Sustainability and Risk Assessment of Integrated Seawater Agriculture Systems for the Production of Biofuels

By

Brian Warshay

A Thesis Presented to the
Masdar Institute of Science and Technology
in Partial Fulfillment of the Requirements for the Degree of
Master of Science
in
Engineering Systems and Management

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Abstract

The aviation sector is and will continue to be dependent upon high energy density liquid fuels. These fuels are typically derived from fossil sources that emit previously sequestered carbon dioxide into the atmosphere when combusted, contributing to anthropogenic global warming. The depletion of easily accessible oil resources is leading to exploitation of higher lifecycle emission intensity fossil fuels like heavy oils and tar sands. As a result, the development of lower carbon intensity, more sustainable, liquid fuel alternatives for aviation is essential for maintaining the sector's growth to meet global mobility needs without increasing its environmental impact. Fuels derived from numerous biomass feedstocks can provide drop-in liquid fuels that have the potential to be more sustainable alternatives to fossil derived sources. A life cycle assessment of a biofuel's entire production system, from planting to combustion, to evaluate its life cycle greenhouse gas emissions, net energy balance, water consumption, resource use, and other environmental impacts is necessary to establish its true sustainability potential. An Integrated Seawater Agriculture System (ISAS) on desert land using primarily seawater for irrigation has the potential to produce more sustainable aviation biofuels when compared to fossil and other biofuel sources. Despite a wide range of uncertainty due to the untested nature of the ISAS operations in Abu Dhabi, the jet fuel produced from the ISAS emits only 5 to 45 percent of the life cycle greenhouse gas emissions released from the production of conventional fossil Jet-A fuel, even without considering the long-term subsurface carbon sequestration potential from cultivating desert land.

This study presents a sustainability assessment that uses a novel life cycle tool to evaluate the production greenhouse gas emissions, net energy balance, and environmental risks of an ISAS for biofuel production in UAE conditions.

This research was supported by the Government of Abu Dhabi to help fulfill the vision of the late President Sheikh Zayed Bin Sultan Al Nayhan for sustainable development and empowerment of the UAE and humankind.

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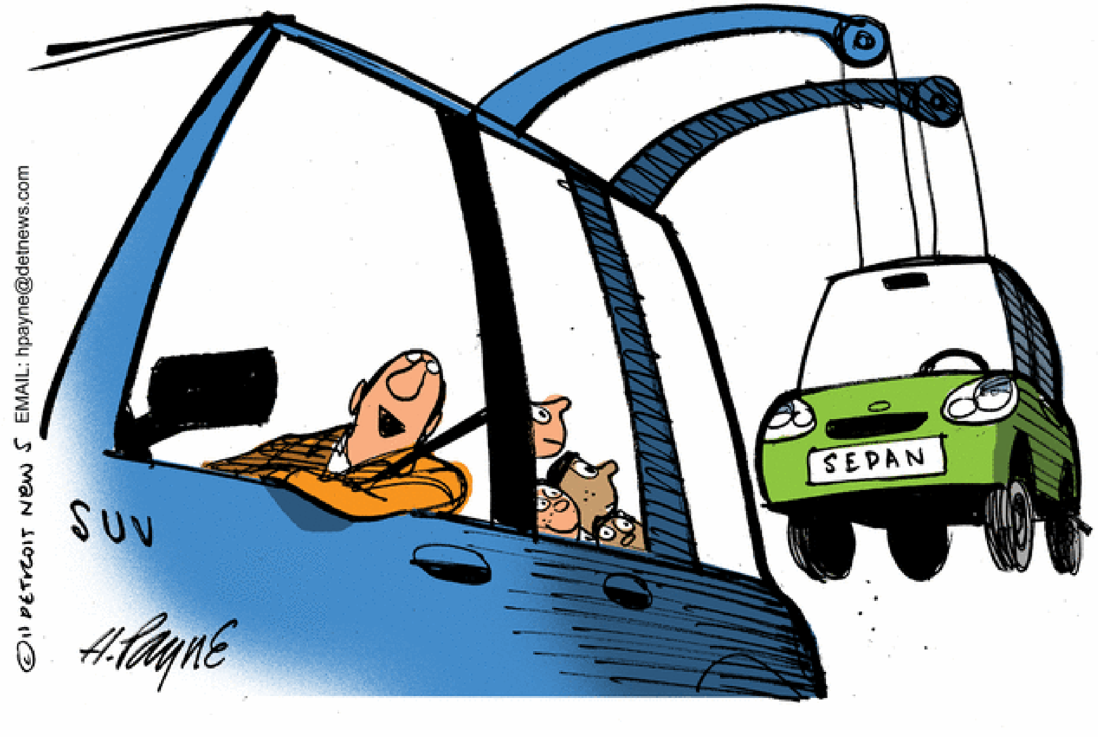
Brian Warshay

Masdar City, May 2011

There are two spiritual dangers in not owning a farm. One is the danger of supposing that breakfast comes from the grocery, and the other that heat comes from the furnace.
- Aldo Leopold, A Sand County Almanac



"And the lifeboat is for when gas hits $4 a gallon."

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CHAPTER 1

1 Introduction

Anthropogenic greenhouse gas emissions, excessive freshwater consumption, and pollution are putting human and ecological health in jeopardy. Society has evolved over the past two centuries by trading Earth’s finite resources, air and water quality, and biodiversity for the sake of quality of life, financial gain, and convenience. The business as usual approach to resource use and energy consumption is certainly unsustainable. To address these issues the aviation industry has been taking steps to improve its fuel efficiency and search for more sustainable alternative fuels that have a lower environmental impact than conventional fossil based jet fuel.

This thesis contributes to the growing body of knowledge regarding biofuel and food production systems, focusing on an integrated system of aquaculture, saline agriculture and silviculture that has the potential to mitigate several of the key criticisms of conventional biofuel production systems becoming a source for more sustainable liquid bio-jet fuel, food, carbon sequestration, and other types of bioenergy. Specifically, this thesis provides the background research and documentation related to potential constraints and limitations of a commercial scale Integrated Seawater Agriculture System (ISAS). It brings to the forefront the data gaps and the technical, environmental, and logistical issues associated with developing a commercial scale ISAS and identifies areas for further research. The thesis also evaluates the ISAS from the perspective of the sustainability criteria detailed by the Roundtable on Sustainable Biofuels (RSB) in their Principles and Criteria for Sustainable Biofuels Production, Version Two dated 5 November 2010 and the Sustainable Aviation Fuel Users Group (SAFUG) Commitment to Sustainable Options [1], [2].

1.1 Sustainability Assessment Objectives and Research Questions

The underlying research question driving this effort could be summarized as follows: “Can Integrated Seawater Agriculture Systems be a sustainable method for bioenergy production from an energy and carbon emission accounting perspective in the conditions of the Arabian Gulf?”

In order to address the research question, our research relies on primary and secondary data evaluation under a lifecycle framework. The primary objectives of this research are to:

(i) Evaluate the sustainability of an ISAS and specifically its energy and carbon balance;

(ii) Identify gaps in the literature that would allow this assessment to be performed with higher precision; and

(iii) Develop a tool for further optimizing the integration of ISAS component processes.

The ISAS analysis considers the life cycle greenhouse gas (GHG) emissions, energy return on energy invested, resource use, and other related impacts of an ISAS. The ISAS is evaluated on a total system basis, including the use of coproducts internally as well as those sold to market. Material and energy imported into the system or exported to market is accounted for and the allocation procedures associated with their impacts will be detailed further in Chapters 4.3 and 0 of this document.

The methodology that was used for this Sustainability Assessment was implemented with the intent of creating a flexible and adaptable tool for the generic evaluation of ISAS processes. The data entered for the model correspond to an ISAS implementation described in Chapter 3 in Abu Dhabi, UAE. However, the tool has been created such that its structure is adaptable to be used at other locations and with other biofuels, provided that the background data is available for a given location or biofuel. This Sustainability Assessment also identifies key data gaps and areas for further research that will be necessary to design and develop a commercial scale ISAS in the Arabian Gulf. The results of these objectives are examined in Chapter 7.

1.2 Problem Definition

Even though the aviation sector is responsible for only 3 percent of anthropogenic global greenhouse gas emissions [3], the potential for emission reductions in other sectors are expected to be larger than in aviation, making it imperative that the aviation sector seek alternative, more sustainable fuel sources. The sector's contribution may increase to between 5 and 15 percent of global anthropogenic emissions by 2050 [3].

In 2006, air transport accounted for 9.5 QBTU, or 2.0 percent of global energy demand, but is projected to grow to 15.0 QBTU, or 2.4 percent of global demand by 2020 [4]. Aviation accounted for 5.7 percent of the global petroleum demand in 2006 and is projected to reach 7.1 percent by 2020. Overall, the air transport sector's energy demand is projected to grow at 3.4 percent annually until 2020, with the air transport sector in developing countries growing at nearly double the rate that it will grow in developed countries [4].

In addition to carbon dioxide, aircraft emit sulfur dioxide, nitrous oxides, particulates, and water vapor contrails. These emissions impact the climate directly and indirectly through complex atmospheric chemical reactions. A multiplier factor over carbon dioxide emissions at a given altitude has been proposed to account for their effect but the high level of scientific uncertainty at this time has precluded its use for policy [5].

As a result, the use of lower-carbon biofuels as alternatives to conventional jet fuels would not significantly change the combustion properties in the jet engine or the mix of the exhaust gases. Additionally, the adoption of non-conventional fuels in aviation is limited by the high energy density requirements for the fuel and by the lag in technology diffusion that is dictated by high capital intensity and rigorous certification requirements of the sector. Therefore any non-drop-in fuel replacements (e.g. hydrogen) would not be widely used for at least the next forty years [6]. In order to reduce its impact on global GHG emissions, the aviation sector is looking to drop-in biofuels that have life cycle GHG emissions lower than those of conventional jet fuel made from fossil sources.

Drop-in alternative aviation fuels and – more specifically – biofuels that can satisfy the industry's technical requirements in the form of synthetic paraffinic kerosene (SPK) are already available and undergoing certification [7], but require further research and development to meet the logistic and scale requirements demanded by the industry. The primary industry concerns are whether these new fuels can provide the same level of service, meet aviation's fuel demand, and reduce the sector's overall carbon impact, and whether they can do so economically [8].

This Sustainability Assessment investigates the ISAS as one system that has the potential to be developed and deployed on a global scale as a low-impact system for biofuel production to mitigate the GHG impact of the aviation industry.

1.3 Biofuel Background

Biofuel is a generic term that encompasses any fuel created from plant biomass that often requires processing to be converted into a more usable form (solid, liquid, or gas). Although fossil fuels are technically biomass-derived, they are considered fossil fuels because the carbon molecules making up a portion of their composition was sequestered from the atmosphere millions of years ago.

Biofuels can be derived from nearly any biomass, including sugar and starch crops, vegetable oils, and woody and herbaceous material that can be processed along numerous conversion pathways into a wide variety of fuels, including green diesel, biodiesel (fatty acid methyl ester, FAME), ethanol, methanol, isobutanol, dimethyl ether (DME), syngas, renewable jet fuel and others depending on the feedstock and desired end product [9]. Most of the processing pathways are proven technologies that include thermal or electrical energy and chemical processes to create the end product. Many biofuels are used in the transportation sector, though there is also a significant interest in using some biofuels for power generation. Each conversion pathway has advantages and disadvantages and most require some energy and material or chemical inputs, often those derived from fossil feedstocks. What is consistent among the different pathways is that there is an exergy penalty due to the energy required to process the less energy dense feedstock into a more energy dense fuel.

The biomass used to create liquid biofuels can be derived from any number of plant species, depending on climatic conditions, soil profiles, and desired end product. The cultivation of biofuel feedstock requires the input of energy, chemicals, air, land, and water to produce economically utilizable crops. These processes impact the energy balance, greenhouse gas and pollutant emissions, and the overall ecological balance of the agricultural/biofuel-conversion system. All existing commercially available biofuel feedstocks have negative impacts on the local environment in some way, from land use change to freshwater consumption or chemical requirements to produce optimal yields. Several food crops can double as biofuel feedstocks and raise a direct food competition issue.

The three main issues with potential large-scale biofuel production, the food, energy, and environment trilemma, so termed by Tilman et al. [10], can be mitigated by using perennial plants grown on degraded lands, crop residues, sustainable wood, double cropping, increasing existing crop productivity or using municipal wastes as feedstocks. There are several feedstock cultivation-processing pathway combinations that may alleviate this trilemma, including low-input high-diversity perennial grass mixtures, corn stover for ethanol, and the ISAS [11-13]. Other high productivity woody plants, such as poplar, willows, and forest residues have shown potential for scalability and high biomass production with minimal land use impacts and chemical inputs. The above processes rely on cellulosic biomass which is often more energy intensive to process into liquid fuels than oil, starch, or sugar crops. However, the use of the coproducts produced along many biofuel pathways can play a significant role in promoting the pathway's overall sustainability and viability.

Comparing different feedstocks and the conventional fossil fuels they may potentially replace becomes more complicated because of the coproducts that are produced in many biofuel processing pathways. Coproducts are secondary energy or material outputs from the cultivation, processing, or development of fuel, including, in some cases, fossil fuels. Coproducts, though they may have more mass or overall energy content than the primary fuel being produced, are not the primary fuel being sought from the process under evaluation. In the case of biofuels, a coproduct example can be leftover biomass from the cultivation of corn that can still potentially be burned to generate electricity or used as cover on the harvested corn field. Another common coproduct from the corn ethanol dry milling industry is called distiller's dried grain with solubles (DDGS). DDGS can be used to supplement livestock feed, therefore 'avoiding' the energy and material required to grow 'conventional' livestock feed [14]. Protein meal is often leftover from the processing of oilseeds, such as salicornia or soybean. The protein meal can be used as a livestock feed component. Accounting for the energy and emissions associated with coproduct production and chosen use is extremely important in lifecycle assessments [15] and can bias the results of an LCA. This makes it essential for the LCA practitioner to carefully and transparently detail the assumptions and calculations used in the analysis. This issue specific to the ISAS LCA is further explored in Chapter 4.

1.4 Biofuel Considerations

Recent criticism of biofuel feedstocks as satisfactory replacements for conventional fossil fuels has been directly correlated with their increased availability and policy incentives spurring their development throughout the world. Challenges that face the biofuel industry include:

- **Negative climate impact due to land use change**. Cultivation land requirements may directly or indirectly contribute to deforestation thus changing a carbon sink to a carbon source [16], [17]. The economic incentive to produce biofuels, if poorly regulated, will continue to put ecologically sensitive regions at risk from encroaching farmers. Even if biomass cultivation for biofuels is regulated to avoid direct land use change, it can still indirectly lead to displacement of other food crops with the effect outlined earlier.
- **Food competition**. By competing for freshwater and land with food agriculture, biofuels may impact the availability and price of food crops [10].
- **Energy imbalance**. Poorly managed feedstocks may require more fossil energy inputs to produce than the fuels they are designed to replace [18].

- **Pollution**. Conventionally grown feedstocks require chemical inputs like fertilizer and pesticides that can pollute proximate land and water through their run-off [19].
- **Scaling**. The scaling up of first-generation biofuels requires significant land areas. As an example, to satisfy just half of the global demand for conventional jet fuel, up to six percent of the planet's arable land could be required [7].

  Such criticism is not new. Over a decade ago, it was stated that, "Large-scale biofuel production is not an alternative to the current use of oil and is not even an advisable option to cover a significant portion of it" [20].

