete with food crops, or use arable land. The incubator laboratory screens both seeds, seedlings, waste treatment, ecosystems with a variety of controlled saline, lighting, and nutrient conditions preliminary to transitioning to the outdoor laboratory. Successful biomass treatments are then transported and implemented on a larger scale more realistic of actual soil and water conditions in six parts of the world in the outdoor facility. The climatic adaptive approach enables saline-tolerant plants to prosper in freshwater environments as well as adapting freshwater species to prosper in saline environments. The adaptation is extended to fish, which in turn supply rapid growth, reproduction, and nutrients. Aquatic life, primarily fish, becomes the health-monitoring system for the GreenLab. Reclamation of contaminated waters becomes a necessity, and those algae from the incubator laboratory are both tested for reclamation and sources of fueling biomass.

To date, plants, fish, and soil have been adapted to salinity conditions from freshwater (specific gravity = 1) to seawater (specific gravity = 1.025) in increments of 0.005. Thirteen seedlings and plant varieties have been tested and studied in the indoor or incubator laboratory and several varieties of algal species along with 13 plant varieties in the outdoor facility. Biomass plants adapted include *Salicornia*, seashore mallow, and mangroves to some degree, with native algae species as the most sustainable algal form.

To offset the GreenLab Research Facility power consumption, alternative and renewable energy from wind and photovoltaic (proposed microgrid) technologies reduce the major environmental impact of commercial electricity. The ultimate

goal is to have a 100 percent clean energy laboratory dedicated to biomass research within the framework of a self-sustainable ecosystem that can be duplicated anywhere in the world and can potentially be used to mitigate the shortage of food, fuel, and water.

Biomass derived biofuels represent viable alternative fuel resources for the field of aviation with byproducts for feed or direct use as food and residuals as energy sources. Utilizing wind and solar technology as alternative renewable energy resources supplements the GreenLab energy and power demands.

We hope to join with other entities that are interested in Green solutions for long-term human needs and invite others to copy our concept and share their solutions with the world. A very simple recommendation is that we need to put forth an effort to solve the world's fuel, food, and water crises and the development of the GreenLab Research Facility can begin the debate on how to successfully implement solutions.

Glenn Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, December 23, 2011

References

1. Reilley, John; Paltsev, Sergey; and Choumert, Frederic: Heavier Crude, Changing Demand for Petroleum Fuels, Regional Climate Policy, and the Location of Upgrading Capacity. MIT Joint Program on the Science and Policy of Global Change, Report No. 144, 2007. <http://web.mit.edu/globalchange/www/MITJSPGCRpt144.pdf> Accessed September 8, 2011.
2. Daggett, D.L.; Ben-Amotz, A.; and Benemann, J.: Feasibility of Algal Oil for Renewable Jet Fuel. Submitted to J. Appl. Phycol., 2011.
3. NASA Aeronautics Research Mission Directorate: N+2 Advanced Vehicle Concepts NRA Draft Solicitation Synopsis. 2010. http://www.aeronautics.nasa.gov/calendar/era_preconference_synopsis.htm. Accessed September 8, 2011.
4. U.S. Energy Information Administration: World Energy Demand and Economic Outlook. International Energy Outlook 2009, DOE/EIA-0484(2009), 2009. [http://www.eia.gov/oiaf/ieo/pdf/0484\(2009\).pdf](http://www.eia.gov/oiaf/ieo/pdf/0484(2009).pdf) Accessed September 8, 2011.
5. U.S. Energy Information Administration: World Energy Demand and Economic Outlook. International Energy Outlook 2010, DOE/EIA-0484(2010), 2010. <http://www.eia.doe.gov/oiaf/ieo/world.html> Accessed September 8, 2011.

6. Daggett, D.L.; Ben-Amotz, A.; and Benemann, J.: Feasibility of Algal Oil for Renewable Jet Fuel. Submitted to J. Appl. Phycol., 2011.
7. Daggett, D., et al.: Alternative Fuels and Their Potential Impact on Aviation. NASA/TM—2006-214365 (ICAS 2006-5.8.2), 2006.
8. California Distributed Energy Resource Guide: The California Energy Commission. 2011. http://www.energy.ca.gov/distgen/equipment/energy_storage/energy_storage.html Accessed September 9, 2011
9. <http://www.windenergy.com/>
10. <http://www.xantrex.com/>
11. OutBack Power Radian Series. 2011. <http://www.outbackpower.com/> Accessed September 9, 2011.
12. Argonne National Laboratory: Electrochemical Energy Storage. Argonne National Laboratory, 2011. http://www.cmt.anl.gov/Electrochemical_Energy_Storage/default.shtml Accessed September 9, 2011.
13. <http://www.power-thru.com/>
14. EIA. Renewable Energy Consumption and Electricity Preliminary 2007 Statistics. Table 1: U.S. Energy Consumption by Energy Source, 2003–2007 (May 2008).

