Integrated Renewable Energy and Energy Storage Systems

Prepared for the

U.S. Department of Energy
Office of Electricity Delivery and Energy Reliability

Under Award No. DE-FC-06NT42847
Hawai‘i Distributed Energy Resource Technologies for Energy Security

Subtask 2.2 Deliverable 2

By

Hawaii Natural Energy Institute
School of Ocean and Earth Science and Technology
University of Hawaii

September 2009

Acknowledgement: This material is based upon work supported by the United States Department of Energy under Award Number DE-FC-06NT42847

Integrated Renewable Energy and Energy Storage Systems

TABLE OF CONTENTS

Integrated Renewable Energy and Energy Storage Systems

List of Figures

List of Tables

1.0 INTRODUCTION

The use of distributed energy resources (DER) technologies using renewable energy resources is rapidly increasing, driven by strengthened federal and state policies and financial incentives. While this trend holds promise for a significant shift away from the use of imported fossil energy, and therefore enhanced energy security, the limited capability of the utility grid to integrate intermittent renewable DER generation will constrain expansion of grid-connected DER. Among the grid integration issues that require the continued development, testing, and validation of DER and grid-support technologies are transmission congestion, capability to provide peak power, and capacity to manage intermittent renewable technology deployment.

Three technology areas that are key to larger-scale deployment of renewable resource-based DER are examined in this report - photovoltaic (PV) electricity, biomass energy, and energy storage. An evaluation of each of these technologies relative to their appropriateness to Hawaii is provided to enable understanding of the degree to which Hawaii can serve as a platform for testing and demonstration of integrated energy systems. These technologies, opportunities for their development and use, and related research conducted under this project are further discussed in this report.

1.1 Photovoltaic Electricity Production

Due to Hawaii's high electricity prices there is growing interest in distributed and large-scale grid-integrated PV power production. However, power delivery is variable based on the time of year, the time of day and on weather conditions. It is clear that in the long-term, practical solar-to-electric power generation will require not only efficient and cost-effective conversion technologies, but also practical large-scale storage and transmission schemes. Important avenues of PV research are still needed to help identify the best pathways forward to practical large-scale PV implementation in Hawaii.

Work on the design and deployment of a versatile and modular PV evaluation test platform capable of handling a wide range of solar cell technologies under carefully controlled and monitored operating conditions is described. Data from such a test bed would be valuable in identifying the best performing PV systems in Hawaii’s environment. Data from various PV technologies could also provide valuable data for future scenarios, in which large-scale grid connected PV is deployed.

1.2 Bio-energy Crops and Technologies and Biomass Conversion Technology

A review of land-based energy crops and a survey of conversion technologies considered for Hawaii are provided, with commentary on technology gaps and the status of technology development. Research and testing conducted to analyze and evaluate contaminants in product gas from biomass gasification is described. The research involves the analysis of permanent gas species, tar compounds, sulfur compounds, and ammonia produced from a bench scale (~1kg/h) fluidized bed biomass gasifier. Two commercial Ni-based catalysts and one commercial ZnO sorbent were evaluated under varied conditions. The Ni-catalysts targeted tar destruction and ammonia reduction and ZnO sorbent to remove sulfur compounds.

This research supports the continued development of gasification technology for the conversion of Hawaii's biomass resources for a wide range of transportation and power generation applications. As a distributed energy resource, biofuels offer a means, along with storage technologies, to enable increased grid integration of variable renewable energy generation.

1.3 Grid Energy Storage Systems

The state of Hawaii is moving from central-station, oil-based firm power to more renewable and distributed energy systems. Particularly in the case of wind and photovoltaic technologies, these new systems can be disruptive to grid stability and will increase the operating risks of the electric utilities. The state of Hawaii and its utilities will need to assure a stable electric grid to minimize disruption to service quality and reliability. The discussion of potential energy storage systems to ameliorate these impacts will be summarized for the state of Hawaii. While the commercial readiness of rapid response and bulk energy storage technologies have been analyzed extensively this discussion will focus on the appropriateness of specific storage technologies in Hawaii and the status of these activities.

2.0 PHOTOVOLTAIC ELECTRICITY PRODUCTION

2.1 Overview

Photovoltaic (PV) cells are specialized semiconductor devices that directly convert sunlight into DC (direct current) electricity. PV-based solar-electric energy systems are becoming increasingly important as alternative sources of utility power, on residential, commercial and industrial power-production scales. For remote or stand alone power generation, a PV system is typically coupled with a battery storage system and charge controller circuitry to sustain a DC electricity bus. Alternatively, the PV-generated DC electricity can be converted using power-inverter technology into AC (alternating current) electricity for powering conventional AC equipment or for feeding into utility grids.

Solar conversion technologies such as PV are particularly important to renewable energy development, especially considering the immense scope of the solar resource. The sun is continuously bombarding the earth with approximately $178{,}000\text{x}10^{12}$ or 178,000 TW of radiant power. Although a substantial fraction of this is immediately reflected to space, over 82,000 TW of the radiant energy reach the earth's surface- 36,000 TW of this falling over the world's collective land masses. In comparison, our current human energy demand is on average about 13 TW (approximately 2 TW in electricity usage), with future projections up to 25 TW in the next 40 years. There is clearly an over-abundance of solar energy reaching earth. Although about half of this energy is vital for driving the planet's climate and life cycles, there is sufficient remainder for conversion to useable forms of energy for human consumption.

There are, however, certain logistical challenges in harnessing the vast solar resource. The sun is a constant power source, but at a given location on earth, power delivery is variable based on the time of year, the time of day and on weather conditions. The sun is an immense power source, but the per area energy density is relatively low. The peak solar flux at the earth's surface is only slightly over 1 kW/m^2. In terms of the net solar energy received at the latitudes of the United States and Europe, typical insolation levels range from 4 $\text{kWh/m}^2\text{/day}$ in northern regions to 8 $\text{kWh/m}^2\text{/day}$ in the sunniest regions. Using an average value of 6 $\text{kWh/m}^2\text{/day}$, and assuming a 10% solar conversion efficiency, approximately 80,000 million m^2 of land area would be needed to supply our current net electric consumption levels of 48 TWh/day (i.e., 2 TW x 24h/day). This is a significant land mass, although the unpopulated area of the Sahara desert is significantly larger, at over 9,000,000 million m^2.

Covering the Sahara desert with solar cells could convert enough solar energy to meet mankind's electricity demands, but the physical cost of this endeavor would be enormous with current conversion technologies, and there would be significant problems in storing and transmitting the electricity for consumption in populated regions around the world. It is clear that in the long-term, practical solar-to-electric power generation will require not only efficient and cost-effective conversion technologies, but also practical large-scale storage and transmission schemes.

The two primary routes for viable solar-to-electric energy conversion include solar-thermal and PV. In solar-thermal electricity production, which utilizes solar energy to heat the working fluid in a thermodynamic cycle, the high-temperature operating conditions required for high efficiencies can be severely limiting. PV, on the other hand, is a direct solar-to-electricity conversion process that can achieve relatively high conversion efficiencies at low operating conditions, but its viability depends on the large-scale deployment of cost-effective semiconductor materials systems.

State of the art semiconductor materials systems for PV applications include silicon (in crystalline, multicrystalline/polycrystalline, ribbon and amorphous forms), III-V crystalline compounds (such as gallium-arsenide and indium-gallium-phosphide), and thin-film compounds such as cadmium-telluride (CdTe) and copper-indium-gallium-diselenide (CIGS). Material systems in the exploratory stages include organic semiconductors and dye-sensitized metal oxide systems. Demonstrated PV conversion efficiency ranges from less than 1% in exploratory systems to 43% in the most sophisticated laboratory-scale systems. Photovoltaic efficiency for commercially available silicon-based solar cells ranges from 6% in amorphous silicon to 20% in crystalline silicon, with efficiency values from 12%-18% in multi-crystalline and ribbon silicon. Demonstrated PV efficiencies for thin-film CdTe and CIGS range from 14-20%. There remains, as in any technology, an inherent trade-off between performance and cost. 42% efficient PV cells based on multi-junction III-V crystalline semiconductors can be up to 100 times more costly to produce than their lower-efficiency silicon counterparts.

Materials performance and cost are critical to the long-term viability of PV electricity production, though balance of system improvements, including possible solar-tracking, solar-concentration, and power-inverters, are also important. Maximum-power-tracking and grid-tie systems are also important considerations. Overall, there are advantages and disadvantages to large-scale PV deployment, as summarized below:

Advantages	**Disadvantages**
Vast power source (solar energy)	Low energy density of the solar resource, as well as local intermittency based on sun cycle and weather conditions
No emissions, no combustion, no radioactive waste as part of power generation	Energy consumption and environmental impact resulting from large-scale processing of PV-grade semiconductor materials
Low operating costs: - no moving parts (avoiding wear) - ambient temperature operations (avoiding materials degradation and safety issues)	High up-front installation costs
High reliability in demonstrated PV modules (20-30 years)	Reliability issues remain in balance of system components (such as storage, tracking and concentration systems), though power inverter technologies have recently demonstrated reliabilities rivaling PV modules.

2.2 Status of Commercial Readiness

PV technology is commercially available today, though the high-cost of large-scale implementation remains a barrier. Nevertheless, the world PV market installations reached a record high of 5.95 gigawatts (GW) in 2008, representing growth of 110% over the previous year. Europe accounted for 82% of world demand last year, with Spain and Germany taking first and second place in the market ranking. The US advanced to number three, while rapid growth in Korea allowed it to become the fourth largest market, closely followed by Italy and Japan. In the US, the grid-tied PV market led the overall PV market with 292 MW installed in 2008, a growth rate of 81 percent from 2007. California was the leader among state grid-tied PV installations with 178.6 MW. New Jersey followed with 22.5 MW installed and Colorado was next at 21.6 MW. Nevada installed 13.9 MW and Hawaii installed 11.3 MW.

On the supply side, world solar cell production reached a figure of 6.85 GW in 2008, up from 3.44 GW a year earlier. Overall capacity utilization rose to 67% in 2008 from 64% in 2007. China and Taiwan continued to increase their share of global solar cell production, rising to 44% in 2008 from 35% in 2007. Polysilicon supply to the solar industry grew by 127% in megawatt terms, sufficient to substantially ease supply limitations in 2008. United States polysilicon production accounted for 43% of the world's supplies. Average global wafer capacity grew to 8.30 GW (up 81%). Meanwhile, thin film production also recorded solid growth, up 123% in 2008 to reach 0.89 GW.

In the U.S., new manufacturing facilities for solar cells and modules in Massachusetts, Michigan, Ohio, Oregon, and Texas are adding enough capacity to produce thousands of megawatts of solar devices per year within the next few years. In late 2008, for example, Sanyo Electric Company, Ltd. announced its decision to build a silicon-PV manufacturing plant in Salem, Oregon, which is planned to reach a full production capacity of 70 MW per year by April 2010. Also in late 2008, First Solar, Inc. broke ground on an expansion of its Perrysburg, Ohio facility that will add enough capacity to produce another 57 MW per year of Cd-Te-PV modules, bringing its total capacity to roughly 192 MW per year. Recent growth has been impressive, but not all the news is good for PV. Some market researchers expect a decline in the photovoltaic industry in 2009, due to overcapacity, plunging prices, and weak demand for solar as a consequence of the global economic recession.

The “bottom line” is that the cost of PV electricity is still too high to compete against fossil-fuel plants, despite rising fossil fuel prices. Semiconductor materials and processing costs are the primary reason. Silicon, which comprises over 90% of the current PV market share, is one of the earth’s most abundant elements; still the processing of PV-grade silicon is both energy and cost intensive. A common method used to express economic costs of electricity-generating systems is to calculate a price per delivered kilowatt-hour (kWh). For PV, the cell efficiency and lifetime in combination with the available irradiation will determine the electricity costs. Commercially available silicon solar cells have efficiencies ranging from 6 to 20% (for amorphous to crystalline silicon, respectively) and warranted lifetimes up to 30 years. As a result, current PV electricity generation costs range from ~0.60 US$/kWh down to ~0.30 US$/kWh in regions of high solar irradiation. This electricity is generally fed into the electrical grid on the customer's side of the meter. Compared with prevailing retail electric pricing, which varies from 0.04 US$/kWh in the US up to 0.50 US$/kWh worldwide, PV-generated electricity is relatively high-priced.