  Even second generation biofuels, namely cellulosic ethanol, could have limited market penetration due to land use issues, logistical challenges, and freshwater constraints. For example, a 50 million gallon per year facility would require a truckload of biomass to be delivered every six minutes, all day, every day [21]. Despite these issues, the risk of global climate change is driving industry to find more sustainable alternatives to the dwindling supply of fossil fuels that have been the facilitators of economic growth over the last two centuries. In 2008, 21.5 billion gallons of biofuels were produced, of which 80 percent was ethanol (which is equivalent to 344 facilities of 50 million gallons capacity each or a total of more than 30 million truckloads of biomass delivered in one year [21]), with the remainder being biodiesel.

  First generation biofuels typically include crops that are conventionally grown for food consumption but have properties that can be converted into biofuels, including sugar and starch crops (sugarcane, corn) that can be fermented to make ethanol and oilseed crops (soybean, rapeseed, palm oil) whose oil can be converted via transesterification into biodiesel or hydroprocessed into renewable diesel (HRD) or renewable jet fuel (HRJ). First generation biofuel feedstocks often require a large amount of arable land. The United States, the largest corn producer in the world, dedicates approximately 30 percent of its corn crop to displace six percent of its gasoline needs [22]. In 2008, Europe dedicated 60 percent of its rapeseed harvest to biodiesel which replaced 3 percent of its diesel fuel consumption [21]. Presently, biofuels displace approximately 4.3 and 1.5 percent of global gasoline and diesel consumption, respectively [22]. This growing demand for energy dense liquid fuels and the increasing scarcity of conventional oil [23] contributes to the market niche for more sustainable and secure alternative liquid fuel supplies. In fact, it is forecast that by 2022, globally, biofuels will replace nearly 9 percent of jet fuel, 8.4 percent of gasoline, and 7.4 percent of diesel [22].

1.5 Motivation

Second generation biofuels typically include lignocellulosic biomass products derived from the waste of other agricultural processes (corn stover, forest residue) or feedstocks grown on marginal land (switchgrass, jatropha). Though many second generation biofuel feedstocks have the potential to produce fuels with lower environmental impacts than their conventional fuel counterparts, they still require land that could serve alternative uses, often require some freshwater, and require significant chemical inputs to produce economically viable yields. Overall, Rockstrom et al. [24] determined that, due largely to society’s reliance on fossil fuels and industrialized agriculture, human activities have reached a level that could damage the systems that keep Earth in a state desirable for human development and survival. The result could lead to irreversible and abrupt environmental change. Already, Rockstrom et al. [24] stated that of their ten proposed planetary boundaries, three have already exceeded safe levels, one of which is the nitrogen cycle which is nearly four times the proposed boundary safe for sustainable development. The removal of nitrogen from the atmosphere to make it bioavailable for agriculture, mainly through the production of fertilizer, has resulted in the pollution of waterways and coastal zones, accumulating in land systems and being re-emitted into the atmosphere as nitrous oxide (N_2O), one of the more potent non-CO_2 greenhouse gases.

Salicornia bigelovii (salicornia) cultivated as part of an ISAS is an emerging option that presents an opportunity for scalable commercial biofuel development while posing less environmental risks than many first or second generation biofuels, namely the use of seawater for irrigation instead of freshwater and the cultivation of non-arable desert land instead of arable or even marginal cropland. Additionally, the ISAS reduces the chemical fertilizer requirement of the agriculture system and generates much of its own power, reducing the requirement for artificial nitrogen and fossil fuel inputs. If commercially proven and scaled to its potential, the ISAS has the capability to contribute at a scale of one of the stabilization wedges proposed by Pacala and Socolow [25] by providing long-term carbon sequestration for 0.5-1.0 gigaton of carbon per year [26] and providing low-carbon alternative transportation biofuels.

A life cycle assessment (LCA) is necessary to analyze the overall impacts of each stage of cultivation, production, and distribution of the feedstock to determine its true systemic environmental and social cost. Due to the numerous valuable coproducts associated with an ISAS, an LCA can be used to allocate the associated energy, material, and GHG flows into and out of the system being studied and amongst the coproducts. In this way, ISAS biofuel production can be accurately compared to that of conventional fossil based fuels as well as to other commercially available or emerging biofuel feedstocks.

1.6 Objectives

This project is aimed to determine the potential greenhouse gas, energy, and other environmental implications of a commercial scale ISAS, using data from the literature, information provided by experts, and our defined design assumptions. The conceptual ISAS facility that was modeled was assumed to be located in Abu Dhabi, UAE and incorporates aquaculture, salicornia halo-agriculture (saltwater agriculture), and mangrove silviculture to provide biofuels, food, and soil carbon sequestration. The LCA will cover a range of variables in a sensitivity analysis to account for the uncertainty around the actual parameter values of a commercial-scale ISAS in this region. This LCA can provide the basis to develop a theoretically optimal configuration for the ISAS as well as confirm initial claims that a properly managed ISAS can provide a technologically viable aviation biofuel, seafood, and a net carbon and energy benefit without impacting freshwater supplies, causing chemical pollution, or using arable land. The results from this LCA can be used to compare the ISAS to conventional fossil fuels and first- and second-generation biofuel production systems. Due to the limited availability of reliable data for the ISAS and salicornia, the tool developed for this Sustainability Assessment will require refinement and verification when experimental and empirical field data become available for growing salicornia in the region. The existing literature on salicornia relies on older studies and/or unverified data for the climate of Abu Dhabi.

1.6.1 Aviation Focus

The aerospace industry is one of the sectors that is most impacted by oil price volatility and climate change regulations due to its high usage of fossil energy to run their day-to-day business operations. The aviation sector’s most pressing challenges are to reduce GHG emissions, manage fuel price volatility, and meet growing transportation demand. Future regulations may force airlines to look for new sources of clean energy to offset emissions. For instance, the International Air Transport Association (IATA) goal is for its members to use 10 percent alternative fuels by 2017 [27]. This situation has created a pressure for airlines to find new ways to offset their emissions.

1.6.1.1 *Alternative fuels in practice*

There have been several recent test flights using a variety of alternative aviation fuels and fuel blends on pilot scales. The results have been promising and are summarized as follows:

- 1 February 2008: **Airbus** flew between Filton, UK and Toulouse, France with one of its four A380 engines (Rolls Royce) powered by Fischer-Tropsch Natural Gas to Liquid (GTL) fuel provided by Shell International Petroleum [28], [29];
- 23 February 2008: **Virgin Atlantic** flew between London and Amsterdam with one of its four Boeing 747-400 engines (General Electric) operating on a blend of Jet A-1 and 20 percent fuel made from babassu palm and coconut oil [7];
- 30 December 2008: **Air New Zealand** flew between Auckland and Wellington with one of its four Boeing 747-400 engines (Rolls Royce) operating on a 50 percent blend of jatropha derived HRJ and 50 percent Jet A-1. This test flight illustrated the potential viability of HRJ as an alternative aviation fuel and resulted in a fuel burn savings of 1.2 percent that was achieved due to the higher energy content of HRJ compared to Jet A-1 [7];
- 7 January 2009: **Continental Airlines** flew out of Houston with a Boeing 737-800 with one of its two engines (CFM International, [30]) operating on a blend of 50 percent conventional jet fuel HRJ composed of an oil from *Jatropha curcas* (47.5 percent) and algae (2.5 percent) [7];

- 30 January 2009: **Japan Airlines (JAL)** flew out of Tokyo with a Boeing 747-300 with one of its four engines (Pratt & Whitney, [30]) operating on a blend of 50 percent conventional jet fuel and 50 percent HRJ composed of oil from *Camelina sativa* (42 percent), Jatropha (8 percent) and algae (<0.5 percent) [7];
- 12 October 2009: **Qatar Airways** flew from London, England, to Doha, Qatar with an Airbus A340-600 with all four engines (Rolls Royce) on a 50 percent GTL mix [31]; and
- 23 November 2009: **KLM Royal Dutch Airlines** flew out of Schiphol Airport in Amsterdam with one of its Boeing 747 engines (General Electric) operated using blend of 50 percent conventional jet fuel and 50 percent Camelina oil derived HRJ [32].

1.7 ISAS Overview and Thesis Structure

An Integrated Seawater Agriculture System, or ISAS, is a biofuel and food production system envisioned to take advantage of the synergies and interactions that exist between several integrated desert ecosystems. It can be developed on traditionally non-arable coastal desert land and is irrigated with full strength seawater pumped in from the ocean. The overall concept has three main biological processes, aquaculture, halo-agriculture of an oilseed, salt tolerant crop, and mangrove silviculture. There are numerous supporting ancillary processes to make the system function properly, one primary technological process that converts oil from the biofuel crop into liquid biofuel for aviation (hydroprocessing), and another process that converts leftover biomass from the halo-agriculture and silviculture into either bio-electricity or other liquid biofuels. The benefits of the integrated system stem from the use of coproducts from each process to supplement energy or material inputs for the other processes (see Figure 1).

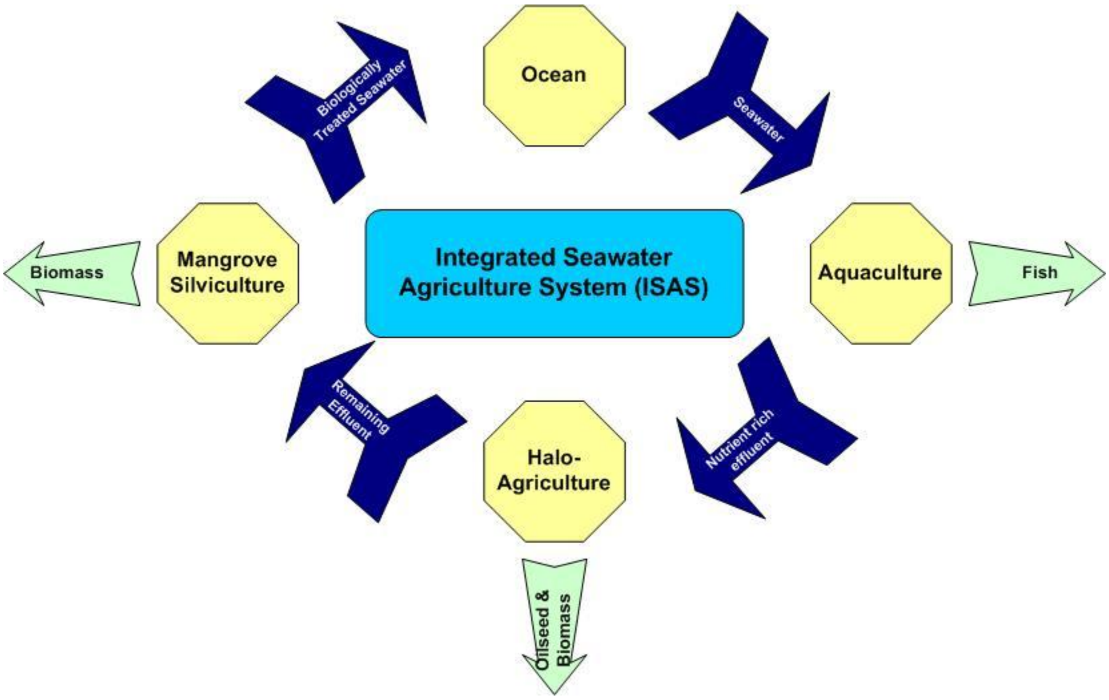


Figure 1 High-level Conceptual ISAS Diagram

Some halophytic crops (in this case, *Salicornia bigelovii*, described in more detail in Chapter 2.3) have the potential to provide vegetable oils and biomass that can be used as sustainable feedstocks for a variety of biofuels, food, and other bio-based products, without consuming freshwater supplies or infringing upon arable land. Within the ISAS they can be produced in a nearly closed system by using aquaculture effluent as fertilizer and the irrigation water treatment benefits of a mangrove wetland ecosystem. This system has been prototyped on a pilot scale only once in Massawa, Eritrea (see Chapter 2.3.2).

The ISAS design considered here uses seawater pumped into an aquaculture system in which fish and shrimp are produced. Most of the feed components are purchased from the market while a portion of it is produced within the ISAS using the salicornia meal leftover from the salicornia seed oil extraction process. The effluent that leaves the aquaculture is high in nutrients including nitrogen and phosphorous that is leftover from uneaten feed and fish waste in the water. This effluent is often the cause of eutrophication and algae blooms in poorly managed coastal aquaculture systems [33].

However, in the ISAS, this ‘waste’ product is used beneficially by the salicornia and mangroves as a liquid fertilizer. Salicornia is harvested annually for its oilseeds and biomass (salicornia straw) and mangroves are periodically thinned, also producing biomass. The nutrient rich aquaculture effluent is biologically treated to safe levels as it travels through the salicornia fields and into the mangrove wetland, resulting in treated seawater that is returned to the ocean from which it came.

A detailed description of the components of the ISAS subprocesses including mechanism, yields, and inputs is presented in Chapter 2 and based on extensive literature surveys and interviews with experts. The specific characteristics of the UAE conditions and how they would influence an ISAS process implementation along with the specific design of the UAE-based conceptual ISAS evaluated are outlined in Chapter 3. Chapter 4 presents the methodology used for the lifecycle assessment of the ISAS process while Chapter 5 summarizes the potential risks from widespread deployment of ISAS. Our survey of existing information on ISAS indicated the existence of substantial gaps or uncertainty due to conflicting results in the knowledge of critical ISAS outputs. Chapter 6 summarizes these gaps and explains the wide range of assumptions between the worst, base, and best case values used to generate the lifecycle assessment results. The results themselves and the conclusions that can be drawn from them are presented in Chapter 7. Taking a broader perspective, the Sustainability Assessment concludes with the mapping of the ISAS process against the Roundtable of Sustainable Biofuels (RSB) criteria in Chapter 8.

CHAPTER 2

2 Literature Review

This chapter is a comprehensive review of the available literature and data sources relevant to the ISAS, including aquaculture, halo-agriculture, mangrove silviculture, biofuel processing technologies, and other systemic considerations. Though a wide range of data is presented here for discussion purposes, the quantitative data used in the LCA model is presented in Appendix A with the relevant sources.

2.1 Data Sources and Availability

Despite several decades of research and publications, salicornia is not yet cultivated on a commercial scale. Additionally, mangroves are typically reintroduced to coastal regions that have been decimated by human development, but are not typically managed in silvicultural applications. Although tilapia and shrimp aquaculture technologies are existing and proven in many locations around the globe, there is little peer reviewed literature relating to aquaculture operations in Abu Dhabi, especially given the high water temperature (see Chapter 2.3.6) and salinity (up to 46 ppt whereas seawater can be less than 37 ppt [34]) in the Arabian Gulf (see Chapter 3.1.2). The biomass produced in the ISAS will be processed using gasification, Fischer-Tropsch synthesis, or pyrolysis, all of which have had some success in specific applications around the world but none of which have been used to process salicornia straw or mangrove biomass. As such, there is limited reliable, verifiable, empirical, and recent data available for these processes within the ISAS, especially for the conditions of Abu Dhabi, UAE. It was therefore appropriate to work with experts in the specific fields where data was lacking in the literature to refine the data and assumptions as close as possible to a potential practical ISAS operation in Abu Dhabi. The following experts were interviewed to provide insight into various ISAS processes:

- **Halo-Agriculture** – Professor Dr. Edward Glenn, soil, water, and environmental scientist from the Environmental Research Laboratory of the University of Arizona.
- **ISAS Operations –** Dr. Philippe Vandevivere, formerly of Seawater Farms Eritrea.
- **ISAS Operations** – Dr. Carl Hodges of Global Seawater, Inc., The Seawater Foundation, and Seawater Farms Eritrea.
- **Aquaculture** – Professor Dr. Michael Timmons, aquaculture, environmental sustainability, and entrepreneurship professor from Cornell University.