Bibliography

- Daggett, D.L., et al.: Alternate Fuels for Use in Commercial Aircraft. NASA/TM—2008-214833 (ISABE-2007-1196), 2008.
- Elbuluk, M.; and Idris, N.R.N.: [The Role Power Electronics in Future Energy Systems and Green Industrialization](#). IEEE 2nd International Power and Energy Conference, 2008, pp. 1–6.
- [Evans, A.L.](#); [Reid, R.L.](#); and [Hendricks, R.C.](#): A Feasibility Study of a Combined Wind-Solar System for Space and Domestic Hot Water Heating. Proceedings of the International Solar Energy Society Annual Meeting, Sections 14–25, 1977, pp. 19–41 to 19–45. Accessed September 8, 2011.
- Hendricks, R.C.: Sustainable Secure Alternate Aviation Fueling. 2007 NASA Seal/Secondary Air System Workshop, NASA/CP—2008-215263/VOL1, 2008, pp. 75–99.
- Hendricks, R.C.; Bushnell, D.M.; and Shouse, D.T.: Aviation Fueling: A Cleaner, Greener Approach. Thirteenth International Symposium on Transport Phenomena and Dynamics of Rotating Machinery, ISROMAC-13, 2010.
- http://www.cmt.anl.gov/Electrochemical_Energy_Storage/default.shtml
- http://www.energy.ca.gov/distgen/equipment/energy_storage/energy_storage.html
- <http://www.nrel.gov>
- McDowell, M., et al.: Biofuels as an Alternative Energy Source for Aviation—A Survey. NASA/TM—2009-215587, 2009.
- National Renewable Energy Laboratory. 2011. <http://www.nrel.gov> Accessed September 9, 2011.

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</p> <p>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YYYY) 01-12-2011		2. REPORT TYPE Technical Paper		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE NASA's GreenLab Research Facility: A Guide for a Self-Sustainable Renewable Energy Ecosystem				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) McDowell Bomani, B.M.; Hendricks, R., C.; Elbuluk, Malik; Okon, Monica; Lee, Eric; Gigante, Bethany				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER WBS 561581.02.08.03.16.03	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191				8. PERFORMING ORGANIZATION REPORT NUMBER E-17888	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001				10. SPONSORING/MONITOR'S ACRONYM(S) NASA	
				11. SPONSORING/MONITORING REPORT NUMBER NASA/TP-2011-217208	
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Categories: 07, 44, 45, and 51 Available electronically at http://www.sti.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 443-757-5802					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT There is a large gap between the production and demand for energy from alternative fuel and alternative renewable energy sources. The sustainability of humanity, as we know it, directly depends on the ability to secure affordable fuel, food, and freshwater. NASA Glenn Research Center (Glenn) has initiated a laboratory pilot study on using biofuels as viable alternative fuel resources for the field of aviation, as well as utilizing wind and solar technology as alternative renewable energy resources. The GreenLab Research Facility focuses on optimizing biomass feedstock using algae and halophytes as the next generation of renewable aviation fuels. The unique approach in this facility helps achieve optimal biomass feedstock through climatic adaptation of balanced ecosystems that do not use freshwater, compete with food crops, or use arable land. In addition, the GreenLab Research Facility is powered, in part, by alternative and renewable energy sources, reducing the major environmental impact of present electricity sources. The ultimate goal is to have a 100 percent clean energy laboratory that, when combined with biomass feedstock research, has the framework in place for a self-sustainable renewable energy ecosystem that can be duplicated anywhere in the world and can potentially be used to mitigate the shortage of food, fuel, and water. This paper describes the GreenLab Research Facility at Glenn and its power and energy sources, and provides recommendations for worldwide expansion and adoption of the facility's concept.					
15. SUBJECT TERMS Biomass; Green aviation; Fueling; Energy; Conservation; Climatic adaption					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 26	19a. NAME OF RESPONSIBLE PERSON STI Help Desk (email: help@sti.nasa.gov)
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (include area code) 443-757-5802