Until rising fossil fuel prices result in a fivefold increase in retail electric prices, the cost-competitiveness of PV-electricity will depend on development of lower-cost PV semiconductors, such as the thin-film CdTe or CIGS, with lifetimes rivaling silicon; or alternatively, on breakthroughs in lower-cost silicon manufacturing. In the meantime, the rise and fall of the PV industry is being fueled in substantial part by tax incentives and government subsidies.

2.3 Hawaii Photovoltaic Resources and Incentives

The use of solar energy via photovoltaic conversion to electricity is on the rise in Hawaii. The Hawaiian Islands' abundant sunshine in conjunction with heavy reliance on imported fuels for energy and high electricity cost (relative to the US mean) are providing strong incentives for accelerated investment in PV. The average solar resource in Hawaii is among the highest in the United States, and considerably higher than in most of the populated world. On average, about 5.7 kWh/m2/day of solar energy can be available in Hawaii for flat panel PV-conversion, while approximately 7kWh/m2 can be converted with tracking PV systems.

Even with the exceptional solar resource in Hawaii, PV development would not be possible without the considerable state and federal incentives. The Solar and Wind Energy Credit, originally enacted in 1990, allows individuals or corporations to avail an income tax credit of 35% of the cost and installation charges for a solar thermal or photovoltaic system. Amendments to the original measure indicate consistent support for increased PV use. In 2003, Senate Bill (SB) 855 revised the tax credit and extended it through 2007. In 2004, SB 3162 allowed a taxpayer to claim a credit exceeding his income tax liability to be carried forward until it was exhausted. House Bill (HB) 2957 was enacted in June 2006 to remove the credit's sunset date, and eliminate the deduction of new federal tax credits from the calculation of the cost of the system eligible for the state tax credit. SB 644, enacted in 2008, provides that a single family residential property owner can avail a credit of 35% of a purchased PV system's cost or $5,000 whichever is less. The credit for a multi family residential property owner is 35% of the system's cost or $350 per unit, whichever is less. Commercial property owners are eligible to claim a credit of 35% of the photovoltaic system's cost or $500,000, whichever is less.

PV-equipped homes and businesses in Hawaii that produce more solar electric energy than they use and are connected to the utility grid can use surplus power to offset their electricity bills in a “net-metering” arrangement. “Feed-in-tariff” systems are also being considered by Hawaii. Federal tax credits are also available to partially subsidize PV systems, which can cost about $20,000 or more for a typical residential PV system without battery backup.

Hawaii’s favorable environmental and political climate has lead to a rapid rise in PV installations across the state in recent years. The state is among the leaders in the nation in grid-tied PV installations, with over 11 MW installed. To accommodate this, dozens of Hawaii-based PV-installer companies are currently licensed. In the past few years, a number of commercial-scale PV installations have also been successfully completed, or are near completion. The 309 kW solar array at a US Naval facility on Ford Island, installed by PowerLight using Sharp Corporation polycrystalline-silicon modules, has been operational for over two years. During the daytime, this PV system generates energy equivalent to that normally used to power over 300 homes. Another notable example is the Mauna Lani resort on the Island of Hawaii which since 2003 has the distinction of having the most solar electric generating capacity of any luxury resort in the world - over 500kW of SunPower silicon-based PV systems.

More recently, Castle & Cooke Inc. has built the largest solar photovoltaic energy farm in the state of Hawaii on 10 acres in Palawai Basin, Lanai. The Lanai solar farm, built with panels from California-based SunPower Corp., currently produces up to 500 kilowatts of energy, which is expected to rise to 1.2 megawatts upon completion in late 2009. This will be enough to provide up to 30 percent of the island's daily peak electrical needs. Under a 25-year power purchase agreement approved by the state Public Utilities Commission, Maui Electric will purchase Lanai PV-power from Castle & Cooke Solar Management, LLC for 27 cents a kilowatt hour for the first 10 years, 30 cents a kilowatt hour for the second 10 years, and 33 cents a kilowatt hour for the following five years. It is intended that the solar farm will provide financial relief to Lanai residents from the highest electric rates in the state, which now top 50 cents a kilowatt hour.

2.4 Overall Appropriateness of PV in Hawaii

In the big picture of “Hawaii’s Renewable Energy Development” it is extremely appropriate and important to foster the implementation of PV technologies for converting the state’s abundant solar resource to consumer electricity. Some general comments regarding PV, which are consistent with the findings of the 2006 DBEDT report “Photovoltaic Electricity in Hawaii”, can be summarized as follows:

- Hawaii is ideal for PV, based on its oil dependence, high electric costs and rich solar resource; research into the “best” PV for Hawaii is ongoing;
- PV is cost-effective in parts of Hawaii already, but up-front costs are high;
- Roof top PV in Hawaii is attractive (non-competitive with other land use);
- Residential PV systems today are expensive, costing $15k-$25k up front for 2-3kW systems; policy and market forces will eventually lead to more competitive costs;
- Net-metering in the near-term is an attractive option for consumers and the utilities;
- New grid infrastructures will be vital in the long-term for handling intermittent sources such as solar and wind;
- Financial incentives are also vital to spur growth in the PV market (including subsidies, tax-credits, ‘pay as you save’, etc.);
- PV performance and price data are insufficient to define long term trends.

Regarding the final point in the bullet list above, important avenues of PV research are still needed to help identify the best pathways forward to practical large-scale PV implementation in Hawaii. These include:

- For different PV semiconductor technologies, identification of the specific temperature sensitivities in PV conversion efficiency - particularly related to the expected environmental operating conditions in Hawaii's different micro-climates;
- For different PV semiconductor technologies, identification of the specific spectral sensitivities in PV conversion efficiency - particularly related to the various atmospheric operating conditions in Hawaii's different micro climates;
- For different PV semiconductor technologies, quantification of the degradation rates and module lifetimes when subjected to Hawaii's different micro climates;
- Quantification of Hawaii's statewide variations in solar resource on a transient second-by-second basis resulting from weather patterns, which can have significantly influence the impact of PV on grid stability;
- Studies, on a sub-second transient level, on the grid impact of large-scale PV penetration;
- Identification of the most effective auxiliary system components in different scaled PV installations, including conventional power-inverters versus single-panel micro-inverters.

2.5 Photovoltaic Module Evaluation Project

The Photovoltaic Module Evaluation Project responds to several of these research needs. The initial phases of this project involve the design and deployment of a versatile and modular PV evaluation test platform capable of handling a wide range of solar cell technologies under carefully controlled and monitored operating conditions. Performance data will be collected for comparative analyses and to identify the most appropriate PV systems for the Hawaiian environment. Data from various PV technologies could also provide valuable data for future scenarios, in which large-scale grid connected PV is deployed. HNEI has been working with a local contractor to design and cost the site improvements required to allow PV testing at a location other than the Hawaii Gateway Energy Center (HGEC), due to collaborative support received at the alternative location.

2.5.1. Project Background

Photovoltaic (PV) technologies will have a significant impact on Hawaii's energy future. High electricity prices in Hawaii reduce the economic barriers for PV power systems, and there is a growing interest in identifying the best PV systems in terms of technology and economic performance, specifically for deployment in the unique Hawaiian environment. In recent years, HNEI has worked on a number of island-based PV system evaluation projects. These have included the Hawaii Electric Company's (HECO) "*SunPower for Schools*" program, comprising over 25 statewide PV installations (typically in the 2kW power range, such as the system at Jarrett Intermediate School Figure 1), and the Navy's "Ford Island PV Demonstration Project" (Figure 2), operating up to 300kW.

Figure 1: HECO 2 kW "SunPower for Schools" PV installation at Jarrett Intermediate School comprising 10 mono-crystalline silicon panels

Figure 2: The Navy's 300kW Ford Island PV installation comprising 1454 poly-crystalline panels

To date, these projects have provided important information relating to PV operations in the Hawaiian environment. HNEI's analysis of the Ford Island PV data (as shown in Figures 3a and 3b), for example, has validated the dramatic effect of moderate seasonal temperature changes on efficiency of the solar energy conversion.

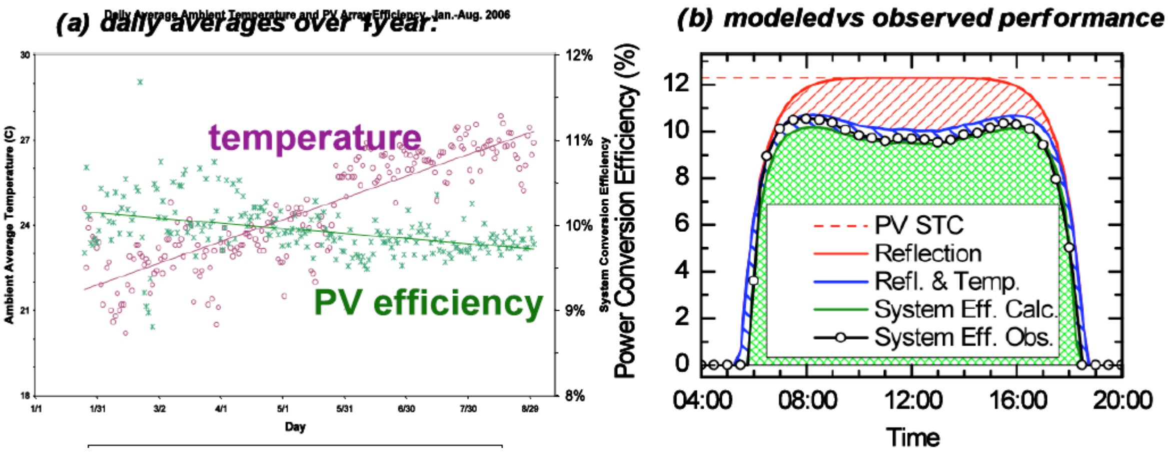

Figure 3: (a) Seasonal trends in PV conversion efficiency at Ford Island poly-crystalline silicon system; (b) analysis of typical day's PV operations validating that efficiency drops at higher operating temperatures are consistent with material system models

2.5.2 The Problem

PV performance is very dependent on the PV materials and module design, and environmental variables (solar radiation, temperature, cloud shadowing, wind, etc.) that make accurate prediction of the PV array performance at any instant in time, difficult. The most severe condition in PV generation is encountered when the sudden passage of a cloudbank sweeps a portion or the entire PV generator, resulting in an immediate loss of power. The negative impact of this abrupt power loss on the electrical grid's stability can be exacerbated if masking of the PV array occurs at a time of sudden change in load demand. The utility must be able to quickly respond to these variations with its own backup generation (spinning reserve). The effect of PV on grid system dynamics will vary in severity depending on the response characteristics of individual technologies, array designs, geographic location, array size, and distribution (e.g., centralized multi-megawatt arrays vs. smaller distributed residential systems). As the penetration level at any sector of the grid increases, it will become increasingly difficult to regulate grid stability. This is already becoming a problem in Hawaii and will be further exacerbated with the push for more renewable energy systems as a result of the Hawaii Clean Energy Initiative's drive to achieve 70% clean energy by 2030. Additionally, the Department of Defense has announced plans for substantial PV power on Hawaii bases that may lead to similar difficulties in management of base power systems.

Unfortunately, all the current evaluation projects in Hawaii are fundamentally limited by: (1) the restricted number of solar-cell technologies, module types and power-conversion equipment under test; (2) a lack of comprehensive instrumentation and monitoring systems to evaluate performance under different environmental operating conditions; (3) a lack of high-speed data-acquisition and real-time analysis capabilities, and (4) their inflexible installation configurations (i.e., fixed panel positioning and lack of temperature control).

2.5.3 The Project

To address the problem, HNEI has initiated a project to develop and deploy a versatile and modular PV evaluation platform capable of handling a wide range of solar cell technologies under carefully controlled and monitored operating conditions. The overall objective is to conduct side-by-side field evaluations of a broad range of commercial and experimental PV module technologies using this evaluation platform installed at different locations throughout Hawaii. It has become clear that Hawaii's unique sub-tropical environmental conditions can have a significant effect on performance in terms of efficiency and durability of the solar cells. A side-by-side comparison of PV modules based on numerous semiconductor material systems, including mono- and poly-crystalline silicon, as well as thin films such as amorphous-silicon, cadmium-telluride, and copper-indium-gallium-diselenide, will be monitored and characterized under local environmental conditions to determine long-term aging and corrosion effects on steady-state performance, as well as dynamic electrical response, which is especially critical to grid compatibility.