It is anticipated that remaining data gaps (see Chapter 6) and existing assumptions will be further refined following the issuance of this Sustainability Assessment and with empirical data gleaned from field experiments.

In each of the following subchapters we investigate the individual subcomponents of an ISAS starting with the aquaculture component in Chapter 2.2.

2.2 Aquaculture

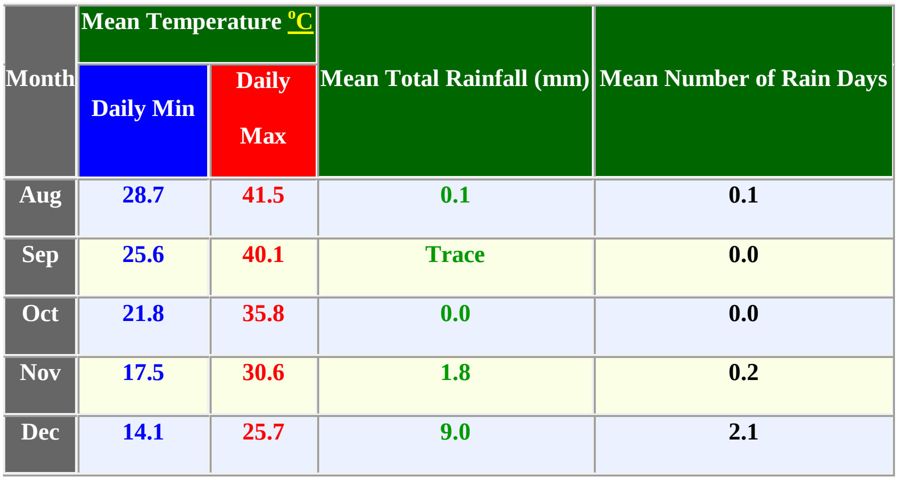
It is assumed that an ISAS designed for Abu Dhabi will include an integrated aquaculture portion consisting of shrimp and tilapia grown in semi-intensive open ponds. This option was chosen based on a desire to maximize aquaculture product outputs with the least amount of energy input, as opposed to the super-intensive operation that was employed in Massawa, Eritrea (see Chapter 2.3.2). Additional aquatic species (such as shellfish or algae) may be included at a later date or for a larger farm, but are not considered at this time. The tilapia will be grown in ponds downstream of the shrimp ponds to take advantage of the nutrients not captured by the shrimp. Integrated pond systems allow non-retained nutrients, such as uneaten feed, to be converted downstream into harvestable products [35], increasing the system's resource use efficiency. In fact, shrimp and tilapia polyculture has been practiced widely throughout the world, especially in Thailand and the Philippines, and was relatively successful at the Seawater Farms Eritrea pilot project, though the shrimp farming in Eritrea was more intensive than that proposed for the ISAS under consideration. The typical tilapia species used in shrimp-tilapia aquaculture in Thailand are Red Tilapia (*Oreochromis* spp.), Nile Tilapia (*Oreochromis niloticus*), and Mozambique Tilapia (*Oreochromis mossambicus*) while the shrimp produced in Thailand are Giant (or Black) Tiger Prawn (*Penaeus monodon*) [36].

A key consideration that will need further investigation is determining how producing a large quantity of fish products will impact the local seafood industries. Though seafood products from the ISAS may end up being more sustainable or cost-effective than other aquaculture operations or wild caught fish, the potential social impact of out-competing other members of the industry should be addressed, though it is likely that their market niches are different.

2.2.1 Design Considerations

Air and Pond Temperature: Due to the high air temperatures in Abu Dhabi, it may not be suitable to maintain active aquaculture facilities year round as the temperature of the pond water may exceed the upper limit of tolerance for both shrimp and tilapia which is typically around 33-35ºC [37]. Lethal low temperatures for most tilapia species is 10-11ºC, though some species such as Blue Tilapia (*Oreochromis aureus*) can survive temperatures as low as 8-9ºC. Preferred water temperatures for tilapia growth are from 29-31ºC, leading to growth rates three times greater than under the same conditions in 22ºC water [38]. Even though the incoming seawater temperature may be within this range in the summer, the shallow pond depths will likely result in water temperatures closer to that of the air. The annual air temperature in Abu Dhabi is presented in Figure 2. To mitigate this issue, Timmons [37] recommended avoiding year-round outdoor cultivation, though there have been examples at UAE University in Al Ain where low-tech shading devices were used to effectively maintain viable water temperatures in the ponds. This option will be evaluated in future research and is not addressed further in this Sustainability Assessment. Eight months of active aquaculture (from October to May) could still produce viable yields of both shrimp and tilapia, would reduce the risk of mortality from water temperature, and would provide an opportunity in the summer to clean out the ponds each year, reducing the risk of pathogens in subsequent cultures. This practice would also allow the nutrient rich sediment in the pond bottoms to be harvested each summer and deposited on the salicornia fields. Summers could also be used to cultivate breedstock indoors as well as operate an indoor recirculating aquaculture system, though this option is not evaluated in this Sustainability Assessment. The summer temperatures in Abu Dhabi are also too hot to grow salicornia [39].

Month	**Mean Temperature ºC**		**Mean Total Rainfall (mm)**	**Mean Number of Rain Days**
	Daily Min	**Daily Max**		
Jan	**11.8**	**23.8**	**3.9**	**0.8**
Feb	**13.2**	**24.6**	**42.0**	**3.5**
Mar	**15.8**	**28.6**	**24.8**	**3.9**
Apr	**19.1**	**33.4**	**7.3**	**1.4**
May	**22.8**	**38.4**	**Trace**	**0.0**
Jun	**24.8**	**39.6**	**0.0**	**0.0**
Jul	**27.6**	**42.0**	**Trace**	**0.0**



Month	Mean Temperature °C		Mean Total Rainfall (mm)	Mean Number of Rain Days
	Daily Min	Daily Max		
Aug	28.7	41.5	0.1	0.1
Sep	25.6	40.1	Trace	0.0
Oct	21.8	35.8	0.0	0.0
Nov	17.5	30.6	1.8	0.2
Dec	14.1	25.7	9.0	2.1

Figure 2 Climatological Information for Abu Dhabi, UAE [40]

Cages: Cages are not recommended because the densities required to make cage culture feasible could lead to low oxygen conditions and stress, reduced growth and feed conversion, and mortality [37].

Tilapia Species: The dominant tilapia species being used worldwide, primarily for growth rate and fillet yield superiority, is Nile Tilapia [37]. However, Nile Tilapia is the least saline tolerant of the commercially important species, withstanding salinity up to 15 ppt. Blue Tilapia (*Oreochromis aureus*) grows well in water with salinity up to 20 ppt. Athi River Tilapia (*Oreochromis spilurus*) and Mozambique Tilapia grow and can reproduce in salinities at or near full-strength seawater, though the Red Tilapia is preferred for more saline aquaculture [38]. Stickney [41] provides a review of tilapia saltwater tolerance revealing that although Redbelly Tilapia (*Tilapia zilli*) and Mozambique Tilapia are among the most salt-tolerant species, neither is among the most desirable for culture. Mozambique can grow well in 32-40 ppt salinity (tolerating salinities as high as 49 ppt). Fillet yields of Mozambique are the lowest of most commonly cultured species (probably less than 30 percent yield by weight of the whole fish whereas other species can have marketable yields near 40 percent by weight for tilapia fillets [37], [38]). Growth rates are not as high as Nile Tilapia. Given the scale of a commercial ISAS, a selective breeding program using either straight line Nile Tilapia or a hybrid cross of Nile and Mozambique may be feasible (for the conditions in Abu Dhabi). The Red Tilapia[1] is a cross between the Mozambique and Nile and is recommended for use in conditions similar to that of Abu Dhabi [43]. Leonard [43] further elaborated that not all Red Tilapia are the same and would take some due diligence to determine the most appropriate strain. An intensive system with aeration may be most effective for Red Tilapia on full strength seawater and could result in significantly higher yields, but this option is not evaluated here. Seawright [44] identified Mozambique or one of its hybrids as potentially the most practical species to use. Nile Tilapia grow exceptionally well up to 12 ppt, approaching a practical limit at 20 ppt salinity, with 30 ppt salinity being very stressful. The heritability of salinity tolerance in Nile Tilapia is unknown.

Tilapia are typically more naturally resistant to viral, bacterial, and parasitic diseases than other cultured fish. At water temperatures above 16-18ºC and without other stressors, tilapia rarely become diseased. Stress from low temperatures, handling, overcrowding, or poor water quality may result in disease or fungal infections, especially from *Saprolegnia* [38].

Timmons [37] also mentioned that Sea Bream could be a reasonable alternative to tilapia, though growth rates would be much lower than tilapia (about 30 percent lower). Sea Bream could be cultured intensively in recirculating systems, however this approach is not considered here.

Shrimp Species: The dominant shrimp being cultured worldwide are white shrimp, more specifically *Litopenaeus vannamei* (formerly *Penaeus vannamei*), also known as Pacific White Shrimp. This species is a variety of prawn (not shrimp) of the eastern

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[1] The Red Tilapia is usually developed from Mozambique Tilapia and/or *Oreochromis urolepis hornorum* stocks (for the red color) and often also crossed with Nile Tilapia or *Oreochromis aureus* to improve growth and other characteristics. It should be noted that many Red Tilapia lines do not breed true and therefore require continuous selection to maintain a high percentage of Red Tillapia offspring. The reader is directed to Popma and Lovshin [38] and Timmons et al. [42] for detailed information about tilapia growth, breeding, and other characteristics.

Pacific Ocean commonly caught or farmed for food[2] [37]. However, in the UAE, *Penaeus semisulcatus*, *Metapeanaeus mastersii*, and *Penaeus latisulcatus* are found naturally with *P. semisulcatus* being the most common and commercially important species. *P. semisulcatus* and *P. indicus* have been reared successfully in the UAE [45]. Sourcing multiple species of white Penaed shrimp should be feasible in the region and there are existing major commercial hatcheries supplying post larval animals in the Middle East and Thailand [37].

Pond Area Allocation and Yields: The pond area allocation between the shrimp and tilapia ponds can vary based on market conditions or other factors. For illustrative purposes, assuming an equal pond allocation (e.g. 50 percent of the ponds for shrimp, 50 percent for tilapia), the potential yields per year (based upon 8 months of aquaculture and 10,000 ha of aquaculture) are presented in Table 1. About twice the fry are needed for the number of desired adult fish harvested.

Table 1 Potential Yield of Shrimp and Tilapia with a 50:50 Pond Area Allocation [37]

Species	Animals/ m^2 harvested	Size at harvest (g)	Yields per harvest, kg/ha	Ha allocated per species	Crops per year	MT per farm per year
Shrimp	20	15	3,000	5,000	2	30,000
Tilapia	0.3	1,000	3,000	5,000	1	15,000

Feed: Feed should be readily available in the region from either Israel or Egypt and potentially even Turkey [43]. Detailed feed composition is provided in Appendix A. Growth, feed conversion, and effluent characteristics are directly related to the degree of digestibility of the feed. Generally, plant protein ingredients such as soybean and

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[2] The difference between shrimp and prawn is biological, relating to differences in their suborder classification, gill structure, abdominal segments, and other features.

corn gluten meals have the desirable characteristic of a lower P/N ratio, which makes them appropriate for use in low environmental impact diet formulations. Only a limited amount of protein can be salvaged from the offals that result from post-harvest processing of tilapia, with nothing usable expected to remain from shrimp processing. This is due to the fact that most of the protein on the carcass is in the fillets that are sold. Additionally, the carcass will have a high ash content. High quality fish meal typically includes whole small fish. In the USA there are no approved drugs that may be used in aquaculture and hormonal use is minimal and typically breakdown within 24 hours of application. Though conditions in Abu Dhabi may require some drugs, it is expected to be insignificant to the overall system budget and environmental impact. Feed for both shrimp and tilapia will likely be pellets, though the tilapia pellets will float and the shrimp pellets will sink slowly [37], [42]. Commercially available feeds supplemented with salicornia meal should provide a majority of the vitamins required for optimal growth for both shrimp and tilapia. Additional vitamins and minerals missing from the feed (once the optimal feed composition is defined) can be calculated and provided from market available sources but are not factored into the calculations in this Sustainability Assessment.

Effluent: The nutrient loading of the effluent from tilapia and shrimp aquaculture can be estimated from Figure 3 and calculated specifically for the feed composition described in Appendix A.

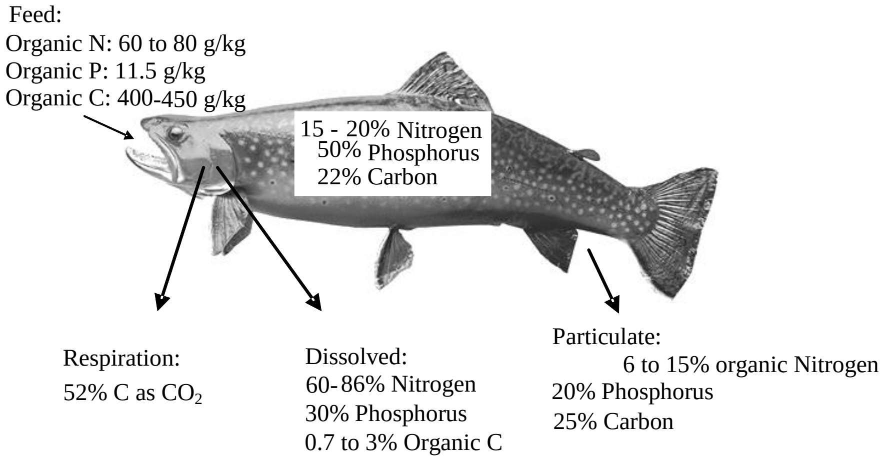

Figure 3 General Mass Balance on Feeding Fish [42]

Hatchery: The tilapia hatchery will likely require entirely freshwater for its operations, though hatcheries can use water with less than 5 ppt salinity and then transfer the fry to higher salinity water for further growth. In addition, water temperatures in the hatchery should be above 20ºC with the optimum reproduction occurring in water above 25ºC, but under the maximum water temperature levels mentioned earlier [38]. For safety, 100 percent of the system volume is exchanged daily. Breeding stock requires higher protein feeds (38 to 43 percent protein) than growout tilapia, which require only around 32 percent. In the first 30 days after hatching the tilapia fry will be fed the high protein diet. Afterwards, fingerlings (20 to 100 grams) can be fed a diet of 35 to 38 percent protein. Hatchery pumping requires both pumping for circulation and aeration as well as pumping to exchange new water. The shrimp hatchery will have similar pumping requirements [37], [42].

Growth Rate: The number of cycles that can be achieved in the 8 month growing season that is being considered depends largely upon the target market (approximately 900-1000 g for tilapia and approximately 15 g for shrimp) and the initial stocking size. Stocking a larger animal early in the season greatly enhances the potential for a larger animal at harvest. The growth rate for shrimp is about 1 gram per week (once the shrimp are placed in the growout ponds at a size of nearly 1 gram).