HNEI plans to develop the modular PV evaluation platform and deploy the initial beta-testing prototypes at the Pu'u Wa'a Wa'a region on the Big Island. The initial prototype evaluation station will comprise up to seven individual module evaluation platforms, each capable of operating and monitoring an array of two individual PV modules (rated up to 300 watts per module) of a given solar-cell technology.

This project, while building on the experience base of the Hawaiian Electric Company and U.S. Navy installations, will offer advanced PV-evaluation capabilities, including: (1) versatile test-bed designs allowing simultaneous evaluation of several different module types; (2) a more comprehensive sensor set allowing for expanded measurements of voltage, current localized insolation and temperature for all individual modules, in addition to improved power monitoring and control; (3) higher speed instrumentation and data acquisition (1 Hz) to allow for dynamic response characterization; and (4) an expanded environmental monitoring station including relative humidity measurement in addition to ambient temperature and wind speed.

The versatility and advanced measurement features of our proposed testing stations will allow for a comprehensive technical and economic evaluation of a broad spectrum of commercial, near-commercial, as well as experimental photovoltaic technologies and power-conditioning equipment in the Hawaiian and similar environments. We anticipate that the information acquired for PV performance trends as related to environmental conditions will be invaluable in the selection of the most appropriate PV technologies for Hawaii-based use. It will also be vital to developing integrated systems models for evaluating the overall impact of large-scale PV implementations on Hawaii's current and future electrical grids. Such integrated systems models will be developed over the course of this program's period, leveraging related efforts in other HNEI ongoing programs.

3.0 BIOENERGY CROPS AND TECHNOLOGIES

3.1 Overview - Issues and Enabling Technology Needs

This section addresses technology issues related to bioenergy development in Hawaii within the framework of crops and conversion technologies presented in Figure 4. The plants listed on the left hand side of the figure are not all inclusive but represent a selection of the broad spectrum that are being considered as potential bioenergy species. These plants were selected based on their capacity to generate the intermediate products depicted in the figure; sugar, starch, fiber, and oil. Sugarcane (*Saccarum officinarum*) and sweet sorghum (*Sorghum vulgare*) can produce both sugar and fiber. Corn (*Zea mays)* and cassava (*Manihot esculenta*) are starch and fiber producers. Both grass and tree species are considered for their fiber production - guinea grass (*Panicum maximum*), banagrass (*Pennisetum purpureum*), *Eucalyptus sp.*, and *Leucaena (Leucaena leucocephala*). Oil bearing species include the widest variety, including *Jatropha* (*Jatropha curcas*), kukui (*Aleurites moluccana*), microalgae (eg., *Chlorella sp.*) and diatoms, soybean (*Glycine max*), peanut (*Arachis hypogaea*), sunflower (*Helianthus annuus*), and oil palm (*Elaeis guineensis*).

As shown in Figure 4, the intermediate products are transformed into bioenergy products using conversion technologies. Starch is hydrolyzed into sugars which can then be fermented to produce ethanol or butanol. The hydrolysis step is not required for sugar bearing crops. Fiber can also be used to produce ethanol or butanol by hydrolyzing its cellulose and hemicellulose portions to simple sugars that can be fermented. Fiber can also be converted into a number of bioenergy products including electricity, heat, synthetic diesel, charcoal, etc. The primary conversion technologies required to realize these transformations include gasification, pyrolysis, and combustion. Finally, oils from oil seed, tree nuts, or algae can be directly combusted to produce heat and power or converted to biodiesel for use as a transportation fuel or in stationary power applications.

Figure 4 illustrates that multiple pathways exist between plant/crop options on the left of the diagram and bioenergy products on the right. A number of technology components may be required for any given pathway. Agricultural producers in Hawaii have grown a variety of crops and the basic cultural practices of land preparation, seed production, planting, fertilization, and weed control are well understood and are not viewed as primary technology challenges. Crop harvesting and the transportation of the material from field to conversion facility are two remaining unit operations. Many of the crops proposed for bioenergy development have not previously been grown commercially in the state and cost effective harvesting techniques will be important. For sugar cane, harvesting accounts for ~30% of total production costs, thus harvesting costs play a large role in determining economic viability. Due to Hawaii's agricultural worker wage rate (>$10 per hour) and anticipated prices for bioenergy products, hand harvesting techniques are not considered to be viable and mechanized harvesting techniques will be required.

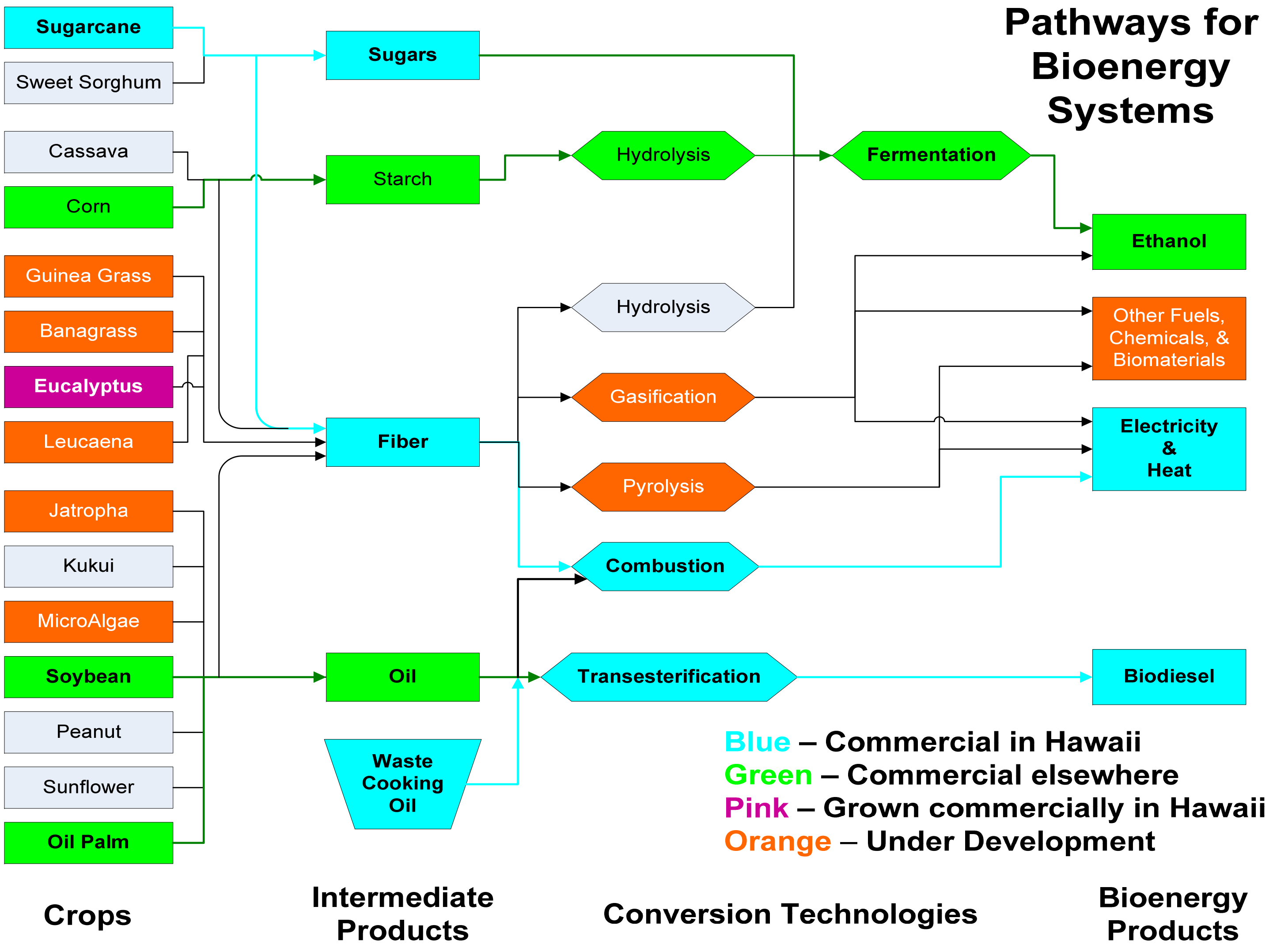

Figure 4: Pathways for Bioenergy Systems

3.2 Crop Production Technology

3.2.1 Sugarcane

Sugarcane (*Saccharum officinarum*) originated in the southern Pacific region, most likely New Guinea. It grows well in the tropics where temperatures are warm, with moderately high rainfall, and heavy soils. Sugarcane has been grown commercially in Hawaii for more than 170 years and the technology for producing and processing sugarcane is well established in the state.

Soil preparation for sugarcane in Hawaii typically consists of leveling, as necessary; cross-ripping and dragging; multiple passes with large disc harrows; followed by rip-dragging the entire field. Sugarcane seed pieces, vegetative cuttings of young sugarcane stalks, are planted in furrows at a density of roughly 7 tonnes per hectare (3 tons per acre), using mechanical planters. Fertilizer (N, P, and K) could be applied at the time of planting or shortly thereafter.

Fertilizer requirements for sugarcane are high, ~200 kg per hectare (~200 lb per acre) of N, ~200 kg per hectare (~200 lb per acre) of K, and significant levels (~50-300 kg per hectare [~50-250 lb per acre]) of P probably would be needed annually. These can be applied initially with the planter as solid fertilizers or soon after planting via irrigation tubing. Thereafter, soluble formulations containing N and K would be applied monthly through the drip irrigation tubing.

Weeds usually can be kept under control with an effective weed control program. Weed control measures for the plant crop might include a pre-emergence herbicide, inter-row herbicide applications at approximately one month, and then spot applications, as needed. Canopy closure should occur within eight weeks of planting (slightly longer during the winter), after which in-field weed control would not be needed. Considerably less weed control would be required for ratoon (unseeded regrowth following harvesting) crops owing to heavy ground cover from harvesting operations and rapid canopy closure following harvesting.

For optimal growth, sugarcane needs ~180 cm (70 inches) of irrigation (via rainfall or applied mechanically) per year. If rainfall amounts are not adequate, it is assumed that sugarcane would be irrigated, using drip irrigation.

Sugarcane grown commercially in Hawaii normally is ripened (through a combination of water withdrawal and the application of a chemical ripener) toward the end of its growth cycle, to maximize sucrose content. The field normally is burned immediately before harvesting to reduce the amount of extraneous fibrous material (called “sugarcane trash”) that needs to be handled in the processing facility (the sugar mill).

Throughout most of the cane-growing world, the plant crop (i.e., the seeded crop) for sugarcane is harvested at 14 to 18 months of age, then, annually, in ratoon crops. By contrast, sugarcane grown commercially in Hawaii is harvested, nominally, at 24 months intervals. Though Australian-style billet harvesters have been used commercially in this state (mostly for cutting seed cane), in Hawaii, sugarcane typically is harvested using push rakes (V-cutters and other mechanical harvesters also have been used in the past). The reaped cane is consolidated into large windrows in the field, and loaded into truck-trailers using hydraulic cranes. The sugarcane truck-trailers typically carry loads of 20-50 tonnes (about 20-50 tons) of cane to the sugar mill. There has been considerable debate over whether sugarcane grown for energy (ethanol or other biofuels) purposes might be better harvested on a one-year rotation, unburned, using billet harvesters. Their use in Hawaii probably would require selection of new sugar cane varieties that are better suited to the shorter rotation. Energy cane, i.e., sugarcane varieties that have been selected for fiber rather than sugar production, is also a bioenergy crop option.

Most sugarcane producers have owned and maintained large networks of private agricultural roads including a broad, paved, cane-haul system that interconnects all fields with the sugar mill. This road network provides adequate infrastructure to transport harvested sugarcane from the field to any processing facility.

Technology Gaps

Because sugarcane has been produce commercially in Hawaii for nearly two centuries, there are no major technology gaps in the production, harvesting, and delivery of sugarcane, though refinements potentially could increase yields and reduce costs incrementally. Whether sugarcane produced in Hawaii should be grown under a one- or two-year cycle and whether sugarcane grown for energy purposes should or should not be burned prior to harvesting, continue to be debated. Decisions on such questions would impact agronomic, harvesting and transporting practices as well as the breeding and selection of commercial sugarcane varieties.