Tilapia growth rates can also be enhanced by stocking larger animals in the growout ponds (therefore initiating breeding and broodstock during the summer in the hatcheries or an indoor recirculating system). Stocking a larger animal in the growout ponds can yield much faster growth rates than smaller animals. The expected growth rates of tilapia can be approximated using Equation 1 and Table 2, under the assumption that appropriate feed and feeding rates and other best management practices are employed [42].

Equation 1 Fish Growth Rate Equation [42]

$$Growth\ Rate\ (cm/month) = \frac{T - T_{base}}{TU_{base}}$$

Table 2 Temperature Growth Units for Trout, Tilapia, Perch, and Hybrid Striped Bass, °C (°F) [42]

	Trout	Tilapia	Perch	H. Striped Bass
T_{base}	0 (32)	18.3 (65)	10 (50)	10 (50)
TU_{base}	6.12 (28)	3.28 (15)	5.47 (25)	5.47 (25)
T_{max}	22.2. (72)	29.5 (85)	23.9 (75)	23.9 (75)

Harvesting: Partial harvests may occur shortly before the full harvest. If employed, this process would be mostly manual labor, requiring one person about every two meters on a drag net that spreads the width of the pond. Full harvest is usually performing by draining the entire pond and then scooping up the animals and placing them onto a truck. Ponds typically have a slightly sloped grade such that as the pond is being drained the animals concentrate in the deepest section, facilitating the harvest once drainage is complete. Harvesting can be mechanized or performed manually. For the purposes of this analysis, only the pumping and trucking requirements (from the ponds to the processing facility) are accounted for [37], [42].

Pond Pumping and Aeration: The ponds may have to be aerated to maintain proper temperatures and to provide oxygen. Densities under 5 to 10 MT/ha may not need additional pumping for aeration, but might still require pumping to maintain temperatures. However, aeration increases evaporation rates and therefore salinity [37], [42]. For the purposes of this analysis, it is assumed that the stocking densities will be low enough to avoid aeration and pond temperatures will be able to be maintained at safe levels due to the additional pumping required already to counter the salinity increase resulting from evaporation. This issue will need to be clarified in future designs.

Potential Aquaculture Emissions and Solid Wastes: It is estimated that the emissions from aquaculture operations should be negligible (this is referring to the volatilization of GHG's or other emissions emanating from the ponds, not the emissions associated with the energy input for operations, such as pumping and feed production, which are accounted for). The carbon dioxide emitted from fish respiration will be part of the carbonate cycle and support algal growth, and as such will be bound up in algae, a portion of which will be consumed by the tilapia. Nitrogen will be primarily in the form of ammonia and will further nitrify into nitrate (NO_3) in the effluent, which has the potential to be taken up by the salicornia. It is expected that some denitrification will occur from NO_3 into N_2 gas, but it is likely that less than 5 percent of the NO_3

would be denitrified and would only occur under low oxygen (anoxic) conditions [37]. Regardless, N_2 is not a GHG.

Aside from the waste and other materials used in the hatchery, harvesting (nets), post-harvest processing, and packaging material for market ready product, which will be disposed of largely by the municipal system and is ignored in this analysis, there will be minimal waste that requires disposal from the system operations. The organic carbon and protein will be mineralized by bacteria and assimilated by other organisms (fish, shrimp, algae, other bacteria). The leftover minerals in the feed should end up bound in other organisms downstream within the ISAS, including the salicornia, the sandy soil, and the mangrove wetland [37].

Considerations of Culturing Fishmeal Fish instead of Tilapia: One design parameter under discussion was the opportunity to culture fish onsite that are typically caught in the open ocean and used as fishmeal. This would contribute to a more closed-loop aquaculture system, providing all of the fishmeal for the shrimp feed within the ISAS, especially given the high environmental impact of fishmeal capture and production relative to other feed components (see Chapter 2.2.3). However, cursory analysis of this option from an economic perspective reveals that it would be uneconomical due to the relatively low cost of fishmeal in the open market, despite the potential ecological benefits [37]. As such, this option is not considered for this study.

2.2.2 Shrimp-Tilapia Polyculture

There are several potential benefits of producing tilapia and shrimp together. Integrating aquaculture systems allows the waste of one resource to become fertilizer or feed for another. This more balanced ecosystem approach to aquaculture and agriculture provides benefits including nutrient bioremediation capability, mutual benefits to the cocultured organisms, economic diversification, and increased profitability per cultivation unit per pond area [46], as well as avoiding economic and environmental costs associated with wastewater treatment and disposal. In Thailand, Yi and Fitzsimmons [36] found that the economic returns from shrimp-tilapia simultaneous polyculture were higher than shrimp monoculture systems practiced previously. In addition, shrimp-tilapia systems improved water quality, reduced diseases, and minimized the chemicals required for the polyculture systems.

Growing shrimp and tilapia in parallel can be an effective management practice because the two species utilize different niches in the ponds with the shrimp grazing on pond bottoms while tilapia feed in the upper water column [36]. Shrimp feed is often one of the most expensive components of aquaculture operations and is typically of a higher economic and nutrient value than tilapia feed. Tilapia are relatively hardy, omnivorous fish that require a much lower value feed than shrimp, thereby allowing them to thrive on shrimp wastes, leftover feed, algae in suspension, with the supplement of additional tilapia feed when necessary. Using tilapia directly in the ponds or alternating with shrimp in rotation has been shown to reduce bacterial infections in the shrimp culture from *Vibrio harveyi*, due to various mechanisms, not all of which are completely understood [36], [47]. However, the large-scale of the proposed ISAS may make this type of polyculture system logistically constrained, which is why only separate ponds for shrimp and tilapia are evaluated in this Sustainability Assessment.

2.2.3 Aquaculture Feed

The aquaculture feed composition for both tilapia and shrimp can vary based upon species, aquaculture operations (intensive, semi-intensive, open pond, cages, raceway, recirculating), and the systems interaction with outside sources of nutrients (algae or plankton present in input water). The feed component sources and production can play a significant role in the overall system-wide environmental impacts of an aquaculture system. Gronroos et al. [48] found that feed raw materials and manufacturing accounted for approximately 83 percent of the GHG emissions and 84 percent of the total energy consumption from a typical rainbow trout production system in Finland.

Feed components typically include agricultural byproducts such as cottonseed meal, wheat middlings, and some vegetable oils, agricultural products such as corn meal, soybean meal, peanut meal, and rice flour, and fish products such as fishmeal, shrimp head meal, squid meal, and fish oil [49], [50]. When determining the environmental impact of feed production, cottonseed meal and wheat middling components are excluded because they are byproducts that are produced as a result of cotton fiber and wheat flour production and the ecological burden is typically associated entirely with those primary products [50].

On the other hand, the quantity of fishmeal in an aquaculture feed plays an important role in the system's overall environmental impact [51], especially from an ecological perspective because 40 percent of marine fishmeal production and 80 percent of marine fish oil production are used in aquaculture feeds. In fact, 4.5 kg of live fish are necessary to produce 1 kg of fishmeal [50]. Papatryphon et al. [52] found that fish meal and oil production (including fish capture) accounted for most of the energy use in an examination of various feed ingredient combinations (though Boyd & Polioudakis [50] consider fish oil a byproduct of fishmeal production and therefore allocate all environmental burdens to the fishmeal). Papatryphon et al. [52] also found that fish feed with the highest fishmeal content also had the largest net primary production use (in kg C) and acidification potential (kg SO_2 equiv), from a lifecycle perspective. Gronroos et al. [48] found that switching the typical feed to a soy based feed reduced the aquaculture system GHG emissions and energy consumption by more than 11 and 15 percent, respectively.

In the scope of the ISAS, one of the synergistic benefits of the system is captured by producing much of the feed and by processing the tilapia and shrimp for market onsite. Belal and Al-Dosari [53] found that up to 40 percent of tilapia (*Oreochromis niloticus*) feed's fishmeal component could be replaced by salicornia meal with no adverse impact on yield and overall fish health. Acosta-Ruiz [54] found that up to 14.4 percent of shrimp feed (by mass) could be replaced by salicornia meal with no adverse impact on yield or quality. These values were used to formulate a baseline and range of values for incorporating salicornia meal into the feed for both species to minimize the environmental impact of producing the feed.

2.3 Salicornia Agriculture

2.3.1 Historical Perspective of ISAS

The idea of seawater agriculture (halo-agriculture), growing salt-tolerant crops on land using water pumped from the ocean for irrigation, was first taken seriously over 60 years ago, in 1949, when ecologist Hugo Boyko and horticulturalist Elisabeth Boyko attempted to create an attractive landscape that would bring settlers to the newly formed state of Israel following the conclusion of World War II [55]. Without freshwater, the Boykos pumped brackish well water and seawater directly from the ocean to show that many plants could survive with saline irrigation beyond their typical limits. These initial experiments fueled the inspiration for the potential of using the plentiful supply of saline water available worldwide to irrigate food and fuel crops in arid climates for the benefit of humanity without infringing upon the limited resources of freshwater and arable land.

There are two schools of thought when it comes to irrigating crops with saline water: converting salt-tolerant plants into potential crops or converting existing freshwater crops into salt-tolerant varieties. Both perspectives utilize the tools of modern science and agriculture to meet their goals, including molecular biology, genetic engineering, and breeding, and both have had some success. For the ISAS considered in this LCA, only the conversion of salt-tolerant plants into economically viable crops is considered. The latter, converting freshwater crops into more salt-tolerant varieties, was considered as early as 1979 by Emanuel Epstein's team at the University of California at Davis. Epstein was successful in uncovering many of the mechanisms of salt accumulation and management in plants and has shown the ability of some traditionally freshwater crops to grow in low levels of salt [55], [56]. However, this approach has not produced good candidates for seawater irrigation. Tests on several genotypes of wheat seeds have shown substantially reduced germination percentages, delayed emergence, and reduced biomass from regular exposure to saline irrigation water [57]. The maximum salt tolerance of even the most robust crops, such as the date palm, is still less than five parts per thousand (ppt)[3] [55]. Normal seawater is typically about 35 ppt salt, but many gulfs and coastal deserts are bordered by seas with seawater at or above 40 ppt, with the Arabian Gulf no exception, having salinity reaching 46 ppt in some areas [34].

Salicornia bigelovii (hereinafter referred to as salicornia) emerged, with about a dozen other halophytes, as a potential crop suitable for seawater irrigation after several hundred potential halophytes (from 2,000–3,000 halophyte species worldwide) were screened for nutritional content and salt tolerance in a lab setting by Glenn et al. [55].

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[3] For the purposes of comparison in this report all published salinity concentration measurements were converted into parts per thousand (ppt) according to the conversion figures presented in Table 7.9 of [58][58][57][58][58][58][60] http://www.saltlandgenie.org.au/all-about-saltland/unit-7-toolbox/measuring-salinity-and-waterlogging.htm [58]. Note that these conversion rates are not necessarily accurate across all ranges of salinity concentrations in water but suffice here for illustrative purposes only.

Salicornia was chosen for further research in part due to its high yield potential, with oilseed yields nearly four times that of its close relative, *Salicornia europaea* [12]. It is important to note that despite several decades of research, salicornia is still an undomesticated plant that has not been successfully bred or cultivated on a commercial scale.

A successful halophyte crop must be cost-effective. To this end, it must be able to produce useful products at yields high enough to justify the large expense of pumping the high quantity of seawater necessary to avoid hypersalinization of the soil, a side effect of irrigating with seawater if irrigation is not closely managed. To be considered more sustainable than conventional agriculture, halo-agriculture must not damage the environment. Fortunately, if an appropriate site is chosen, the environment in which halophytes can be cultivated is typically non-arable and would pose minimal risks to freshwater sources and biodiversity (see Site Selection Criteria Chapter 3.1). To minimize any impact on freshwater resources, an ISAS should be located at a site where soil and groundwater salinity are relatively high compared to land that is suitable for freshwater agriculture. Depending on a site's pre-existing conditions, irrigation with seawater can either increase or decrease soil and groundwater salinities. Hydrological analysis should be conducted at potential sites to assess and minimize any impact on the suitability of existing water resources for alternative uses. In terms of biodiversity impacts, ISAS would typically increase the biodiversity at a given location through a significant increase in net primary productivity. However, a site assessment should still include analysis of potential impacts on sensitive ecosystems in order to minimize any biodiversity risks.

Sustainable halophyte cultivation of coastal deserts will likely enrich the sandy soil with organic matter, increase biodiversity, and provide jobs for local workers. There is a risk of the aquaculture effluent irrigation water escaping into the sea causing eutrophication. This risk has been shown to be mitigated by proper drainage channel design, irrigation management, soil improvement (buildup of the nutrient pool), and the incorporation of a constructed mangrove wetland to filter the drainage water before it enters the sea [59].

2.3.2 Salicornia Growing History

In 1978 field trials began at Puerto Peñasco, Mexico with several crops being irrigated daily with seawater that was 38 to 42 parts per thousand (ppt) salt. It was quickly realized that the daily flooding of these fields in Mexico used an immense quantity of water, roughly 20 meters annually [55]. Other studies, however, found that much lower quantities of water, given the right climate and soil conditions, could be used to achieve similarly high biomass yields [60].

The first main field trials growing salicornia on a pilot scale continued from 1978 in Mexico through 1988 on a 0.5 hectare field with sandy soil. The field was divided into 200 m^2 flood plots. Several of the plots were grown with seawater that first passed through a shrimp aquaculture farm in which nitrogen and other nutrients were introduced into the seawater from the shrimp feed and waste. No other supplemental fertilizer was needed for these plots. Rainfall was less than 90 mm per year and soil salinity remained at or slightly above seawater salinity year round [12].

Another test plot was irrigated directly with seawater enriched with at least 200 kilograms of nitrogen per hectare as urea, diammonium phosphate, or ammonium nitrate. In these initial trials the seeding rate was 25 kg per hectare which produced a mean density of 3,230,000 plants per hectare [12]. Glenn et al. [12] also found that planting date played a crucial role in the productivity of a salicornia crop. Though total biomass was unaffected by planting date, seed yield and the ratio of seed to biomass increased significantly with later planting dates, indicating that sowing in early April enhanced salicornia's ability to grow and produce seeds. Annual mean yields ranged from 13.9 to 24.6 metric tons (tonnes, or MT) of dry biomass per hectare (ha), with a five year average of 19.9 MT/ha. As a reference, soybean and sunflower dry biomass yields range from 17.0 to 20.4 MT/ha and 10.2 to 15.9 MT/ha, respectively, in the United States irrigated with freshwater [12]. The oil yields of these three crops are also comparable, ranging from as low as 0.35 MT/ha to just over 1.0 MT/ha for best cases [18], [61-64]. It is very important, however, to note the wide variability in the potential yields of salicornia under different growing conditions. Le Houerou [65] noted that salicornia[4] may have a biomass yield of 2 to 5 MT of dry matter per hectare (MT DM/ha) when the land is not degraded and yields of 0.5 to 2.5 MT DM/ha on more degraded land.

2.3.2.1 *Previous Experience with Salicornia – Case Studies*

So far, ISAS projects have not been commercially deployed. Adverse results have occurred due to technology complexity, mismanagement, and, in the case of Seawater Farms Eritrea, political instability. Table 3 summarizes the objectives and results for the salicornia and ISAS case studies evaluated, with further detail provided afterwards in this subchapter.

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[4] Note that Le Houerou did not specify which species of salicornia the data related to.