3.2.2 Banagrass

Bana or Elephant grass (*Pennisetum purpureum* Schumach) is of tropical African origin but has been introduced to all tropical areas of the world and has become naturalized throughout Southeast Asia. It typically grows as a perennial in tropical areas of South America and Asia. Banagrass is not being produced commercially in Hawaii at this time, though cultivars of banagrass have been grown in the islands for use as windbreak and on trial basis as energy and forage crops. Banagrass grows on a wide range of soil types, best in deep, well-drained friable loams with a pH of 4.5-8.2. Banagrass grows best in temperatures between 25 and 40 °C (75 and 100 °F), with little growth below about 15 °C (60 °F), and in elevations ranging from sea level to 2000 meters (6500 feet) (Cook *et al*., 2005).

Though not fully optimized for commercial production, cultivation and harvesting strategies have been developed for banagrass grown as an energy crop and ongoing research is being conducted on this species at the University of Hawaii at

Manoa. Owing to similarities between banagrass and sugarcane, production strategies often mimic those for sugarcane, with a few exceptions, as noted below.

Soil preparation would be very similar to that used in sugarcane. The planting density of banagrass seed would be considerably lower than for sugarcane, around 2 to 3 tonnes per hectare (1 to 1.5 tons per acre). Fertilizer application would be comparable to sugarcane both in rate (kg of N, P, and K applied per hectare-year) and method of application. The method and rate of application of irrigation water also would be similar to sugarcane. Banagrass is listed as an invasive species in the Pacific Islands and in Florida; though it can be controlled by regular cutting or by applying herbicide.

It is anticipated that banagrass would be harvested, nominally, at eight months of age, though trials being performed by the University of Hawaii at Manoa are investigating much shorter rotation cycles. The harvesting schedule would have to be adjusted to avoid flowering (terminal growth of banagrass and sugarcane ceases once flowering occurs), which takes place during the winter and early spring in stands exceeding four months of age. Two types of systems for harvesting and transporting banagrass have been tested in Hawaii: (1) sugarcane billet harvesting systems and (2) forage harvesting systems. The billet harvesting system had been tried on a fairly large scale, approaching 400 hectares (1000 acres), at the former Waialua Sugar Company on Oahu, more than a decade ago. Both billet sugarcane harvesters and forage harvesters are commercial but their application to Hawaii conditions would require additional evaluation to determine the best set of technology options to serve both crop production (adaptability to terrain, field efficiency, harvesting throughput, etc.) and conversion facility (feedstock particle size, moisture content, etc.) requirements. It is anticipated that banagrass would be ratooned multiple times before being replanted.

Technology Gaps

Most of the practices presently being used for growing and harvesting banagrass have been extrapolated from sugarcane production and have not been optimized for banagrass. Major technology gaps for banagrass include breeding and selecting superior cultivars, establishing crop management practices specifically tailored to banagrass, and developing better harvesting and transporting systems.

3.2.3 Eucalyptus

(This section on Eucalyptus was taken largely from Friday (2006).)

Eucalyptus trees, originally from Australia, were brought to Hawaii as a prospect for commercial timber production after the 1960s. Various species have been introduced into the state and can be found on at least six of the major inhabited islands. Eucalypts generally prefer temperate to tropical regions with sufficient rainfall that is distributed throughout much the year. There are possibly 600 species of *Eucalyptus* worldwide; more than 90 (not including ornamental species) have been planted in Hawaii. The most commonly planted species in Hawaii are *E. botryoides, E. camaldulensis, E. citriodora, E. deglupta, E.*

globulus, E. grandis, E. microcorys, E. paniculata, E. pilularis, E. resinifera, E. robusta, E. saligna, and *E. sideroxylon.*

The most productive species grow best in areas of moderate to high rainfall (>110 cm [>45 inches]). Other species grow well on lands having as little as 50 cm (20 inches) rainfall. Eucalyptus typically is not irrigated; species are usually selected to match rainfall at the particular location. Eucalypts tolerate acid soils. Some species are adapted to warm temperate regions and in Hawaii grow at elevations up to 2000 meters (7000 feet). Above this, moisture becomes severely limiting. The most productive sites in Hawaii are below 1000 meters (3000 feet) elevation.

If trees are planted on abandoned canelands, heavy rollers would be used to cut and crush cane and other vegetation. If the area is covered with very heavy vegetation or brush, a tractor equipped with a bulldozer blade could be used. The blade is held above the ground to knock down heavy brush so that a harrow or roller can crush the material. On some lands, a tractor equipped with wide-gauge shoes would be used to pull a heavy-duty, off-set cutaway harrow. After clearing, herbicide spray could be applied if the vegetation returns before planting. Tree seedlings are planted about two weeks after herbicide spraying.

Young trees do not compete well with weeds, especially in fertile soils. The critical period of development is two to three months after planting, when regrowth of a previous crop or weeds compete with the tree seedlings. Weeds should be kept under control with one application of herbicide prior to planting and two or three applications following planting. Post-planting weed control is performed with manual backpack sprayers or using tractor-mounted sprayers. At the early stage, trees are sensitive to herbicide so care should be taken to avoid contact between the herbicide and the young plants.

Tests have shown that *Eucalyptus* responds well to fertilization, particularly to nitrogen. *Eucalyptus* grown on oxisols has shown phosphorus deficiency. Intercropping *Eucalyptus* with the nitrogen-fixing legume *Falcataria moluccana* (common name albizia) greatly improved growth and production of the *Eucalyptus* over chemically fertilized trees on the Hamakua coast.

Optimal harvesting age varies with species and environments, but normally is around seven or eight years. The harvesting operation for trees would be fully mechanized using commercially available equipment. A feller buncher unit, capable of cutting 0.35 m (1 foot) diameter stems, could be used to harvest standing trees. In this system, stems are sheared at the base using hydraulic shears located at the base of the feller buncher. Clean shearing would be required to minimize stump damage for good coppice regrowth. Most production scenarios, however, favor replanting over coppicing. Following tree felling, skidder/forwarders would collect the felled trees and transport them as logs, to hauling units or to centralized in-field locations where the trees would be chipped.

In-field chipping units would chip the whole trees and discharge the chips into wood chip vans.

Technology Gaps
As noted above, a large number of Eucalyptus species have been planted in Hawaii; while there is opportunity for yield improvement through better selection of species for particular environments, the increases probably will not be dramatic. The most significant technology gap associated with Eucalyptus involves selecting appropriate harvesting and transporting systems that are well suited to Hawaii's challenging terrain and other conditions.

3.2.4 Leucaena

(Much of this section on *Leucaena* was taken from Brewbaker (1980).)
Leucaena leucocephala is a nitrogen-fixing tree or shrub, originating in Mexico and Central America. It was introduced to Hawaii as fodder. "Giant" *Leucaena* is a tree form that shares many of the traits of the more common forms of *L. leucocephala*, but does not seed and has larger stems. *Leucaena* is a drought tolerant species and is usually found in lower elevations in locations having lower rainfall. *Leucaena* grows well in neutral or slightly acid soils, and does poorly in very acid soils. With proper management, the giant *Leucaena* tree grows at a rapid pace from transplanting to mature height, growing roughly one meter (3 feet) per month during the first five months, and >15 meters (50 feet) height and 10 cm (4 inches) diameter in six years. The University of Hawaii at Manoa continues to perform research on this crop.

Nitrogen, Potassium and, possibly, Phosphorus, would be required at planting, but only K and possibly, P, would be required after planting, as *Leucaena* is nitrogen fixing. The response of *Leucaena* to P is not very well known.

Giant *Leucaena* can be established directly from sown seeds or from transplanted seedlings grown to age, 3 to 4 months. Most likely, as an energy crop, this plant species would be grown from transplants. It is anticipated that ~10,000 trees per hectare (~4000 trees per acre) would be optimal for an energy plantation.

When cut down, the tree can produce a cluster of branches to 10 meters (30 feet) in length within one year; however, if planted in a dense stand and harvested regularly, it can be maintained for decades as a low shrub.

Brewbaker (1980) considered five alternative harvesting and transporting systems for giant *Leucaena*. The swathe-felling mobile chipper was proposed as the best methods for harvesting *L. leucocephala* in Hawaii because it is capable of felling trees and chipping them directly in the field with minimal manpower. Other mechanized harvesters like feller bunchers, grapple skidders and roadside chippers require more skilled operators and are better suited to larger trees planted at lower densities.

Technology Gaps

Technology gaps in *Leucaena* production are similar to Eucalyptus; however, because *Leucaena* has not been produced in large quantities in Hawaii, in addition to selecting appropriate harvesting and transporting systems, additional research would be needed to optimize crop management practices.

3.2.5 Jatropha

(Much of this section on *Jatropha* was taken from Duarte and Paull (2006).)
Jatropha curcas L. (Euphorbiaceae) most likely originated in the Mexican - Central American region. It is known in English as Barbados nut, castor oil, Chinese castor oil, curcas, fig nut, physic nut, pig nut, purging nut, and wild oil nut. It has been spread world-wide as a medicinal plant into tropical regions. The plant readily establishes itself and is regarded as an invasive weed in a number of countries. This perennial monoecious species is a shrub or small tree (6 m [20 feet]) with spreading branches.

Jatropha nuts are high in protein and fat; however, they contain an albumin poison, toxalbumen cursin, and a toxin, curcasin, which makes eating them potentially fatal. There has been much interest in non-toxic varieties of *Jatropha* that, potentially, could provide byproducts, such as animal feed, which could make the economics of *Jatropha* production and conversion into biofuels more attractive. The literature reports the availability of such edible (non-toxic) varieties of *J. curcas* (e.g., see Makkar, 2009).

The succulent species can be found in locations ranging from dry tropic to moist subtropical to wet tropical forests. It grows best in temperatures ranging from 20 to 28 °C (70 to 80 °F), and can be found from sea level to 1500 m (5000 feet) elevation. Its adaptability to drier tropical climates and poorer soils makes this oil bearing species an attractive energy crop for application to marginal agricultural lands in Hawaii. Crop research is presently being conducted on this crop by the University of Hawaii at Manoa and by the Hawaii Agriculture Research Center.

The tree can be propagated from cuttings and seeds. The cuttings root readily. Seeds germinate in about 10 days. The best time to start in the field is at the beginning of the rainy season. The young plant is sensitive to weed competition during establishment, although, normally, tillage is not needed (only the area around the plants needs to be cleaned). Planting densities of 2 x 2 m (6 x 6 feet), 2.5 x 2.5 m (8 x 8 feet), and 3 x 3 m (10 x 10 feet) have been recommended. The plant should be hedged and pruned to maintain its shape and has a productive life of 40 to 50 years. As a hedge, the planting distances should range from 15 to 25 cm (6 to 10 inches).

The *Jatropha* plant produces a fruit measuring about 3 cm (1.25 inches) in diameter that contains an oil bearing kernel. In developing countries, the fruit is harvested by hand, but mechanical harvesting would be required in any commercial operation in Hawaii. At present, *Jatropha*'s flowering is not synchronized and this results in fruit at various stages of maturity being present on the plant at any given time. Methods to address asynchronous flowering could include plant breeding, cultural practices, or selective harvesting. The latter would require development of harvesting equipment that removes only ripe fruit and does not disturb immature fruit and flowers. Given that the oil bearing kernel is only a small fraction of the mature fruit weight, the harvesting equipment might also remove the kernel and return the fruit pulp to the field surface as mulch. Use of the fruit pulp as a byproduct could justify whole fruit harvesting. Modified mechanical harvesting equipment for blueberries and olives have been proposed for *Jatropha* harvesting, however, to date, no performance test data have been published.

Technology Gaps

Jatropha presently is in the R&D stage of development in Hawaii. Superior varieties need to be identified and sound management practices have yet to be developed for that crop. The availability of non-toxic varieties of *Jatropha* could improve the economics of biofuel production by providing a seed meal that is rich in protein, which could be used to generate an animal feed byproduct. Mechanical harvesting systems need to be developed.