Table 3 Summary of Past Salicornia and ISAS Case Studies

Date	Location	Project Lead	Objective	Results
2010-2011	Dubai	Internat'l Center for Biosaline Agriculture	Evaluate germination rates, salinity irrigation requirements, and yields for salicornia in UAE	Ongoing
2009-2010	Sonora, Mexico	Global Seawater Inc. and Mexican Gov't	Shrimp, fish, salicornia, mangroves	Mismanagement resulted in extremely low salicornia yields
2009	Kuwait & Sharjah	Dept. of Arid Land Agriculture, Kuwait Institute for Scientific Research	Salicornia research for biomass and animal feed	Promising results for using salicornia as fodder
2002-2009	Ensenada, Mexico	Saline Seed de Mexico	Salicornia production for human consumption	Salicornia tips for salads in Europe were produced
2004-2005	Dubai	Internat'l Center for Biosaline Agriculture	Salicornia research for biomass	Salicornia has the potential to be grown as an oilseed, fodder, or vegetable crop in the UAE
2004-2005	Tucson, Arizona	University of Arizona	Salicornia research and breeding	Breeding program and best varieties evaluated in peer reviewed article
1999-2003	Massawa, Eritrea	Seawater Farms Eritrea	Shrimp, fish, salicornia, mangroves, production of oil, biomass, building material, and fodder	Mixed results. Initial field experiment were successful at establishing salicornia fields and selectively breeding salicornia, as well as producing fish and shrimp and providing jobs to local people. Long-term failure due to political instability, lack of funding, salicornia breeding time, and differing goals among stakeholders
1993-1999	Ras Al Zawr, Saudi Arabia	Behar (Arabian Saline Water Technology Company)	Salicornia research primarily for livestock feed	Mixed results, with yields negatively impacted by weather, though in some seasons high biomass yields were achieved
1978-1994	Puerto Peñasco, Mexico	University of Arizona	Salicornia research	Peer reviewed documentation of results, showing high yields, oil characterization, livestock feed success, and establishing baselines for fertilization and irrigation requirements

ISAS Project: Sonora, Mexico (2009-2010)

Organization: Global Seawater Incorporated, the Mexican Government, and local aquaculture farms.

Technical Lead: Dr. Carl Hodges

Objective: The main objective was the production of shrimp, fish, *Salicornia bigelovii*, and mangroves. The end objective was to irrigate new forests and to produce oil, meal, biomass for fuel, building materials, fodder, and grazing land.

Conditions:

Area: Approximately 200 Hectares

Water salinity: (38-39 ppt)

Soil Condition: Not available

Crop: *Salicornia bigelovii*

Climate: Gulf of California

Results: According to Air Transport Intelligence (ATI) news [66], "Mismanagement in salicornia production is to blame for the delay, Global Seawater co-chairman Carl Hodges tells ATI. The salicornia grown for the trial was not irrigated daily as required, Hodges says. As a result, 1 ha (2.47 acres) of salicornia produced only 80 kg (176 lb) of feedstock. Grown correctly, 1 ha of salicornia should produce between 2,000 kg (4,409 lb) and 3,000 kg (6,614 lb) of feedstock."

Salicornia Project: Kuwait and Sharjah, UAE (Approximately 2009)

Organization: Department of Arid Land Agricultural, Kuwait Institute for Scientific Research, Kuwait

Technical Lead: Dr. Mahdi S. Abdal

Objective: General salicornia research and biomass production for animal feed.

Conditions:

Area: 5 Ha

Water salinity: (34-36 ppt) from well.

Soil Condition: Infiltration rate ranges from 7 to 17 cm/hr with a mean of 13 cm/hr.

Crops: *Salicornia bigelovii*

Climate: Kuwait & UAE (See Abdal [67] for further details)

Results: Project focused on animal feed. The objective was to evaluate the production and utilization of salicornia under Kuwaiti conditions. According to Abdal [67], salicornia appears to be a potentially promising and productive seawater irrigated fodder crop for Kuwait. The results show that salicornia can replace 25 percent of the alfalfa in Kuwait. The study shows positive aspects but also reveals problems related to sandstorms and other environmental issues. The research was not focused on the production of oil.

Salicornia Project: Ensenada, Mexico (Approximately 2002-2009)

Organization: Saline Seed de Mexico

Technical Lead: Mr. Ramon Noriega, OASE

Objective: Salicornia production for human consumption and European market.

Conditions:

Area: 40 Ha

Water salinity: Unknown

Soil Condition: Unknown

Crops: *Salicornia bigelovii*

Climate: Gulf of California

Results: Salicornia tips produced for human consumption (e.g. salads for the European market). According to different sources and conversations (e.g. ICBA and

Jeannette Hoek), there is a company exporting salicornia tips operating in Mexico [68].

Salicornia Project: Dubai, UAE (Approximately 2004-2005)

Organization & Technical Lead: International Center for Biosaline Agriculture (ICBA)

Objective: General salicornia research oriented to biomass production.

Conditions:

Area: Approx. 40 Ha

Water salinity: 46 ppt

Soil Condition: Addition of compost at the ratio of 40 MT/ha

Crops: *Salicornia bigelovii*

Climate: UAE

Results: The research carried out at ICBA demonstrated that salicornia has the potential to be grown as an oilseed, fodder, or vegetable crop in the UAE. As the results show, sandy soil and seawater do not curtail the growth of salicornia. On the sandy coastal areas availability of seawater ensures the smooth farming of the crop. The country has more than 1,300 km of coastline which can accommodate its cultivation at a large scale. Large-scale salicornia production will help reduce the UAE’s dependence on expensive imported fodder [68].

Salicornia Project: Tucson, Arizona (Approximately 2004-2005)

Organization & Technical Lead: University of Arizona

Objective: Salicornia research and breeding program.

Conditions:

Area: Small (greenhouses)

Water salinity: Laboratory 10 ppt

Soil Condition: Good (Laboratory)

Crops: *Salicornia bigelovii* (Testing different seed varieties)

Climate: Controlled environment (greenhouses)

Results: Breeding program and selection of best varieties [69].

ISAS Project: Seawater Farms Eritrea, Massawa, Eritrea (1999-2003)

Organization: Seawater Farms Eritrea

Technical Lead: Dr. Carl Hodges

Objective: The main objective was the production of shrimp, fish, *Salicornia bigelovii*, and mangroves. The end objective was to irrigate new forests and to produce oil, meal, and biomass for fuel, building materials, fodder, and grazing.

Conditions:

Area: Approximately 150 Hectares

Water salinity: 38-39 ppt [59]

Soil Condition: Not available

Crops: *Salicornia bigelovii*

Climate: Relative humidity 60-80 percent, annual precipitation less than 180 mm/yr, summer temperatures exceeding 40ºC from June-August [69].

Results: Initial seed line developed from demonstration plots at Bahia De Kino, Sonora, Mexico, from a line designated SOS-10, derived originally from seeds from Puerto Peñasco. Lessons learned from the project were that it was necessary to plant fields in October or November to harvest plants in April when maximum day temperatures were 30-35ºC. The breeding program in Eritrea focused on a shorter than normal crop cycle, less than 200 days, compared to about 260 days for wild plants (which are harvested in the summer). Also, early-flowering, day-neutral varieties rather than photoperiod-sensitive wild types were preferred [69].

According to experts involved in the project, the project failed in the long term due to political instability, frequent lack of funding, the length of time required for improving desirable traits through selective breeding, and different goals and objectives of the multiple stakeholders. Local producers were more focused on the financial side by producing shrimp and receiving carbon credits rather than in the production salicornia and vegetable oil. According to Vandevivere [59], there was not a significant production of salicornia oil in this project; the main focus was to produce animal feed, though the germplasm from the selective breeding carried out in this project has been shown to be as productive as other varieties [59], [69], [70].

Salicornia Project: Ras Al Zawr, Saudi Arabia (Approximately 1993-1999)

Organization: Behar (Arabian Saline Water Technology Company)

Technical Lead: Dr. Carl Hodges & Mr. Bush

Objective: Salicornia research. Production mainly for livestock feed.

Conditions:

Area: 50 Ha

Water salinity: Unknown

Soil Condition: Coarse sand

Crops: *Salicornia bigelovii*

Climate: Ras Al Zawr

Results: The Ras al-Zawr project belonged to the Arabian Saline Water Technology Company, known as Behar (Arabic for “seas”), owned by 20 Saudi investors. This farm employed the use of giant pivot-irrigation arms to spray seawater pumped straight from the Arabian Gulf to produce the initial salicornia crop in five 50 hectare (123-acre) circles. Weather-related problems affected this pilot effort. In November 1993, winds blew 60 to 70 kilometers per hour (40-50 mph) for 24 hours, kicking up a sandstorm that mowed down newly emerged plants. A possible mitigating measure is to erect higher and better-placed sand berms to deflect the winds, and management practices to ensure that the crop is well established before autumn storms hit [71]. Other experiments were carried out in Saudi Arabia on a laboratory scale. However, they were more focused on the production of feed for animals rather than being focused on the production of oil [72]. In addition, Vandevivere [34] stated that this site had quite high yields (more than 2 MT/ha of seeds) thanks to the beneficial soil characteristics and irrigation practices, though excessive irrigation led to detrimental rise of the water table.

Salicornia Project: Bahia Kino/Puerto Peñasco/Others, Mexico (Approximately 1978-1994)

Organization: University of Arizona Environmental Research Laboratory

Technical Lead: Dr. Edward Glenn

Objective: Salicornia research

Conditions:

Area: Unknown

Water salinity: California Gulf (38-39 ppt)

Soil Condition: Unknown

Crops: *Salicornia bigelovii*

Climate: Gulf of California

Results: Dr. Glenn and others have documented results of these experiments in several papers [12], [26], [55], [73-76]. Salicornia straw was found to be a sufficient supplement to livestock feed for goats. There was an increase in food and water consumption in livestock fed diets with salicornia straw in them, likely due to the higher salt content of the salicornia straw, but no significant difference in growth or carcass quality was found.

2.3.3 Basic Salicornia Physiology

Salicornia bigelovii is a member of the flowering plant family Chenopodiaceae [77], which contains about 20 percent of all halophyte species [55]. It is a C_3, dicotyledonous annual halophyte [78], [79], or salt-tolerant plant, that is native to North America and the Caribbean [69], and is arguably the most salt tolerant vascular plant [79], reportedly able to yield as much biomass and seed as conventional crops even with soil solution exceeding 70 ppt TDS, about twice seawater salinity [12], [60], [75]. It is also known as pickleweed, sea asparagus, samphire, dwarf saltwort, pousee-pied, sea beans, or glasswort in various journals and websites [69], [71], [80-83]. Salicornia is a leafless, salt marsh plant with green, succulent, jointed stems that terminate in fruiting spikes on the upper one-third of the plant with many small (weighing approximately 0.6 to 0.9 mg) oilseeds [34], [69] and can grow up to 50 cm tall, see Figure 4 [12]. Typically, the seeds germinate directly on seawater in the winter or spring and flower for 30 to 60 days in summer. They ripen by September or October [12]. However, in very arid climates, such as that in equatorial Africa and the Middle East, it is often advisable to plant salicornia in the fall (October) and harvest after at least 140 days, before spring (April) [39].

Figure 4 Pictures of Salicornia in Different Stages of Growth [39]

When in bloom, salicornia has numerous flowers along its spikes each of which, if fertilized, can produce one seed each. The flowers typically emerge baring only their stigmas for a few days to weeks to allow for interbreeding with other individuals within a population until the anthers emerge outstretched above the stigmas to allow for self-fertilization if the flower has not already been fertilized. Under typical conditions, salicornia outcrops approximately 30 percent of its flowers and selfs the remaining 70 percent [39]. Throughout the flowering period, the spikes continue to elongate producing new flowers. As a result, a given population may have flowers, seeds, and every maturation stage in between, leading to some issues with timing the harvest when salicornia is grown in an agricultural setting and harvested mechanically [69]. It is also important to note that halophyte seeds typically remain viable and can lay dormant for extended periods of time during exposure to hypersalinity (or other poor conditions) and can begin germination when conditions become viable [84].

2.3.4 Irrigation and Salinity Considerations

Salicornia yields are highly dependent upon soil interstitial fluid, the amount and frequency of irrigation, potential evapotranspiration, soil hydraulic conductivity, and irrigation water salinity. Secondary drivers of salicornia yield are the planting date, planting density, and breeding line [59]. Though soil salinization is an inherent risk of any irrigation project, the risk of soil salinization is exacerbated with seawater irrigation. Salts may accumulate in the soil because plants remove water from the soil through evapotranspiration, leaving salts behind. With insufficient drainage, the salinity of the soil increases to such a point (greater than ~80 ppt) that limestone (calcium carbonate) may precipitate and turn the soil into rock, though this is a slow process. However, through the observance of good agricultural practices, sufficient drainage will maintain steady-state salinity of soil interstitial water below that threshold [85]. Additionally, Glenn et al. [60] notes that soil with high salt concentration can be rinsed with additional water prior to planting to flush out salts that may have accumulated.

Ayala and O'Leary [79] found, in greenhouse experiments, that salicornia grown on 11 ppt salinity water had shoot fresh and dry mass more than twice that of salicornia grown at 0.275 and 33 ppt. This implies that the optimum salinity for salicornia is approximately 11 ppt salinity and that growth was negatively impacted by both lower and higher salinities. However, Glenn et al. [75] indicated that high-salinity water (such as seawater) can be used to irrigate salicornia if specific agronomic practices are employed, namely leaching management. If a sufficient quantity of water is applied so that a portion of the water percolates past the root zone and carries with it excess salt, salicornia can thrive on seawater. This leaching fraction is defined as the depth of water leached below the root zone divided by the depth of water applied at the surface. The higher the leaching fraction, the lower the salinity of the soil water, but the greater the pumping costs and quantity of discharge water to the aquifer or drainage system. Though there is no hard rule to determine the leaching fraction, Ayers and Westcot [86] estimated the minimum leaching requirement (LR) to be calculated using the Equation 2:

Equation 2 Soil Salinity and Leaching Requirement [86]

$$EC_e = EC_w/LR$$

Where EC_e is soil-moisture salinity under irrigation, in dS/m and EC_w is the salinity of the applied irrigation water[5]. It should be noted that this formula is only an approximation.

In contrast to the data from Ayers and Westcot [86], Glenn et al. [60] found in a field experiment with several irrigation rates that biomass yields for salicornia increased in direct proportion to the water application rate and that all irrigation treatments produced a leaching fraction of about 0.35 (Figure 5).

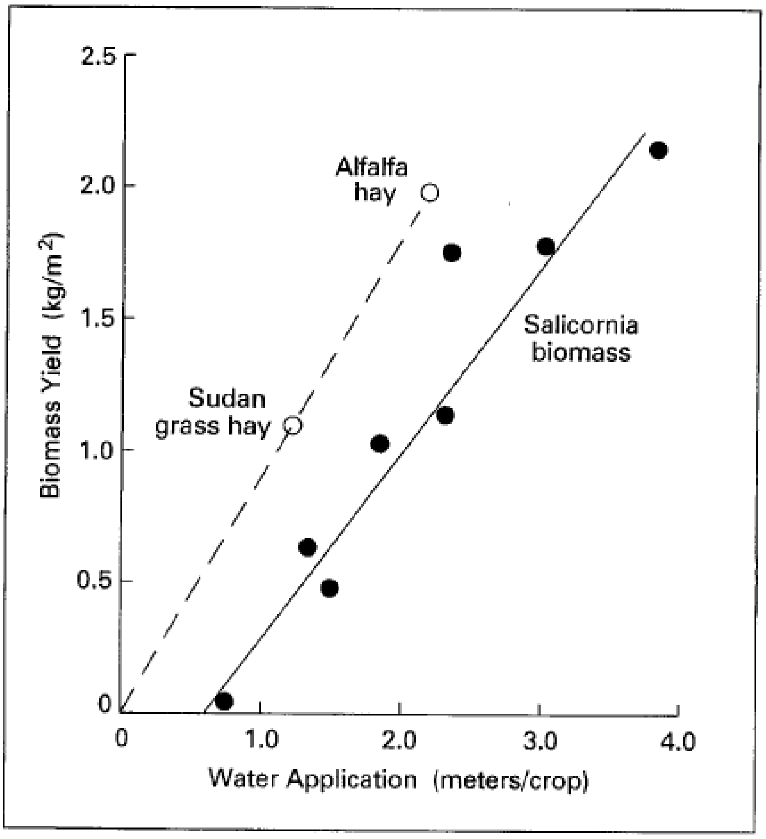

Figure 5 Biomass Yield and Irrigation Requirements of Salicornia with Seawater

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[5] dS/m is converted into ppt by multiplying the dS/m by 0.670, see Table 7.9 of http://www.saltlandgenie.org.au/all-about-saltland/unit-7-toolbox/measuring-salinity-and-waterlogging.htm [58]. This method may not be applicable in all cases, but is used throughout this Sustainability Assessment for illustrative purposes only. Other salinity metrics (i.e. dS/m) may be more appropriate when the ISAS design process is initiated and a site is selected.

Increasing the irrigation depth lowered the soil salinity and increased the plant growth and water use. High yields required soil-moisture salinity to remain below 75 ppt in the top 15 cm of soil, the approximate root zone for salicornia. Consumptive water use by salicornia was comparable to that of conventional biomass crops grown on fresh water, though it required 35 percent more water to compensate for the salinity of the water (so called “salt penalty”). This percentage may vary with the different evapotranspiration rates in the UAE compared with those in this study.

Overall, sandy soils must be kept continuously moist through almost daily irrigation to produce high yields. Soil moisture content should not be depleted below 25 percent when irrigating with seawater to minimize root salinity concentration increases [87]. Reducing the irrigation frequency to three days or longer reduces yields and puts the crop at risk for increased root zone salinization, especially with highly porous soils, despite large irrigation volumes [60]. Irrigation frequency may be more important than irrigation water quantity and quality, though irrigation frequency varies throughout the growing season and is highly dependent upon soil type. Daily irrigation is necessary on beach sands in the summer whereas sandy loam or silty soils can hold enough water for up to ten days without irrigation in winter [87].

Salicornia under daily irrigation may require up to 2.2 times pan evaporation, or 3.8 meters per season for the highest production (for the climate in Puerto Peñasco, Mexico, where this study occurred, [60], [87]). This high water requirement included evapotranspiration (which was about 1.5 times pan evaporation) and the water required to maintain the leaching fraction. Evapotranspiration increased markedly as the crop grew and the plant canopy exceeded 50 percent of the ground surface [60]. The salinity of the soil solution needs to be below 75 ppt to achieve high yields. Glenn et al. [60] also mentions that prior to seeding it may be necessary to flush the soil with additional water because salts tend to accumulate near the surface during non-cropping periods, especially when the water table is relatively shallow.

An approach to maintaining appropriate soil salinity was provided by Vandevivere [85] via the US Salinity Laboratory (see Equation 3).

Equation 3 US Salinity Laboratory Salt Balance [88], [89]

$$C_I I + C_P P = C_E E + C_D D$$

I and P are the amounts of water (depths) from irrigation and precipitation and E and D are water lost from evapotransipiration and drainage below the root zone. C is the concentration of salt in a given stream. If C_P and C_E are zero then the leaching requirement is obtained from Equation 4.

Equation 4 Leaching Requirement

$$D/I = C_I/C_D$$

Using the example from Seawater Farm Eritrea (SFE), Vandevivere [85] found that using 40 ppt seawater for irrigation and C_D less than 80 ppt, to avoid plant toxicity, D/I must then be 0.5, hence “if irrigation water (plus rainfall) is twice a large as evapotranspiration, then soil salinity will remain below 80 ppt, and no irreversible soil calcification will occur.” Vandevivere [85] also determined that evapotranspiration was approximate 50 percent of the potential evapotranspiration. At SFE it was then determined that soil infiltration rates greater than 0.5 cm/hr effectively avoided harmful accumulation of salt in the soil. Plots planted at SFE with infiltration rates less than 0.4 cm/hr resulted in poor harvests in heavy, clayey soils. One management option mentioned is the use of soil amendments (including bottom sediment from the aquaculture effluent settling ponds) to increase infiltration rates. Heavy soils could also be allocated to mangrove silviculture. An alternative irrigation method using central pivot spray irrigation was trialed unsuccessfully on a 5 ha circular plot with a saturated hydraulic conductivity of 2.0 cm/hr, resulting in surface runoff beyond 23 m from the central pivot and salinization of the soil beyond that distance. Pivot irrigation is therefore not recommended on poorly draining soils [59].

Another measure to manage poor infiltration rates in heavy soils is using 0.5 meter deep, V-shaped surface drains at 10-20 meter intervals [87]. These surface drains empty into deeper collection ditches surrounding the field either by gravity, when possible, or with a collection sump and pump. Because many coastal deserts sit atop shallow saline aquifers, there is little risk of contaminating subsurface water bodies. Glenn et al. [87] used this method to irrigate coastal farms for nearly a decade without any noticeable damage to the soil or aquifer. In Abu Dhabi, a seawater irrigation experiment made use of the tides rather than a pump to flood the fields (see Figure 6). Sabkha soils, present widely throughout the Abu Dhabi coastline, tend to be clayey with low infiltration that can be flooded from a single point. This method allows the flooding of a large field (>1 ha) surrounded by an earth berm to a depth of 2-5 cm all at once. Inside the berm a 1 meter ditch around the perimeter of the field distributes water into 0.5 meter ditches 10 meters apart from one another that carry the water to the fields [87].

Auxiliary pumping is often necessary to facilitate this management practice with lateral drainage ditches and the perimeter ditches collecting subsoil drainage in between floodings, controlling salinity in the root zone despite a high water table. The method proved effective in Abu Dhabi for the growth of salicornia and mangroves on sabkha using seawater of 50 ppt salinity. The initial soil salinity was 80–120 ppt in the top 10 cm and was reduced to seawater salinity by just three flooding and draining cycles over one week prior to planting [87]. The water requirement for the sabkha plots was less than what was required for sandy soils because the sabkha retained more of the water, allowing irrigation frequencies to be every 2-3 days in summer and every 4-5 days in winter (Figure 6). However the water usage is still high and irrigation efficiency low compared to conventional freshwater crops, though using the tides to lift water instead of pumps can significantly reduce the energy penalty associated with the high water use required.

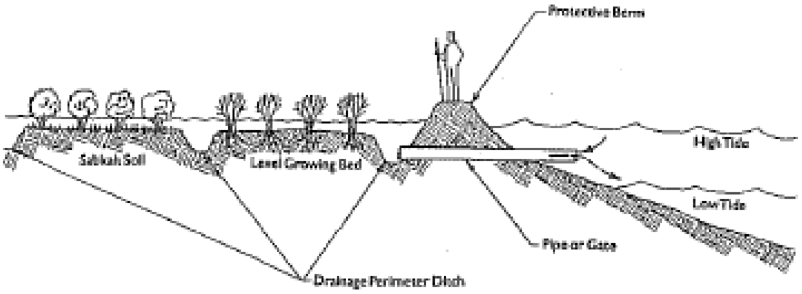

Figure 6 Seawater Irrigation in Abu Dhabi, UAE [87]

Despite the salt penalty, most seawater irrigated crops are located in coastal environments with a large quantity of readily available water that need not be lifted more than several to tens of meters.

2.3.5 Salt Accumulation

There are approximately 6,000 land halophytes [78] out of approximately 272,000 species of flowering plants [90] that have evolved to live on saline water despite the fact that 97 percent of the Earth's water is saline [83]. Nearly 27.5 percent belong to the largest halophyte family, Chenopodiaceae, of which *Salicornia bigelovii* is a member. Halophytes are defined based on their ability "to complete the life cycle in a salt concentration of at least [11 ppt] NaCl under conditions similar to those that might be encountered in the natural environment" [91]. Halophytes, such as salicornia, that can grow at salinity concentrations in excess of seawater (many of which require some salinity to survive) are called euhalophytes (true halophytes) while glycophytes cannot tolerate saline water [79]. Euhalophytes and glycophytes both have reduced growth with salinity increasing past an optimal concentration, but glycophytes typically have reduced growth in water with salinity exceeding 2.75 ppt while euhalophytes do not exhibit reduced growth until salinity exceeds 5.5-11 ppt [79], [91], see Figure 7. The salinity for irrigation water for optimal salicornia biomass growth was determined to be approximately 10 ppt [79], which is the salinity often used in greenhouse experiments [69].

Furthermore, salicornia biomass yields were shown to be reduced by 25 percent between 20 and 33.5 ppt salinity of soil solution and 50 percent at soil solution salinities greater than 33.5 ppt [92], [93]. Salicornia biomass yields were reduced by 25 percent with irrigation water between 33.5 and 45 ppt, with 50 percent reductions with irrigation water salinity greater than 45 ppt [93], [94]. Glenn et al. [87] notes that greenhouse screening trials exhibit a 50 percent reduction in growth of halophytes irrigated with seawater. In stark contrast to greenhouse experiments, field trials using seawater for irrigation have produced halophytes exhibiting growth comparable to that of conventional, freshwater irrigated crops [87]. It should be noted that irrigation water salinity is not the only factor impacting biomass production in salicornia. Irrigation frequency, soil type, and other climatological factors play a significant role in salicornia growth, allowing salicornia to be very productive on irrigation water with salinities in excess of the 10 ppt optimum noted by Ayala and O'Leary [79]. These factors allow for the results published by Glenn et al. [12], [60] claiming that salicornia can thrive in water with salinity up to twice that of seawater (70 ppt).

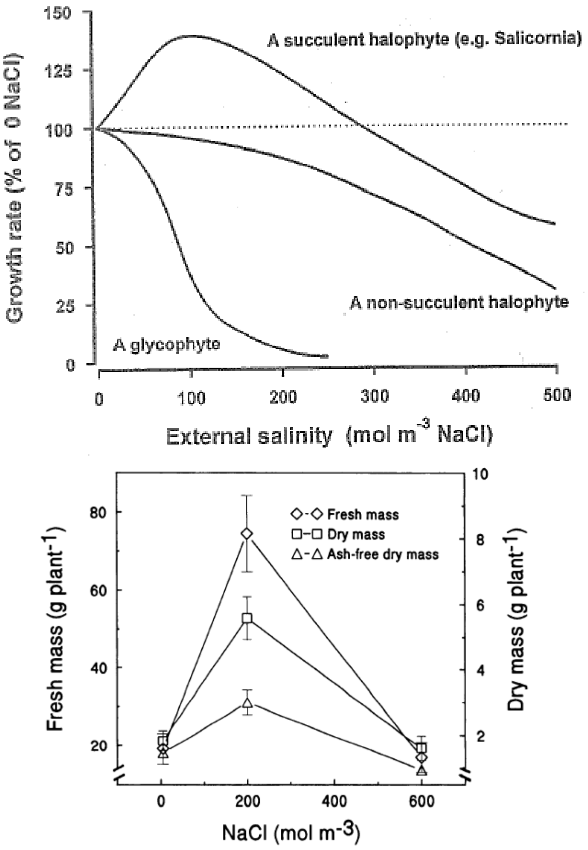

Figure 7 Plant Growth Rate Curves under different Irrigation Salinities [78], [79] [6]

Different species of halophytes have developed various mechanisms for dealing with salinities in soil and water that would kill most freshwater plant species. Salicornia straw can have an ash content ranging from 43 to 52 percent [80], though Ayala and O'Leary [79] and Glenn et al. [87] found that only approximately 30 to 40 percent of dry weight of salicornia biomass is ash content. However, the seeds do not accumulate salt [12].

Some halophyte species secrete excess salt through glands while others have found a way to shed salt-saturated tissues and organs. Still other species can adjust the osmotic potential of different organs or cells within the plant [95] or have roots that are semipermeable membranes allowing water to pass in while filtering salt out. Some species have developed salt bladders that can burst on the leaf surface spreading

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[6] Mol/m^3 can be converted into ppt by multiplying the mol/m^3 by 0.055, see Table 7.9 of http://www.saltlandgenie.org.au/all-about-saltland/unit-7-toolbox/measuring-salinity-and-waterlogging.htm [58]. This conversion is an approximation.

a reflective layer (crinohalophytes, salt excretors, [75]) that cools the leaf [83]. Salicornia is able to store excess salt in the vacuoles of its cells to keep the high salt concentration from negatively impacting metabolic processes [75], [78]. These vacuoles give salicornia its succulence because they end up occupying most of the cell volume. In salicornia the sodium chloride (salt) concentrations in the leaves (and mainly the vacuoles) can exceed 55 ppt.

2.3.6 Germinating Salicornia

Miyamoto [93] examined the germination rates of several halophytes under different salinity irrigation water and noted that though many halophytes experience a 50 percent reduction in seed germination at 10 ppt, a notable exception is salicornia which can germinate readily in seawater. In fact, Stumpf et al. [96] found that salicornia seeds in freshwater were actually inhibited from normal growth compared to 10 or 30 ppt salinity water. Salicornia seeds exhibited a 50 percent reduction in germination at irrigation water salinities in excess of 40 ppt.

Rivers and Weber [97] found that water temperature and salinity play a significant role in the germination of salicornia seeds. They tested the ability of salicornia seeds to germinate at three water temperatures (4.4ºC, 15.5ºC, 26.6ºC) and in a range of salinities from 0 to 80.8 ppt (tests occurred at 0, 10.1, 20.2, 30.3, 40.4, 50.5, 60.6, 80.8 ppt salinity). Results indicated that at lower temperatures the higher salinity water increased germination rates, though it took three to four weeks until most of the seeds germinated. Surprisingly, the experiment at 26.6ºC showed markedly lower germination rates than those at the other two temperatures, though at this higher temperature more germination occurred at lower salinities. Maximum germination at the two lower temperatures occurred at 40.4 ppt, nearly seawater salinity. Higher salinities and water temperatures (such as those of the Arabian Gulf, 40–46 ppt salinity [34], [98] and temperatures exceeding 34ºC in summer) may delay germination and reduce seedlings' vigor and could require dilution of the germination irrigation water (Figure 8).