3.2.6 Oil Palm

The African oil palm, *Elaeis guineensis*, is an economically important crop for many developing countries in the humid tropics. It is the highest yielding and highly profitable oil crop and is relatively easy to grown by large plantations and small farmers alike (Soh *et al*., 2008). The oil palm originated in West Africa but has since been planted successfully in tropical regions within 20 degrees of the equator. Malaysia and Indonesia, combined, produce roughly 80% of the world’s output of palm oil; however, that species is an important export oil crop for a number of countries (Rieger, 2009).

Oil palm grows best in hot, wet tropical lowlands that receive at least 180 cm (70 inches) of rain or mechanical irrigation per year, evenly distributed throughout the year. Temperatures below 24 °C (75 °F) depress growth. Though some varieties of oil palm are being evaluated in Hawaii by the University of Hawaii at Hilo and others, presently no varieties of oil palm have been reported as being superior in Hawaii’s subtropical environments.

Oil palm is propagated by seed. Commercial seeds, produced typically by companies that specialize in palm breeding, are mixtures of hybrids derived from parents that are non-true inbreds. Consequently, considerable genetic variability exists among commercial palms.

Typical commercial plant density is ~140 trees per hectare (~60 trees per acre), in triangular grids, ~10 meters (~30 feet) apart (Rieger, 2009). During the first three years, little or no fruit is obtained and plantations are often intercropped with other crops.

Oil palm flowers are produced in dense clusters and are primarily insect pollinated. Oil palm trees grow to 20-25 meters (60-80 feet) tall, though rarely approach 10 meters (30 feet) in commercial production owing to harvesting limitations, bearing fruits in bunches. The fruit takes five to six months to mature from pollination to maturity. Fruit bunches can weigh 10 to 40 kilograms (20 to 90 pounds). Each fruit contains a single seed (the palm kernel) surrounded by a soft oily pulp. Oil is extracted from both the pulp of the fruit and the kernel.

There are no commercial, mechanical harvesters for oil palm. Oil palm fruit bunches are hand harvested in countries where oil palm is grown commercially. Trees must be visited every 10-15 days, as bunches ripen throughout the year. Harvesting has been semi-mechanized with power cutters and cherry-picker type lifts, but not fully mechanized. Palm fronds and kernel meal are processed for use as livestock feed.

Technology Gaps

There are major technology gaps with oil palm. No commercial varieties of oil palm are known to be well suited for Hawaii's subtropical environment. Irrigation water requirements for oil palm are very high, which could pose a significant strain on Hawaii's water resources. Mechanical systems that are capable of harvesting oil palm fruit bunches need to be developed.

4.0 BIOMASS CONVERSION TECHNOLOGY

4.1 Overview - Issues and Enabling Technology Needs

4.1.1 Fermentation based ethanol production

Ethanol can be produced by the fermentation of sugars by yeast. Sugar based ethanol production is established technology and has been practiced for thousands of years to make beer, wine, and other spirits. At industrial scales, sugars are derived directly from sugar bearing plants (e.g., sugarcane) or indirectly from plant starches (e.g., corn). The cellulose and hemicellulose components of plant fiber can also be processed to provide a source of sugar for fermentation. This latter technology is currently at the pilot plant stage of development. In the U.S. outside of the beverage industry, ethanol is most commonly produced by fermenting milled corn using either wet or dry methods (Anon, 2002; Shleser, 1994).

In the dry milling method, dry corn kernels are ground into a meal, which is mixed with enzymes and water and cooked to liquefy the mixture into a "mash." A second set of enzymes is added to convert starches in the mash to dextrose in a process called saccharification. Yeast then is added to ferment the sugars into ethanol over a 48-50 hour period. The fermented mash, known as "beer," is distilled to extract ethanol at about 96% purity. Additional dehydration results in pure ethanol.

The wet milling method adds a soaking step before grinding, enabling the mechanical separation of corn kernels into individual components. The separate components then can be used to produce a wider variety of higher valued products than the dry milling process. The wet milling process normally requires greater capital outlay and is more costly than the dry milling process. The theoretical yield of ethanol is 124 gallons per ton of corn grain. Typical yields are ~95 gallons ethanol per ton corn.

Production of ethanol from sugarcane or other sugar bearing plants involves extracting the sugars and fermenting them directly. Sugarcane processing facilities can be designed to split the extracted juices between sugar and ethanol production. Molasses contains sugars that are economically unrecoverable in the manufacture of raw sugar and is sold as a byproduct by Hawaii's producers, some of it locally as a cattle feed supplement. The sugars present in molasses can be fermented to produce ethanol and this is the basis for rum production. A yield of ~150 gallons of ethanol per ton of fermentable sugars can be expected from these sources and this translates to ~70 gallons per ton of molasses.

Ethanol from biomass fiber via fermentation pathways has seen continued development. Fiber is composed of cellulose, hemicellulose, and lignin. The first two components are polysaccharides that can be broken down or hydrolyzed into simple sugars such as glucose that can subsequently be fermented into ethanol. Hydrolysis can be accomplished using dilute acid solutions, enzymes, or a staged combination of the two. Pretreatment of fiber to make the chemical linkages between the substituent sugars more amenable to hydrolysis is the focus of ongoing research. Ethanol from fiber is widely viewed as the process that will ultimately provide plentiful supplies of fuel but has yet to be realized at a commercial scale.

4.1.2 Pyrolysis

Pyrolysis, is a process in which biomass is heated rapidly to ~600 °C in the absence of oxygen. The biomass feedstock decomposes and when the products are brought to ambient conditions, the result is a mixture of solid char, permanent gases, and liquid phase. Pyrolysis processes are designed to maximize the production of the liquid called bio-oil or pyrolysis oil. The yield of bio-oil from wood and paper range from 60 to 80% (weight) and 75 to 93% (weight), respectively, correlating with cellulose content of the biomass material. Char and permanent gases account for 4 to 30% and 2 to 20%, respectively, of the initial feedstock mass. The composition of bio-oil is approximately 20-25% water, 25-30% water insoluble pyrolytic lignin, 5-12% organic acids, 5-10% non-polar hydrocarbons, 5-10% anhydrosugars, and 10-25% other oxygenated compounds (Anon, 2001; Oasmaa and Peacocke, 2001; Oasmaa *et al*., 1997). Bio-oil has a heating value of ~7,500 BTU per lb, similar to that of most solid biomass fuels at 10 to 12% moisture. As a liquid fuel, bio-oil has an energy density of ~75,500 BTU per gallon, about 55% of the value for fuel oil. A summary of bio-oil characteristics for Ensyn's RPT^{TM} Process is provided in Table 1 for a variety of feedstocks.

Commercial pyrolysis units are available from two Canadian companies, Ensyn Corporation of Ottawa and DynaMotive Energy Systems Corporation of Vancouver. Pyrolysis oils have commercial markets, mainly as liquid smoke that is applied to meat products. Red Arrow International LLC of Manitowoc, Wisconsin, is perhaps the best-known company marketing this product. Bio-oil may also be used as a chemical intermediate that can be fractionated into its chemical constituents and sold to chemical markets, although this is not currently practiced commercially. Energy products show potential but have seen limited implementation at commercial scales (Freel and Graham, 2000). Red Arrow uses bio-oil to satisfy 6 MW_{th} of industrial energy demand at their manufacturing facility. Bio-oil has also been co-fired with coal in a grate-fired, utility boiler in Wisconsin near Red Arrow's manufacturing facility. Minor modifications were performed on the boiler to allow injection of steam-atomized bio-oil in the over-fire area above the grate. The bio-oil accounted for 5% of the total fuel energy input and emission and performance evaluations concluded that there were no noticeable changes compared to coal.

Table 1. Typical Bio-oil Yield and Quality from Ensyn RTP ™ Process

Feedstock	Wood	Bark	Bagasse	Corn Fiber	Mixed Paper
Typical Product Yields[1] (weight %)					
Bio-Oil	71-80	60-67	75-81	71-76	71-93
Char	12-20	16-28	12-14	7-14	4-20
Gas	5-12	8-17	5-10	10-17	2-12
Bio-Oil Higher Heating Value					
BTU per lb	6,800-8,400	7,780-8,900	7,670-8,350	7,100-8,250	6,700-8,000
BTU per gal	75,500	81,500	79,500	73,500	74,000

[1] Yields are on an ash-free basis

With additional processing bio-oil can be used in combustion turbines. In boilers, bio-oil does not provide energy advantages over firing biomass directly, as any gain in efficiency is more than offset by the energy expended to produce the bio-oil. The potential advantage of bio-oil in steam boiler applications is that it generally has a greater energy density (BTU per ft^3) than the parent biomass material that can be useful if it is necessary to transport fuel from point of production to point of use. There are clear advantages for using bio-oil in combustion turbines and other power generation systems that have higher conversion efficiency than steam-based units and cannot use biomass directly. The use of bio-oil in higher efficiency units will need to address technical challenges. The composition and fuel properties of bio-oil differ considerably from commonly used petroleum-based fuels for which most conversion technologies were developed. Depending on the feedstock and the type of fast pyrolysis method employed, bio-oil composition may also vary significantly. These differences should be taken into consideration in the selection of bio-oil-fired power generation units (Anon, 2001; Anon, 2001a).

Bio-oil may also be upgraded to produce clean transportation fuels using unit operations typically found in an oil refinery. This pathway for bioenergy development could potentially take advantage of existing refinery conversion infrastructure and the products would be compatible with distribution equipment. Hydro-processing would remove oxygen from the bio-oils compounds using high pressure hydrogen in the presence of catalyst to produce hydrocarbon compounds (Huber, 2007).

4.1.3 Gasification

Gasification is the partial oxidation of a solid fuel to form a combustible gas. Generally, the goal of a gasification process is to simultaneously maximize the solid fuel carbon conversion and the heating value of the product gas. Air and steam are commonly used oxidizers when electricity is the desired end product. Oxygen can also be used but the additional expense required to produce a concentrated oxygen stream for the process limits this option to applications where the product gas is to be used to synthesize higher-valued chemical compounds such as methanol.

The composition of biomass varies depending on the species and local growing and harvesting conditions. Nonetheless, on a dry mass basis, biomass typically contains about 48% carbon, 6% hydrogen, and 42% oxygen with the remainder composed of inorganic elements. The fraction of each component varies depending on the type of biomass. Wood for example typically has very little (~0.5%) inorganic material whereas grass species may have ~5%. When subjected to proximate analysis, biomass typically contains ~80% volatile matter and 15% fixed carbon. The volatile matter is classified as the amount of fuel mass which is driven off as a gas when a sample is heated in an inert environment. Complete oxidation using air to produce carbon dioxide and water follows the reaction;

$$\overbrace{CH_{1.5}O_{0.7}}^{\text{Bagasse}} + 1.025\overbrace{\left(O_2 + 3.7N_2\right)}^{\text{Air}} \longrightarrow CO_2 + 0.75H_2O + 3.79N_2$$

This reaction defines a stoichiometric air-fuel ratio of ~5.6 (mass basis) for bagasse combustion, neglecting the mass of ash in the fuel. Boilers are often operated with rates of excess air from 30% to 100% of stoichiometric, (air-fuel ratios of 7.3 to 11.3 (mass basis)), to ensure complete combustion and control temperature. Air blown gasifiers typically operate at about 30% of stoichiometric air (air-fuel ratio of 1.7 (mass basis)) and produce gas composed of CO_2, CO, H_2, H_2O, CH_4, N_2, and higher hydrocarbon compounds. The mixture of these components will vary depending on the gasifier technology employed. Air blown gasifiers are directly heated in that some portion of the fuel reacts with the oxygen and provides the heat required to volatilize or gasify the remainder. Steam may also be fed to an air-blown gasifier to moderate temperatures near the air injection point and to improve carbon conversion and gas quality by increasing the rate of the reaction:

$$C_{\text{solid}} + H_2O_{\text{steam}} \longrightarrow CO + H_2$$

Product gas from air blown gasifiers has a higher heating value in the range of 100 to 135 BTU per ft^3 [1]. A typical gas composition is shown in Table 2. A typical dry gas yield for an air-blown gasification system is ~32 dry ft^3 per lb of dry fuel. Note that this includes the nitrogen input from the fluidizing air.