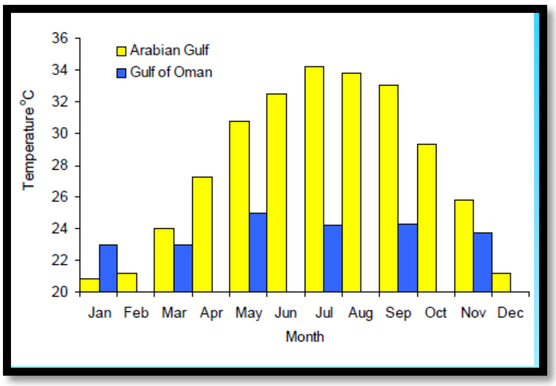

Figure 8 Water Temperature in the Arabian and Omani Gulfs [98]

Rueda-Puente et al. [84] evaluated salt-tolerant, nitrogen-fixing bacteria (plant growth-promoting bacteria, PGPB) that may provide nitrogen to facilitate the growth of salicornia without increasing its chemical fertilizer requirement. One of the main results of their experiment was the wide variability of the four seed ecotypes that were studied and their response to salinity, temperature, and inoculation during germination. One genotype (from Cerro Prieto in Sonora, Mexico), was found in each of the experiments to have the most robust growth habits and tolerance for increased salinity, temperature, and PGPB inoculation. Additionally, when the four ecotypes were inoculated with one of the two PGPB's, *Klebsiella pneumonia* or *Azospirillum halopraeferens*, their germination rates, plant height, root length, and fresh and dry weight all increased. However, germination was most impacted by temperature, with germination delayed in the lower temperature tests. This indicates that salicornia growth could be encouraged by the use of PGPB's during its cultivation, though this method is not further evaluated in this Sustainability Assessment.

In contrast, Troyo-Diéguez and Solis-Cámara [99] tested two salicornia ecotypes, from Sonora and Baja California Sur, Mexico, under various salinity concentrations of diluted seawater. The Sonora seeds germinated faster than those from Baja, though for both ecotypes the percentage of germination was highest under non-saline conditions and after 19 days there was no statistical difference between the germination rates of the two ecotypes. Their results indicate that salinity levels higher than 18 ppt inhibit and reduce the germination rate in both ecotypes.

This could indicate a requirement for diluted seawater during the first few weeks of germination of salicornia in the field. It can be seen from the widely varying results from the numerous experiments presented in this chapter that there is no single best option for germinating and growing salicornia. Ultimately, it will be essential in the early phases of ISAS experimentation to evaluate the viability of germinating salicornia seeds in situ using methods that can be applied to a large scale plantation. This Sustainability Assessment assumes that best practices will be developed and incorporated effectively to germinate salicornia in the field.

2.3.7 Economic Potential of Salicornia

Salicornia, when properly managed, can meet the economic and sustainability requirements described in Chapter 2.3.1. The spikes of salicornia house the seeds and can be harvested for use as a gourmet food item (described as having a ‘wonderfully salty flavor and a refreshing crisp and crunchy texture’ [82]) or the seeds within the spikes can be pressed to extract the oil they contain. The seeds can be extracted from the spikes by drying them and using a hammer mill to knock the seeds from the spikes [55]. The oil can be used directly as an edible vegetable oil, hydroprocessed into HRD or HRJ, or transesterified into biodiesel (fatty acid methyl ester), though this last option is not considered in this LCA. Hydroprocessing is described in detail in Chapter 2.6.1. The properties of salicornia seeds and vegetable oil are examined further in

Table 4. The vegetable oil has a chemical makeup and properties similar to safflower oil.

Table 4 Properties of *Salicornia bigelovii* Seeds and Vegetable Oil [12]

Constituent	Average Percentages
Oil	28.2% of seed weight
Protein	31.2% of seed weight
Fiber	5.3% of seed weight
Ash	5.5% of seed weight
Fatty Acids	
Palmitic	8.1% of Fatty Acids
Stearic	2.2% of Fatty Acids
Oleic	12.5% of Fatty Acids
Linoleic	74.0% of Fatty Acids
Linolenic	2.6% of Fatty Acids

Once the oil is extracted from the seeds, the remaining meal is relatively high in protein and can be used in a variety of livestock and aquaculture feed applications. The leftover biomass that makes up the rest of the support structure for the plant can be dried and used in many ways, including as a component of livestock feed [53], [54], [74], [100] or for energy and biofuel generation.

Al-Batshan et al. [101] tested the impact on the diet of broiler chicks using salicornia meal. Salicornia meal contains an antigrowth factor, saponin, which reduces feed intake and depresses chicken growth. Feed conversion was adversely affected by the salicornia meal in the diet and the salicornia meal was effective in reducing feed intake and body weight gain, but was not effective in reducing abdominal fat deposition. Attia et al. [102] found that blending cholesterol with salicornia meal in broiler chick diets could counter the depressed growth that results from using the salicornia meal as a supplement. Swingle et al. [74] and Kraidees et al. [103] evaluated the growth rates of lambs fed diets with various percentages of salicornia straw and seed meal in them. The dry matter intake was higher for lambs with salicornia compared to the grass control diet. The carcass merit of all lambs was not affected by the test diets. The lambs did not exhibit the negative response to the saponin level in the salicornia meal that inhibited poultry growth described by Glenn [12].

If salicornia biomass is used as forage for livestock, it has been shown that the livestock will have lower feed conversion and higher water intake per unit of growth because of the salt content of the salicornia biomass [74]. This water 'penalty' can be offset from an energy and sustainability perspective due to the widespread availability of seawater compared to freshwater and the relatively low lift typically required for seawater irrigation versus that required to pump freshwater from a deep well. Experimental data showed that lambs fed diets with 30 percent salicornia straw consumed about 85 percent more freshwater and 30 percent more overall feed than those fed a control diet of Common Bermuda Grass (*Cyndon dactylon).* However, many times more freshwater is needed to grow freshwater forage crops than the marginal increase in freshwater required by animals eating a diet composed of halophytic forage crops. If seawater can be used to irrigate a halophytic forage crop, the net savings of freshwater for the crop and livestock feeding system can be significant despite the increase in livestock freshwater consumption [39], [74]. Ultimately, Masters et al. [100] determined that there are ample opportunities to use halophytes to supplement livestock feeds or to select livestock capable of tolerating diets with higher salt intakes to improve the capabilities of producing food in the desert.

The salicornia straw can also be rinsed with seawater and pressed to reduce its salt content (which can range from as much as 30 to 52 percent [39], [80]) to approximately 10 percent making it potentially suitable to be combusted in a conventional boiler or gasified to generate electricity. The straw can also theoretically be converted via the Fischer-Tropsch process into F-T diesel or F-T jet fuel (Chapter 2.6.2) or converted into pyrolysis oil (Chapter 2.6.4).

Salicornia oil has potential for direct consumption as well. The oil from salicornia is between 73 and 75 percent linoleic acid [12], similar to safflower or sunflower seed oil. Dietary studies indicate that diets high in saturated fats pose greater risk for heart diseases while foods high in polyunsaturated fatty acids are typically healthier. Animal fats are high in saturated fatty acids while plant fats are generally high in unsaturated fatty acids. Saturated fatty acids have no double bonds in the hydrocarbon chain. Unsaturated fatty acids have one or more double bond in the hydrocarbon chain [104]. Linoleic acid, the main constituent of salicornia oil, is a polyunsaturated fatty acid with two double bonds in its hydrocarbon chain [105].

In addition to its consumptive uses, salicornia's high tolerance to salinity makes it a potentially valuable plant that can be used in agroengineering projects as numerous other halophytes that are currently exploited for such uses as recycling saline agricultural irrigation drainage water [80] revegetating salt-affected tidal flats, urban landscaping [106], treating aquaculture effluent [107] and phytoremediation of contaminated soils [69].

Glenn and Brown [75] have ultimately come up with four parameters that must be addressed for halophytes to succeed as crops:

1. They must have high yield potential;
2. Irrigation requirements must be within the range of conventional crops and must not damage the soil;
3. Halophyte products must be able to substitute for conventional crop products; and
4. High-salinity agriculture must be adaptable with existing agricultural infrastructure.

The economic and social potential of halophytes evolving as important agricultural crops depend highly upon these four criteria, all of which could be addressed by a properly managed and designed ISAS.

2.3.8 Salicornia Germplasm Varieties and Availability

Salicornia has been experimented upon for nearly thirty years by the researchers at the University of Arizona's Environmental Research Laboratory (ERL) [12], [108]. As a result, some selectively bred lines of salicornia seeds exist at ERL and in various companies experimenting with the crop for various commercial reasons, including for producing salicornia tips for the high-end vegetable market and as a potential crop to treat effluent. Recently, Zerai et al. [69] compared salicornia lines produced in two breeding programs with wild germplasm in greenhouse trials on 10 ppt saline water to evaluate the biomass, oil, and seed yield of the various genetic lines.

The results showed that various seed lines had significantly different yields. Overall, the seeds of five of the varieties averaged 23.7 percent oil content, with a range from 19.6 to 26.4 percent. Biomass averaged 242 grams per plant, with a high of up to 373 grams per plant for one of the cultivars. Harvest index, the ratio of seed to full plant biomass (shown in Figure 9) ranged from 3.5 to 14.3 percent, with a mean of 8.8 percent across lines. Top average seed yields by line ranged from 30.2 to 33.1 grams per plant, with a mean of 23.6 grams per plant among all lines evaluated. Overall, wild salicornia germplasm was found to have sufficient genotypic diversity to support a breeding program. Early improved varieties have exhibited 33 and 44 percent higher seed and biomass yields, respectively, than mean values across lines [69].

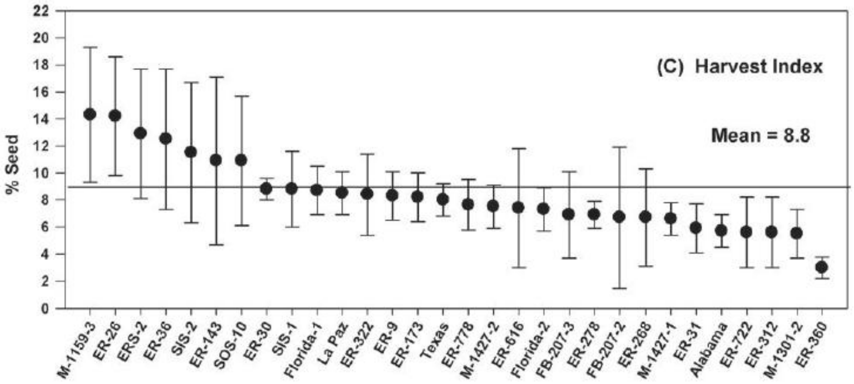

Figure 9 Harvest Index among Seed Lines Evaluated [69]

An interesting result from the experiments was that the plants grown from the Eritrea breeding program (Chapter 2.3.2) had significantly less biomass at harvest and were smaller with more compact flowering but showed no significant difference from their predecessors in terms of seed yield and actually had significantly greater seed size than the wild or Tucson breeding program. The Eritrean lines were selectively bred to compress the crop cycle to avoid the summer months, which are too hot for typical salicornia growth. Thus, early-flowering and reduced biomass growth was selected in the Eritrean breeding program, still preserving seed yields. Massawa, Eritrea is located in the tropics (15º 37’N, 39º 27’E). Eritrea’s climate does not exhibit the seasonal variation of Abu Dhabi (24º 28’N, 54º 22’E). Nevertheless, this seed line may still be suitable for cultivation in an Abu Dhabi ISAS.

2.3.9 Salicornia to Treat Wastewater and Aquaculture Effluent

Grattan [80] found that irrigating salicornia with saline (~12-32 ppt) drainage water from agricultural irrigation was an effective means to reduce irrigation water treatment requirements in California. Brown et al. [107] tested the ability of salicornia to treat the aquaculture effluent from an intensive aquaculture system and found that at even 35 ppt salinity effluent salicornia was able to remove 99 percent of the total nitrogen and nearly 98 percent of the total phosphorous in the effluent. It was also noted that the aquaculture effluent used in this experiment was nearly an order of magnitude higher in nitrogen and phosphorous concentrations than typical shrimp aquaculture effluent. Nutrient removal efficiencies tended to increase with higher salinity effluent. It was also found that a substantial portion of the nutrient removal was due simply to the effluent seeping through the soil. Overall, the concentration of ammonia and nitrate in the leach water (water that could seep into underground aquifers) was always lower than the mean concentration limits recommended by the U.S. Environmental Protection Agency.

2.3.10 Potential Carbon Storage of Salicornia Halo-Agriculture

Glenn et al. [26], [73] evaluated the carbon sequestration potential of cultivating halophytes on a large portion of global drylands and found that halophytes can be grown on approximately 130 x 10^6 ha of coastal deserts, inland salt deserts, and areas of secondary salinization in irrigation districts sequestering between 0.5 and 1.0 Gt of carbon per year. Specifically, the biomass of salicornia grown in Puerto Peñasco, Mexico was found to contain 24.7 percent carbon (and about 90 percent of the total plant's carbon), which is about 5.5 MT/ha of carbon in above ground biomass. Compared to 6.2 MT/ha of carbon combined in above and below ground biomass in managed tree plantations with favorable soil, salicornia presents a significant opportunity for carbon sequestration. Glenn et al. [76] also determined that halophytes require between 225 and 300 kg of fossil fuel carbon input (assuming diesel fuel with 85 percent carbon content) for each 1,000 kg of atmospheric carbon fixed (for all farm operations including pumping water, planting, harvesting, baling, and hauling). As a comparison, cellulosic biomass crops require between 130 and

180 kg fossil carbon per MT of fixed carbon and corn grown as an energy crop requires between 330 and 970 kg fossil carbon per MT of fixed carbon.

To evaluate the potential of long-term below ground carbon sequestration, Glenn et al. [76] plowed halophyte biomass into the soil to determine the quantity of biomass that entered long-term storage as soil humus. It should be noted that desert soils typically have less than 0.5 percent organic carbon to begin with. This low initial quantity of carbon provides an opportunity to enrich the soil by adding organic carbon. The residence time of carbon in dryland soils can be much longer than forest soils [109]. Glenn et al. [26] conducted a field experiment to determine the decomposition rate of buried halophyte biomass in desert soil and found that the decomposition rate depended largely upon the salinity of the irrigation water, the biomass type, and the burial depth. Seawater irrigation significantly slowed decomposition rates compared to fresh water. The experiments indicated that 30 to 50 percent of the buried carbon might enter long-term storage. Additionally, carbon sequestered in the roots of dryland plants is likely to enter long-term storage due to the slower decomposition rates of drylands irrigated with saline water.

As evident in this chapter, much of the data related to the carbon sequestration potential of salicornia has been provided in peer reviewed papers from Glenn et al. [26], [76] that are more than a decade old and seem to be optimistic. Calculations to determine the actual annual carbon sequestration potential for the salicornia fields in this Sustainability Assessment are provided in Chapter 4.6.4. These calculations will need to be verified and refined once empirical experimental data from the region becomes available.

2.3.11 Data Availability and Site Selection Concerns

It should be noted that salicornia and the ISAS are relatively untested systems and the results of this Sustainability Assessment is based on piecewise data for growing salicornia not necessarily in an ISAS. In addition, the yields of salicornia are highly dependent on numerous site characteristics (e.g. soil salinity, water salinity, soil type, climate, etc.) and design considerations (e.g. irrigation method, planting and harvesting periods, field size, etc.). The hypothetical ISAS evaluated in this Sustainability Assessment is not based on a specific site within the UAE or conceptual design. Data and yields, detailed explicitly in Appendix A, may need to be refined when site specific salicornia productivity data becomes available and when a more detailed ISAS design is developed. There is also limited data availability about the long-term environmental impacts of a commercial scale ISAS. For the purposes of this analysis, and using information provided by Glenn [39], unaccounted for negative long-term environmental impacts of an ISAS are assumed to be negligible.