Most of the development efforts currently under way that seek to match biomass gasifiers to combustion turbines have selected bubbling or circulating fluidized bed technologies for the gasification reactor. Schematics of these two types are shown in Figure 5. Fluidized beds contain fine, inert particles of sand or alumina that have been selected for size, density and thermal characteristics. As gas is forced through the bed from below with increasing velocity, a point is reached when the frictional force between particle and gas counterbalances the weight of the particle. This is the point of minimum fluidization, and increases in gas flow rate beyond this point result in bubbling and channeling of the fluid through the bed media. Bubbling fluidized beds are operated in this regime.

Table 2. Typical Gas Composition from Pressurized Air Blown Biomass Gasifier

Gas Component	Air Blown	Steam Blown
H_2	9	22.2
CO	14.1	43.2
CH_4	9	15.8
CO_2	19.2	13.5
N_2	47.4	
Higher Hydrocarbons	1.3	5.5

As shown in Figure 5 (a), the bubbling fluidized bed reactor design includes a larger diameter section at the top, called the disengagement zone, which reduces the flow velocity allowing unreacted fuel and bed particles to return to the lower section of the reactor. Continued increases in gas flowrate beyond minimum fluidization velocity reach a point where the terminal velocity of char and bed particles is exceeded and particles become entrained in the gas flow. Circulating fluidized beds are operated in this manner and particles exiting from the top of the reactor are separated from the gas flow in a cyclone and returned to the bed. In both types of fluidized beds, the inert particles are initially heated at start-up and then serve as an ignition source and thermal energy carrier at steady state conditions. Table 3 provides a comparison of bubbling and circulating fluidized bed characteristics.

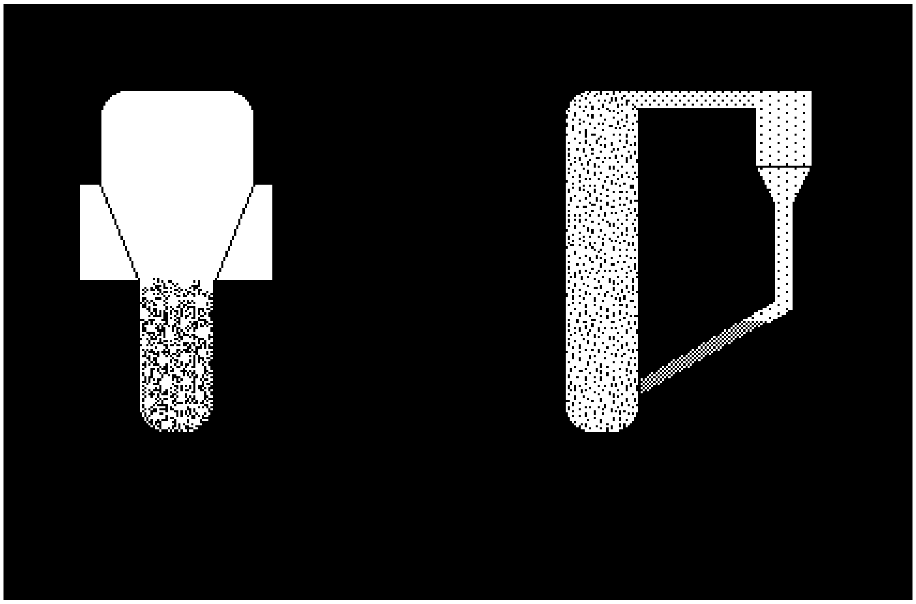

Figure 5: Schematics of Bubbling (a) and Circulating (b) Fluidized Bed Gasifiers

Table 3. Comparison of Circulating and Bubbling Fluidized Beds [2]

	Circulating Fluidized Bed	Bubbling Fluidized Bed
Gas Solid Reaction	Suitable for rapid reactions. Recirculation of small particles is crucial.	Yields a uniform product gas. Large bubble size may result in gas bypass through bed.
In-Bed Temperature Distribution	Temperature gradients in direction of solid flow; may be minimized by sufficient circulation of solids.	Exhibits a nearly uniform temperature distribution throughout the reactor.
Particles	Size of fuel particles determined by minimum transport velocity. High velocities may result in equipment erosion.	Ability to accept a wide range of fuel particle sizes including fines.
Heat Exchange and Transport	Heat exchange less efficient than bubbling fluidized bed, but high heat transport rates possible due to high heat capacity of bed material.	Provides high rates of heat transfer between inert material, fuel, and gas.
Conversion	High conversion possible.	High conversion possible.

Indirectly heated fluidized bed gasifier technology has also been developed. One variant of this is shown in Figure 6. Fuel is fed to a circulating fluidized bed gasifier containing hot bed material that uses low pressure steam as the fluidizing agent. Without oxygen present, the fuel is pyrolyzed and the volatiles react with steam producing a combustible gas. Pyrolysis is the thermal decomposition of fuel to form a mixture of gases when heated in the general temperature range from 200 to 600 °C. With no oxygen present and limited amounts of heat, carbon conversion from solid to gas is incomplete, resulting in a mixture of char and bed material being entrained from the gasifier. This mixture of solids is separated from the product gas in a cyclone and directed to a second circulating fluidized bed that is blown with air and operated as a combustor, yielding a stream of flue gas and hot bed material. A second cyclone disengages the hot solids and they are returned to the gasifier to provide the heat required for fuel pyrolysis and reactions between fuel volatiles and steam. This system effectively decouples the gasification reactions from the combustion reactions, yielding product gas with a small amount of nitrogen compared to an air blown gasifier and a heating value of ~400 BTU/ft^3. Typical gas composition for an indirectly heated gasifier is shown in Table 1 and dry gas yields for this process are ~12 ft^3 of dry gas per lb of dry biomass (Bain *et al.*, 1997).

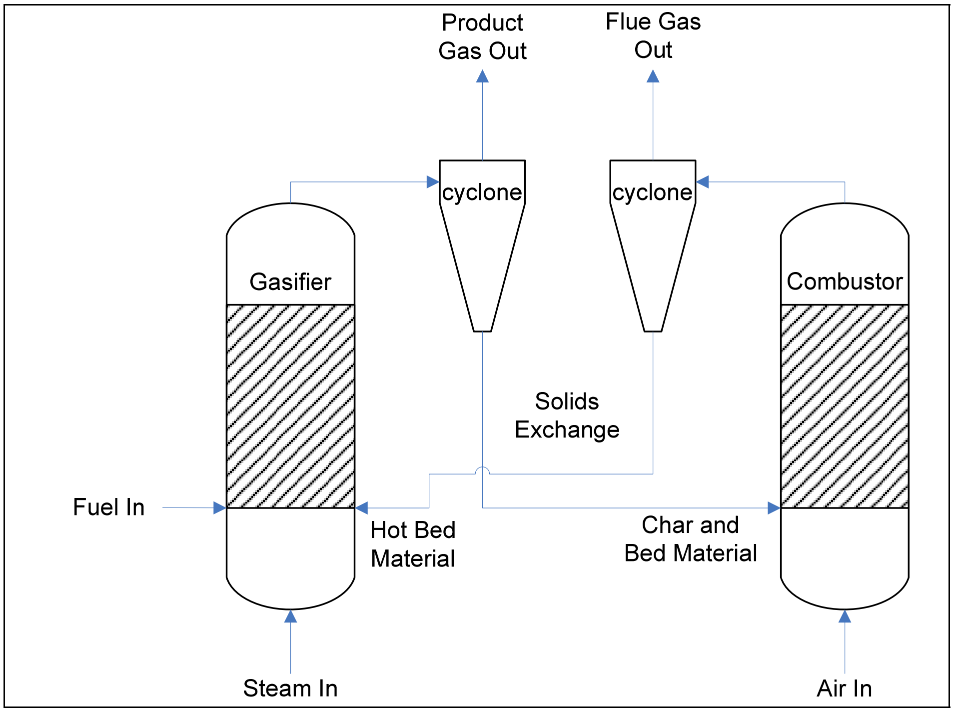

Figure 6: Schematic of Indirectly Heated Fluidized Bed Gasifier

4.1.3.1 Gasification for Power Generation

In a biomass integrated gasifier, combined cycle (BIGCC) application, the product gas would be fired in a combustion turbine to generate electricity in a topping cycle. The hot exhaust products are directed through a heat recovery steam generator (HRSG) and steam raised in this manner is used in a steam turbine to generate additional electricity in a bottoming cycle and to satisfy motive and thermal requirements at the installation. The use of a gas turbine requires the fuel gas and combustion air stream to be pressurized, typically to a minimum of 300 psi, depending on the design of the machine. Two configurations have been developed for meeting these requirements while integrating the gasifier with the power block. The first involves pressurizing the gasifier, maintaining pressure through gas conditioning equipment, and feeding the conditioned product stream to the combustor of the gas turbine. The second approach is to operate the gasifier and gas conditioning equipment at nominally atmospheric pressure, then compress the product gas to satisfy turbine requirements. The former approach is shown schematically in Figure 7. To date, no known BIGCC units are operating commercially.

Smaller scale biomass gasification power projects (5 kW to 5 MW) using reciprocating engines are under commercial development in the U.S., India, and Europe.

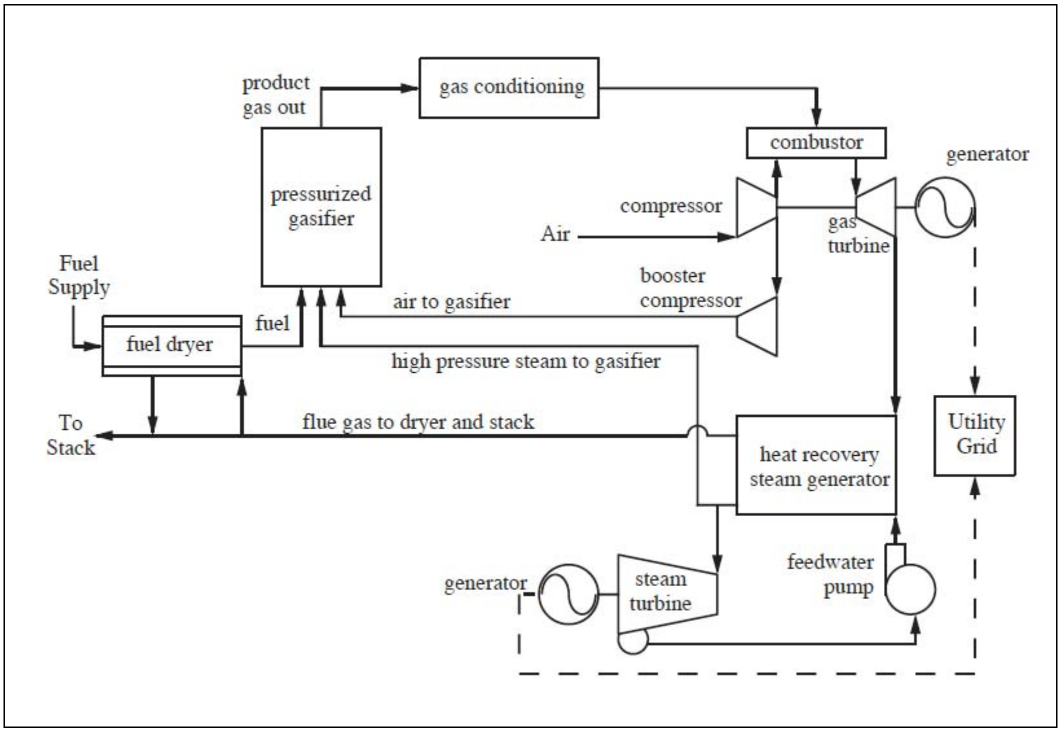

Figure 7: Schematic of Pressurized Biomass Integrated Gasifier Combined Cycle Power System

4.1.3.2 Gasification for Synthesis of Fuels and Chemicals

A variety of fuels and chemicals can be synthesized from gas rich in hydrogen and carbon monoxide commonly called syngas. Syngas containing a prescribed ratio of these two building block molecules is passed over a catalyst at specified conditions of temperature and pressure to synthesize target compounds. The basic concept of a catalyst reaction is that (1) the reactants (H_2 and CO) adsorb on the catalyst surface, (2) the reactants are rearranged in the adsorbed state to produce the desire product, and (3) the product is desorbed from the catalyst surface. Note that the catalyst is not consumed in the reaction. Hydrogen is also produced from the purification of syngas. The most common energy resource used for syngas production is natural gas (primarily methane) but it can be produced from any hydrocarbon material or biomass. A recent report by the National Renewable Energy Laboratory reviewed possible fuel and chemical products that might be produced from biomass via gasification and included hydrogen, Fischer Tropsch liquids, ammonia, methanol, dimethyl ether (DME), acetic acid, formaldehyde, methyl tert-butyl ether (MTBE), ethanol, and mixed higher alcohols. Their review concluded that the best product to pursue were hydrogen and methanol and that ethanol from syngas could potentially be cost competitive but needed to be demonstrated at larger scales.

Most of the hydrogen produced in Hawaii is generated from crude oil in the refining process. Current hydrogen use in Hawaii is mainly limited to use in the refineries, as a coolant in large turbo generators, and in small volume, specialty chemical applications. Hydrogen does not represent a large, near-term market that could be entered from production via biomass.

Ethanol, methanol, and dimethyl ether (a methanol derivative) all have potential for entry into local transportation, power generation, or fuel gas markets. Ethanol has immediate local markets as a transportation fuel in the state-mandated E10 gasoline blend, provided it can be produced and sold at a price that is competitive with imported ethanol. Methanol is a commodity chemical, one of the top 10 chemicals produced globally. It can be used directly as a fuel in spark ignited engines or blended with gasoline. Methanol has been used in the past as a ground transportation fuel in several demonstration programs, e.g., in California and in Hawaii, but is not widely used commercially as a primary fuel today because of its higher cost (relative to gasoline), toxicity, and corrosiveness. Methanol is more corrosive than most other fuels, thus requires special storage and delivery equipment. Methanol will dissolve many of the gasketing and fuel-delivery materials used in gasoline engines (Owen and Coley, 1995). DME can be derived from methanol. It is primarily used as an intermediate in the chemical industry and as a propellant for aerosol cans. DME is a liquid at modest pressures and can be used as a cooking fuel, thereby having potential as a locally-produced biofuel replacement for LPG. DME also has potential as a diesel fuel substitute, having a cetane number comparable to diesel fuel. Use in diesel engines would require modification to the fuel delivery system.

4.1.4 Direct Combustion of Biomass

Direct combustion of biomass for power generation has a long history in Hawaii. Sugar companies have used bagasse as fuel to generate steam for mechanical, thermal, and electrical power. At present, no power plant in the state is operated using a dedicated fuel supply system, i.e., biomass grown only for fuel production. Conventional biomass power generation units combust the fuel in a water wall boiler, raising steam that is used in a turbogenerator to produce electricity. Units are necessarily limited in size by the supply of fuel that can be economically delivered to the plant with transportation costs serving as a major factor. Biomass power plants developed in the 1980's in California using urban wood waste and agricultural residues were typically sized at 25 MW. Larger facilities (~50 MW) exist such as the McNeill Generating Station in Burlington, Vermont, fueled with waste wood from the forest industries and Okeelanta Power in South Bay, Florida, fueled with bagasse and waste wood. Hawaiian Commercial & Sugar (HC&S) on Maui typically produces 29 MW of electricity to satisfy internal demand and exports ~10 MW to Maui Electric Co. In addition to the bagasse produced from sugar milling, HC&S uses coal as a supplemental fuel for periods when the mill is not operating or is at reduced processing capacity (Jakeway, 2006).

Direct combustion, steam-based, biomass power plants are a mature technology. Modern units include grate fired and fluidized bed units. The later boiler units installed at sugar mills in Hawaii were grate fired units operating at pressures of

450 to 900 psi. Many of the biomass power plants installed in California in the last 25 years were fluidized bed combustors selected for their tolerance of a wide range of fuels.

4.1.5 Biodiesel Production

Biodiesel can be produced from vegetable oils, animal fats, or recycled restaurant grease. Converting cooking oil and restaurant grease to biodiesel eliminates the need to dispose of these wastes, and creates a commercial product that reduces air emissions and decreases the nation's dependence on imported fossil fuels (Sheehan *et al.*, 1998; Mittelbach, 1996; Anon, 2003b; Tyson, 2001).

Biodiesel has properties similar to those of petroleum-based diesel fuel with several notable exceptions. Biodiesel is virtually free of sulfur, ring molecules, and aromatics often associated with its fossil counterpart (Sheehan *et al.*, 1998; Mittelbach, 1996). Biodiesel also has slightly lower energy density than petroleum diesel.

Biodiesel is composed of fatty acid methyl esters, derived from medium length (C16-C18) fatty acid chains. Biodiesel is produced by esterification of these fatty acids, which are found in vegetable and animal fats. Oil reacts with ethanol or methanol and a lye catalyst in a process called transesterification, to produce biodiesel (Sheehan *et al.*, 1998; Tyson, 2001). The major byproduct of the transesterification process is glycerin, which is separated from the biodiesel fuel. Glycerin that is not removed in the separation step can cause problems with filter plugging, injector deposition, and cold weather operation, and can build-up in storage and fueling systems. Maximum levels of both free glycerin and total glycerin are stipulated in ASTM standard D6751, Standard Specification for Biodiesel Fuel (B100) Blend Stock for Distillate Fuels.

Use of biodiesel and biodiesel blends is becoming increasingly common, especially in government vehicles, bus fleets, and commercial fleets. To a large extent, this increase has been in response to the EPA Act of 1992, which required fleets to purchase alternative fuel vehicles (AFV). In 1998, the act was amended to allow fleet operators to meet one-half of the AFV requirement by using fuel blends that contain at least 20% biodiesel. Fleet operators obtain one fuel credit for every 450 gallons of neat biodiesel purchased. Each fuel credit counts as one AFV purchased (Tyson, 2001; Anon, 1992).

Biodiesel use has also increased as a result of growing public awareness and greater availability of the fuel. Biodiesel should become increasingly competitive as petroleum supplies dwindle and the technology for producing biodiesel improves. Although generally more expensive, the price of biodiesel has, at times, approached that of petroleum diesel.

Biodiesel, its use, and effect on diesel engines have been researched extensively, though mainly for transportation applications. Most studies report that biodiesel performs comparably to diesel fuel. Operators report no noticeable changes in vehicle performance. Tests have also shown that replacing diesel fuel with biodiesel dramatically reduces particulate matter, carbon monoxide, and net carbon dioxide emissions, and eliminates sulfur emissions. On the down side, biodiesel usually is more costly, has a slightly lower energy density, and produces higher NO_x emissions than diesel fuel (Lue *et al*., 2001; Yamane and Shimamoto, 2001; Graboski *et al*., 1999).

4.2 Biofuels Technology Readiness Summary

The biofuel technologies from the preceding sections are presented in Table 4 to summarize their readiness for commercial application. Each is characterized as pilot scale, demonstration scale, or mature commercial. Pilot scale systems simulate the important parameters of a full scale unit and are used to systematically investigate operating conditions. Feedstock throughput depends on the technology employed, e.g., gasification pilot plants have typically been 5 to 10 dry ton per day units. Demonstration scale units are typically 10 times larger than pilot scale and are constructed to (1) verify the operability of the unit and its subcomponents at near commercial scale in a long duration (~1000 hour) test program(s) and (2) collect engineering and cost data that can be used in the design of commercial units. Demonstration scale tests may yield commercial product but the intent of the program is to verify/validate the technology. Mature, commercial technologies are those that have been successfully demonstrated and are offered by suppliers as turn-key units.

Table 4. Characterization of the Development Status of Biomass Conversion Technologies

	Pilot	Demonstration	Commercial	Appropriate for HI?
Ethanol from Biochemical Route				
Sugar			X	Y
Starch			X	Y
Fiber[1]	X	X		Y
Gasification				
Heat			X	Y
Power	X	X		Y
Synfuels	X	X		Y
Pyrolysis				
Bio-oil production			X	Y
Charcoal production		X	X	Y
Bio-oil production for Fuels	X			Y
Combustion			X	Y
Transesterification			X	Y

[1] Demonstration projects for cellulosic ethanol production currently underway

[2] Pyrolysis for bio-oil production as food ingredient is at commercial scale but use of bio-oil for energy other than combustion applications remains at pilot scale

All of the bioenergy technologies reviewed in this section have potential application in Hawaii but all are not expected to be commercial. The utility of the technologies will depend on completion of technology development for those that are not yet fully commercial and the availability of suitable, cost competitive, sugar, starch, fiber, and oil feedstock resources. Questions of appropriate scale for the technologies will also need to be addressed and will evolve as fossil fuel supplies dwindle and efficiency and conservation serve to reduce energy product demand. A concomitant enhanced appreciation for energy security and economic benefits derived from local production of bioenergy products can be expected to foster policy support.

4.3 Biomass Gasification Gas Analysis Project

The "Contaminants Estimates and Removal in Product Gas from Biomass Gasification" project supports the development of this key biomass conversion technology. Permanent gas species, tar compounds, sulfur compounds, and ammonia produced from a bench scale (~1kg /h) fluidized bed biomass gasifier were analyzed. Two commercial Ni-based catalysts and one commercial ZnO sorbent were evaluated under varied conditions. The Ni-catalysts targeted tar destruction and ammonia reduction and ZnO sorbent to remove sulfur compounds.

Tar components were identified by gas chromatography-mass spectrometer (GC-MS) and quantified by gas chromatography-flame ionization detector (GC-FID). Thirteen compounds ($\geq C_6$) were identified in raw product gas, principally "lighter tar" species at an average concentration of 15.5 g m^{-3} (dry basis). For tar species that were not detected by GC, a gravimetric method was used to obtain the portion of “heavy tar” present at 5.3 g m^{-3} (dry basis). These data are raw gas tar concentrations for the gasifier operating conditions used for the remainder of the tests. The performance of two commercial Ni-catalysts were evaluated by comparing the concentrations of both “light tar” and “heavy tar” after the raw gas passed through the tar reforming reactor.

Concentrations of hydrogen sulfide (H_2S), carbonyl sulfide (COS), and thiophene (C_4H_4S) in the raw, dry, product gas averaged 93, 1.7, and 2.2 ppmv, respectively. C_4H_4S and an additional two sulfur compounds, benzothiophene and one unidentified compound (UN1), were found in the tar trapping solution. Removal of sulfur compounds using ZnO sorbent at varied temperatures and gas hourly space velocity (GHSV) was investigated. The primary sulfur component, H_2S, was reduced to less than 1 ppmv, COS was not reduced significantly, and C_4H_4S concentrations were not affected at all.

Average NO and ammonia concentrations were determined to be 8.2 ppmv and 2662 ppmv in the dry gas, respectively. Both were successfully converted to permanent gas species by nickel catalysts.

5.0 GRID ENERGY STORAGE SYSTEMS

5.1 Overview - Issues and Enabling Technology Needs

Energy storage is an enabling technology for meeting Renewable Portfolio Standards (RPS), while maintaining grid stability and reliability. Hawaii's move from central-station, oil-based firm power to a system that incorporates more as-available renewable and distributed energy resources, such as PV and wind, will increase the operating risks of the electric utilities which may affect customers. Hawaii needs to assure the preservation of a stable electric grid to minimize disruption to service quality and reliability.

Electric grids have no substantial energy storage capacity so there needs to be an instantaneous balance between generated electric power and demand. Balancing is difficult because of multiple power plants and thousands of users, and has to be rebalanced every few seconds (Cole). Lack of storage capacity makes electricity delivery a "just-in-time" process. For an island grid that has no interconnections, all imbalances between customer demand and production result in frequency errors that tend to be more significant in magnitude than on mainland grids. Frequency is managed through local droop response and Automatic Generation Control (AGC). Historically, the grids in Hawaii have been operated with a minimum of regulating reserve to save costs, and the loss of generation can result in under-frequency load-shedding.

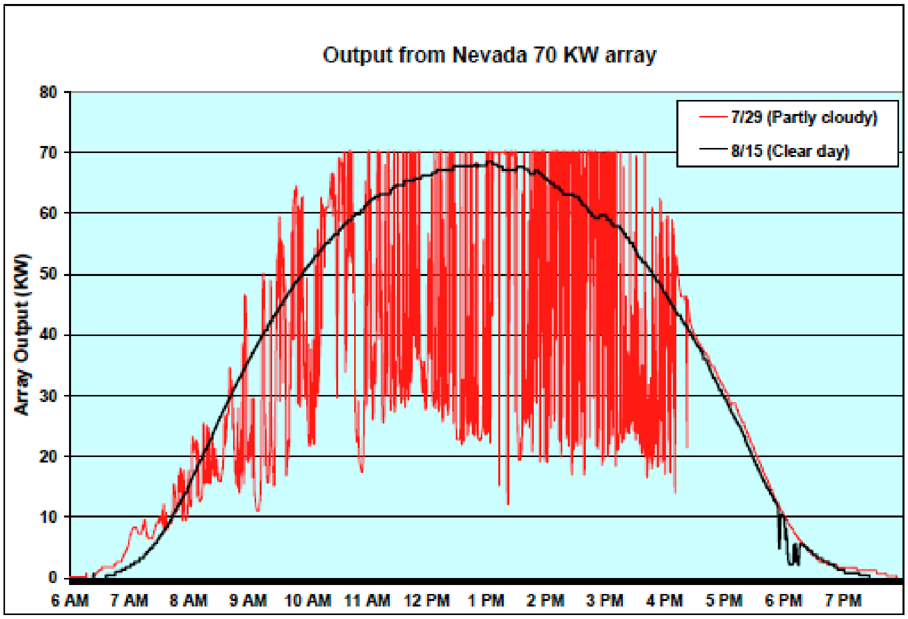

Figure 8: Illustration of PV Short-Term Variability

Figure 8 is an example of the variability of as-available renewable resources. The injection of intermittent energy into the grid from renewable energy resources such as wind and PV exacerbates grid management issues, particularly at the high penetration percentages of renewable energy as envisioned in the Hawaii Clean Energy Initiative (HCEI - 40% by 2030). RPS and greenhouse gas emission reduction goals may mean more wind and PV on the grid, increasing the need for ancillary services that can be provided by storage.

Electricity storage can help balance supply and demand so as to mitigate the impacts of undersized island electric grids (Symonds, 2001). For the purposes of current activities in Hawaii, the focus is on the augmentation of the supply and/or transport of electricity at critical times, generally in the seconds-to-minutes time frame or in the hour-ahead time frame.

A number of reports are available that discuss the attributes of various systems that are either at a demonstration phase or are in the early stages of deployment. Efforts to better incorporate energy storage into the Hawaii grids are still in their early stages as there is an on-going discussion of how to best incorporate these new energy systems to support grid stability and reliability and to provide other ancillary benefits. Two projects will be summarized in this section.

A recent study, "The Development and Evaluation of Sustainable Energy Scenarios for the Island of Hawaii," described scenarios where incorporation of storage to manage hour-ahead ramping issues could be beneficial to the utility in its ability to use less spinning reserve. These were seen to be particularly beneficial for times (most mornings) when the contribution from wind is decreasing as energy demand is increasing. Additional analyses for a second-to-minutes timeframe showed that rapidly responding energy storage systems would ameliorate frequency and voltage sags caused by sudden loss of wind generation capacity. One problem with this particular set of analyses is that the model for performing the analyses is not validated against actual operational data for these storage systems.

Therefore, the Office of Naval Research is funding the installation of a lithium-ion titanate storage system that will be designed to provide relief from second-by-second fluctuations in wind energy output. In this manner, it can be determined how effective fast-response energy storage systems are in supporting the grid. Further, these data will also be used to validate the system models against actual field operational information.

One other on-going project will incorporate energy storage systems as part of its overall effort. Maui Electric Company (MECO) is the host of a project funded by the Office of Electricity as part of the Regional Distributed Systems Integration program. The goals of the project are to reduce peak demand by at least 15% for one part of the MECO system and to provide additional grid stability to the system that has significant percentages of as-available renewable energy resources (both wind and PV) on its grid. One rapidly responding storage system is currently undergoing tests at the Independent Power Producer's wind farm. At least one other system will be installed to address peak demand and grid stability issues.

It is anticipated that both efforts on Maui and the Island of Hawaii will serve to inform the state utilities and the Department of Energy on how effective energy storage systems can be under actual deployment conditions for grids with significant percentages of as-available renewable resources. These data will also serve to provide a basis for better informing state regulators on how to best proceed in amending, if necessary, RPS standards.

6.0 REFERENCES

PHOTOVOLTAIC ELECTRICITY PRODUCTION

A. Luque and S. Hegedus, editors, "Handbook of Photovoltaic Science and Engineering", Wiley, 2003.

T. Markvart and L. Castaner, editors, "Practical Handbook of Photovoltaics, Fundamentals and Applications", Elsevier, 2003.

DBEDT report: "Photovoltaic Electricity in Hawaii", 2006.
http://hawaii.gov/dbedt/info/energy/publications/pv-report06.pdf

US DOE Office of Science: Report on Solar Energy Utilization, 2005

http://www.solarbuzz.com/Marketbuzz2009-intro.htm

http://www.hawaiisenergyfuture.com/index.html

http://solarpowerauthority.com/hawaii/

http://www.renewableenergyworld.com/rea/news/article/2005/10/navy-completes-solar-energy-project-in-hawaii-37972

http://www.pv-tech.org/news/_a/major_market_decline_forecasted_for_the_solar_industry_in_2009_according_to/

http://www.renewableenergyworld.com/rea/news/article/2009/03/us-installs-342-mw-of-solar-pv-in-2008

http://www.renewableenergyworld.com/rea/news/article/2005/10/navy-completes-solar-energy-project-in-hawaii-37972

http://www.iea-pvps.org/ar/ar08/USA.pdf

http://www.yale.edu/cie/hawaii_county_baseline_energ.pdf

http://www.hubbertPeak.com/debate/oilcalcs.htm

BIOENERGY CROPS AND TECHNOLOGIES

Brewbaker, J.L. (editor). 1980. Giant Leucaena (Koa Haole) energy tree farm – an economic feasibility analysis for the island of Molokai, Hawaii. Report to the Hawaii Natural Energy Institute, University of Hawaii at Manoa, Honolulu, HI.

Cook, B.G., B.C. Pengelly, S.D. Brown, J.L. Donnelly, D.A. Eagles, M.A. Franco, J. Hanson, B.F. Mullen, I.J. Partridge, M. Peters, and R. Schultze-Kraft.

2005. Tropical forages: an interactive selection tool. CSIRO, DPI&F(Qld), CIAT and ILRI, Brisbane, Australia. Available at http://www.tropicalforages.info/key/Forages/Media/Html/Pennisetum_purpureum.htm. Accessed on May 9, 2009.

Duarte, O., and R. Paull. 2006. *Jatropha curcas* L. Euphorbiaceae. Unpublished report.

Friday, J.B. 2006. *Eucalyptus* spp. Unpublished report.

Makkar, H.P.S, K. Becker, and B. Schmook. 2009. Edible provenances of *Jatropha curcas* from Quintana Roo state of Mexico and effect of roasting on antinutrient and toxic factors in seeds. Institute for Animal Production in the Tropics and Subtropics, University of Hohenheim, D-70593 Stuttgart, Germany. Available at http://www.jatropha.de/schmook1.htm. Accessed on May 10, 2009.

Rieger, M. 2009. Oil Palm - *Elaeis guineensis*. University of Georgia. Available at http://www.uga.edu/fruit/oilpalm.html. Accessed on May 10, 2009.

Soh, A.C., K.K. Kee, K.J. Goh, B.N. Ang and L.H. Ooi. 2008. Encyclopedia of Fruits and Nuts. J. Janick and R.E. Paull (eds). CABI Publishing, United Kingdom.

BIOMASS CONVERSION TECHNOLOGIES

Anon. 2002. How is ethanol made? American Coalition for Ethanol, available at (http://www.ethanol.org/howethanol.html)
Shleser, R. 1994. *Ethanol production in Hawaii*. Report prepared for the State of Hawaii, Department of Business, Economic Development and Tourism. available at (http://www.hawaii.gov/dbedt/info/energy/transportation/ethanol/studies/ethanol94.pdf)

Anon. 2001. *Fast pyrolysis of bagasse to produce bio-oil fuel for power generation.* Dynamotive Energy Systems Corporation, Presented at the 2001 Sugar Conference, available at (http://www.dynamotive.com/biooil/technicalpapers/2001SugarConferencePaper.pdf)

Anon. 2001a. *Bio-oil combustion due diligence: The conversion of wood and other biomass to bio-oil.* Ensyn Group Inc., available at (http://www.ensyn.com/info/01062001.htm).

Oasmaa, A., and Peacocke, C. 2001. *A guide to physical property characterization of biomass derived fast pyrolysis liquids*. VTT Publication 450. VTT Technical Research Centre of Finland, Espoo, Finland. Available at (http://virtual.vtt.fi/inf/pdf/publications/2001/P450.pdf)

Oasmaa, A., Leppamaki, E., Koponen, P., Levander, J. and Tapola, E. 1997. *Physical characterization of biomass-based pyrolysis liquids: Application of standard fuel oil analyses*. VTT Publication 306. VTT Technical Research Centre of Finland, Espoo, Finland. Available at (http://virtual.vtt.fi/inf/pdf/publications/1997/P306.pdf)

Freel, B. and Graham, R. 2000. *Commercial bio-oil production via Rapid Thermal Processing*, available at (http://www.ensyn.com/info/11122000.htm).

Huber, 2007. Breaking the chemical and engineering barriers to lignocellulosic biofuels: next generation hydrocarbon biorefineries. National Science Foundation, American Chemical Society, and Dept. of Energy, Washington DC.

Bain, R., K. Craig, and K. Comer. 1997. Biomass Technology Review in Renewable Energy Technology Characterizations. Prepared for the Electric Power Research Institute and the U.S. Department of Energy. EPRI Document No. TR-109496.

Owen, K., and Coley, T. 1995. Automotive Fuels Reference Book Second Edition. Society of Automotive Engineers.

Shleser, R. 2006. Personal communication with S. Turn. Robert Shleser contact information, office tel. (808) 259-5042, email: shleser@aloha.net

Deutmeyer, M. 2006. BTL – High yield, low CO_2, second generation biofuel. Presentation at the 6th World Gas to Liquids Summit. London, May 19th, 2006.

Sheehan, J., Camobreco, V., Duffield, J., Graboski, M., Shapouri, H. 1998. An Overview of Biodiesel and Petroleum Diesel Life Cycles. National Renewable Energy Laboratory.

Mittelbach, M. 1996. Diesel Fuel Derived From Vegetable Oils, VI: Specifications and Quality Control of Biodiesel. Bioresource Technology.

Tyson, S.K. 2001. Biodiesel Handling and Use Guidelines. National Renewable Energy Laboratory, report number TP-580-30004.

Anon. 2003b. The Fuel, Pacific Biodiesel, (http://biodiesel.com/biodiesel_fuel.htm).

Anon. 1992. EPAct of 1992. available at (http://www.usaid.gov/policy/ads/500/epactof1992_subtitlef.pdf).

Lue, Y.-F., Yeh, Y.-Y., and Wu, C.-H. 2001. The Emission Characteristics of a Small D.I. Diesel Engine Using Biodiesel Blended Fuels. Journal of Environmental Science and Health.

Yamane, K., Ueta, A., and Shimamoto, Y. 2001. Influence of Physical and Chemical Properties of Biodiesel Fuels on Injection, Combustion and Exhaust Emission Characteristics in a Direct Injection Compression Ignition Engine. International Journal of Engine Research.

Graboski, M.S., McCormick, R.L., Alleman, T.L., and Herring, A.M. 1999. Effect of Biodiesel Composition on NOx and PM Emissions from a DDC Series 60 Engine. National Renewable Energy Laboratory.

Jakeway, L. 2006. Personal communication with S. Turn. L. Jakeway contact information: office tel.: (808) 877-2968. email: ljakeway@hcsugar.com

GRID ENERGY STORAGE SYSTEMS

Cole, Van Hertem, Meeus, Belmans, Energy storage on production and transmission level: a SWOT analysis. (http://www.leonardo-energy.org/webfm_send/938)

Symons, Opportunities for Energy Storage in Stressed Electricity Supply Systems, Panel Session on Electrical Storage IEEE PES Summer Power Meeting, July 16, 2001