2.4 Mangroves

Mangrove wetlands are especially important ecosystems throughout the world, acting as nursery and breeding grounds for birds, fish, crustaceans, shellfish, reptiles, and mammals, supplying a renewable source of wood, protecting shorelines from wave and tidal erosion, providing a site for the accumulation of sediments, contaminants, carbon, and nutrients, and protecting inland areas against coastal erosion [95], [110]. Mangroves have also been shown to be beneficial economically by providing wood for construction, fuel, and charcoal production as well as non-timber products such as tannin for leather tanning, and their leaves as livestock fodder [111]. However, over the last fifty years nearly one-third of the world's mangrove forests have been wiped out [112] with an additional one to three percent of global mangrove land area (~15-18 x 10^6 ha) lost each year [110], [113]. As a comparison, total global wetland land area is conservatively estimated at approximately 20 x 10^6 ha [114]. Perhaps even more surprising is that mangroves and other coastal ecosystems (coral reefs, salt marshes, and seagrass meadows) have been estimated to deliver the highest annual value in ecosystem services (mangroves at $9,990 per ha per year compared to $2,007 per ha per year for tropical forests, values in 1997 USD) compared to all other natural ecosystems on the planet [110], [115].

One of the main causes of mangrove destruction, among the numerous anthropogenic reasons that include land reclamation, coastal development, excess sediment, overfishing, and logging, is from rapidly expanding aquaculture industry [110], [116]. The ISAS provides an opportunity to develop aquaculture and agriculture in a system that can reclaim mangrove forests and provide a habitat that actually improves the coastline, providing countless ancillary benefits relating to biodiversity and ecosystem health, including the inherent ability of mangroves to act as efficient systems for the removal of nutrients and other anthropogenic pollutants [117]. In fact, during the short time that Seawater Farms Eritrea was operating, it was reported that the mangrove wetlands became home to over 200 species of birds and many other animals that had not thrived in the region for years [64].

One of the most common mangrove species throughout the UAE and Arabian Gulf is the Gray or White Mangrove, *Avicennia marina*. *A. marina* has been studied in the UAE and has been found to have optimal seedling emergence in water with 40 ppt salinity, indicating that it is well adapted to the region. The upper limit for seedling emergence in this study was found to be 60 ppt. Seedlings did best between 0 and 2 meters from the seawater line. It was also found that *A. marina* can be effectively grown away from the shoreline at inland seawater ponds [111]. Similar to other halophytes, some mangroves (*Avicennia* spp.) have well-developed salt glands that appear to function by allowing the plant to excrete excess salts onto the surface of the leaf, thereby providing a reflective layer on the leaf that keeps the plant cool (see Chapter 2.3.5) [75], [78].

A study conducted by the UAE Marine Resources Research Center in Umm Al Qaiwain [118] showed that mangrove forests of *A. marina* reached heights of up to 5 meters after 10 years of irrigation with discharge from tanks and ponds of aquaculture. Seedlings were cultivated both in situ and in greenhouses, with varying success rates in both experiments. Once the mangroves reached a height of approximately one meter (about three years after planting), mortality became negligible. Additionally, soil color and texture in mangrove forests changed over time indicating the accumulation of organic matter from decayed and decaying mangrove foliage. It was determined that the most obstructive factors for *A. marina* planting in sabkhas is the extremely high soil salinity, though this species of mangrove is considered the most appropriate for afforestation in the UAE.

There is limited data available to account for the potential carbon sequestration in a constructed coastal mangrove wetland. In fact, there is an imbalance between the media attention about mangrove forest degradation and related research efforts to study them. Of the published research on coastal ecosystems, 60 percent is on coral reefs while only 11 to 14 percent is related to mangroves despite mangroves receiving more popular media coverage than coral reefs [110]. However mangrove ecosystems are considered highly productive and diverse ecosystems [119], responsible for between 35 and 50 percent of the carbon production of the coastal ocean with primary production rates comparable to those of the rainforest [119], [120]. Mangrove forests are thought to produce organic carbon in excess of the ecosystem requirements, with excess photosynthetic carbon in these ecosystems (export rate plus storage) representing about 40 percent of the net primary productivity [120]. Constructing a mangrove wetland on a previously unproductive coastline could therefore provide an opportunity for significant long-term carbon sequestration. The average age of organic carbon in the upper 1.5 m of sediment in a Brazilian mangrove forest was found to be between 400 and 770 years old. Further, approximately 10 percent of mangrove production was estimated to enter into long-term storage in the sedimentary pool [117]. Global mangrove primary production (assuming ~16 x 10^6 ha of global mangrove ecosystems) is approximately 218 +/- 72 Tg of carbon per year, or approximately 13.63 +/- 4.5 MT (of carbon/ha [121]. However, it is also noted that more than 50 percent of the carbon fixed by mangrove vegetation is unaccounted for in the literature.

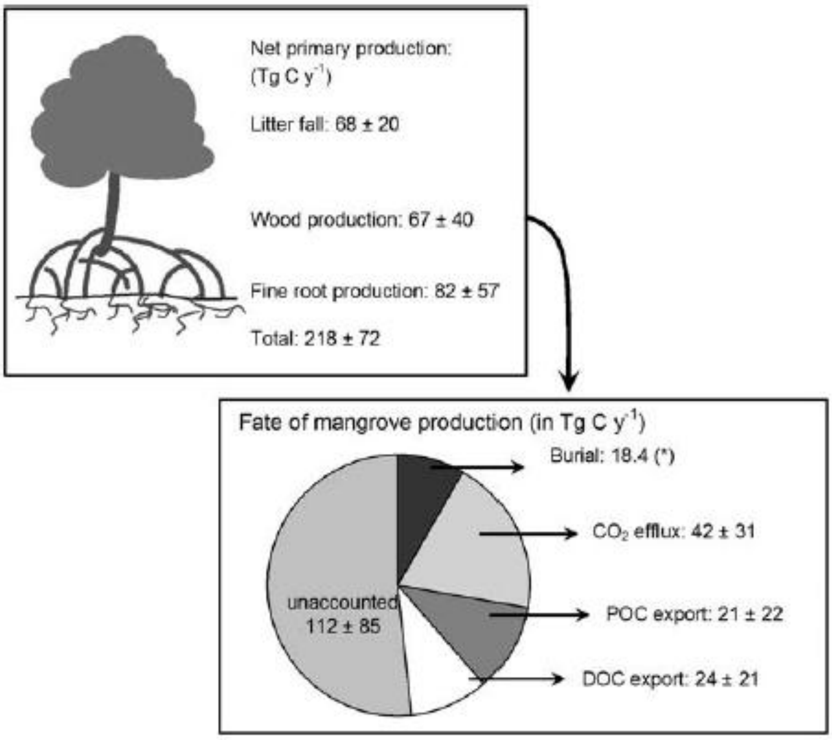

Figure 10 Summary of Mangrove Production [121]

A significant portion of carbon entering long-term storage in mangrove ecosystems is from litter fall. However, newly-fallen litter loses 20 to 40 percent of its organic carbon by leaching when submerged in seawater for 10 to 14 days [117]. But it is unclear how much carbon storage results from this process and how much of the potential litter would be collected in annual thinning and harvests of mangrove biomass for energy production in the ISAS. Approximately 31, 31, and 38 percent of the overall production of mangroves is from litter fall, wood, and root production, respectively [121]. This data is a rough estimate and should be validated further with additional experiments. Kristensen et al. [117] note that estimates for belowground biomass range from 10 to 55 percent of total mangrove biomass. It was also noted that organic carbon and CO_2 emissions from sediments and the water column can be approximately 45 percent of the mangrove production [121]. Poungparn et al. [122] found that elevation and soil temperature were two of the primary factors causing significant rates of soil respiration (CO_2 emissions) in a mangrove forest, with an average rate of respiration from 0.456 to 0.876 [mu]mol CO_2 per m^2-s, lower rates of soil respiration than typical upland forests.

Fujimoto [123] found that over several hundred years carbon was buried at a rate between 0.53 and 0.93 MT of carbon/ha/year in a Micronesian mangrove forest. Christensen [124] found that the mangrove *Rhizophora apiculata* generated aboveground biomass (trunks, branches, prop roots) at a rate of 20 MT/ha/yr. Moreover, leaf production contributed another 6.7 MT/ha/yr. Using carbon content for several typical wood species, though not mangrove wood (49.7 to 55 percent carbon [125]), the resulting aboveground biomass of the mangrove forest studied by Christensen [124] was between 13.3 and 14.7 MT carbon/ha/yr. Another study conducted by Kusmana et al. [126] found that three different species of mangroves in

East Sumatra, Indonesia, had aboveground standing biomass from 40.7 to 279 MT dry weight/ha. However, Kusmana et al. [126] did not provide annual accumulation rates. Duart, Middelburg, and Caraco [116], using the geometric mean of a comprehensive global study of 154 sites by Chmura et al. [114], found that organic carbon burial rates of mangrove ecosystems range from about 139 to 165 grams of carbon per square meter per year (~5–6 MT CO_2e/ha per year). Chmura et al. [114] further stated that the rates of carbon sequestration in mangroves and salt marshes average 210 +/- 20 grams of carbon per square meter per year (~7–8.5 MT CO_2e/ha per year). The results from these studies provide a rough idea of the scale of biomass production possible in mangrove forests, but are not necessarily directly comparable to the species and conditions that would be used for the ISAS. The wide ranges provided in these studies also shed light on the large uncertainty associated with accounting for long-term carbon storage in mangrove ecosystems.

The Seawater Foundation's Mexico Seawater Forestry Project Clean Development Mechanism Report [127] provides theoretical data for the carbon sequestration potential of a mangrove system and species similar to the ISAS. However, it must be noted that this data is not peer reviewed and, to the best knowledge of this team, this report was not approved by the UNFCC as a CDM project. That being said, Poynter [127] found that the net anthropogenic GHG removal by sinks of the proposed system over 20 years of operations is over 19 MT CO_2e/ha/yr. In addition, it is unclear how harvesting biomass from mangroves for further processing (see Chapter 2.5) will impact the carbon balance of the system. The harvesting process for the mangrove biomass is also not well defined, as it may be highly labor intensive.

For comparison purposes, Barford et al. [128] studied long and short term sequestration of atmospheric CO_2 in a mid-latitude forest and found that 1.6 +/- 0.4

MT carbon/ha/yr was stored over eight years, with 60 percent of the carbon in live biomass and the rest in woody debris and soil. The U.S. Environmental Protection Agency [129] notes that pine plantations in the southeast USA can store approximately 2.57 MT of carbon/ha/yr over 90 years, which is approximately 9.42 MT CO_2e/ha/yr.

2.5 Salicornia Straw and Mangrove Biomass Processing

The decision for how to use the salicornia straw and mangrove biomass in an ISAS will play an important role in its LCA, especially because the salicornia straw accounts for nearly 90 percent of the harvestable mass from the salicornia fields. Three biomass conversion technologies are considered; gasification and subsequent combustion to generate electricity, biomass to liquid fuels using Fischer-Tropsch synthesis, and pyrolysis to bio-oil. Glenn et al. [76] noted that though the heating value of halophyte biomass varies with the species, with ash content being a major variable, typical halophyte biomass heating value falls within the range of lignite A or B coals.

2.6 Oil and Biomass to Biofuel Processing

2.6.1 Hydroprocessing

Conventional jet fuel is composed of the kerosene fraction of crude oil. It distills between the gasoline fraction and the diesel fraction and accounts for approximately four to five percent of the initial crude oil [130]. Thermal cracking and hydroprocessing allow further utilization of the crude oil to the above fractions especially since heavier crudes have become more prevalent. As global oil demand continues to increase over the next two decades sustained investment is necessary to account for the decline in output from existing fields, which will drop by two-thirds by 2030 [131]. Supplementing this, a substantial supply (approximately 50 percent by

2030) of crude oil is forecasted to come from fields "yet to be developed or found" and unconventional oil [131]. This uncertainty in the oil supply chain is putting pressure on transport sectors dependent on oil-based fuels to curb their consumption and find alternative sources of fuel to mitigate the impending social, environmental, and economic costs associated with continued fossil fuel consumption [131].

Though biodiesel and ethanol derived from biomass feedstocks are technologically proven fuel alternatives for some modes of ground transport, both are limited from becoming aviation fuel substitutes. Aviation requirements rule out ethanol due to its relatively low energy density (26.8 MJ/kg [132]) compared to that of conventional Jet A fuel (43.2 MJ/kg; [61]). Biodiesel is unacceptable as a drop-in alternative for Jet A due to its high freezing point (around 0ºC) while Jet A needs to be able to withstand temperatures below -40^{o}C [30].

2.6.1.1 Hydroprocessed Renewable Jet Fuel

Proprietary processes developed by UOP Honeywell and Neste Oil among others allow the conversion of nearly any vegetable oil into a jet fuel that has characteristics similar to conventional Jet A [30]. Hydroprocessed Renewable Jet (HRJ) Fuel, also referred to as biomass-derived synthetic paraffinic kerosene (Bio-SPK), is actually derived from further refinement of Hydroprocessed Renewable Diesel (HRD). Because of this additional step, HRJ generation is more energy and carbon intensive, and yields less jet fuel per unit volume of vegetable oil than creating HRD. Hydroprocessing requires energy inputs in the form of natural gas and electricity and a substantial amount of hydrogen. Hydrogen is typically produced by the steam reformation of natural gas, and is a well-defined, proven process used in numerous industries [133]. Byproducts of both the HRD and HRJ processes include propane mix gas and, in the case of HRJ, naphtha [134].

HRJ has proven to meet or exceed almost every measurable parameter that conventional Jet A is required to meet by ASTM standards. Engine tests revealed that HRJ in a 50-50 blend with conventional Jet A meets or exceeds all measureable operational characteristics and has no ill effects on engine components. In fact, HRJ has less sulfur and a higher energy density (44.1 MJ/kg, [61]) than conventional Jet A [30]. It is anticipated that HRJ will be approved internationally as an aviation fuel in 50-50 blends with conventional Jet A by the end of 2010 in accordance with ASTM D-4054 and D-7566 [7]. The 50-50 blend is currently necessary to maintain a minimum level of aromatics necessary for proper fuel system seal function, aromatics that HRJ lacks in pure form. It is expected that a 100 percent HRJ fuel with blended aromatics will be certified for use in commercial aircraft in several years. Bio-derived naptheno-aromatics have the potential to be used as replacements for the aromatic components of Jet A, but require experimental verification and are unlikely to be certified in the near-term. Naphtha is not typically used directly as a fuel but it can be converted into gasoline through catalytic reforming [135].

Table 5 HRD and HRJ Energy and Hydrogen Requirements, calculated from ICAO [134]

HYDROPROCESSED DIESEL (HRD)							
	Inputs		**Process Energy, MJ/MT oil**		**Products, MT/MT oil**		
HRD Conversion	**Oil, MT**	**H_2, MJ/MT oil**	**Electricity**	**Natural Gas**	**HRD**	**Propane mix**	
Worst	1.000	0.015	135	208	0.830	0.020	
Base	1.000	0.027	161	208	0.842	0.048	
Best	1.000	0.038	188	208	0.860	0.050	
HYDROPROCESSED JET FUEL (HRJ)							
	Inputs, MT & MJ		**Process Energy, MJ/MT oil**		**Products, MT/MT oil**		
HRJ Conversion	**Oil**	**H_2, MJ/MT oil**	**Electricity**	**Natural Gas**	**HRJ**	**Propane mix**	**Naphtha**
Worst	1.000	0.022	148	229	0.578	0.020	0.258
Base	1.000	0.034	194	250	0.587	0.048	0.262
Best	1.000	0.045	245	271	0.599	0.050	0.268

2.6.2 Gasification

Gasification can be used to convert any carbon containing material into syngas (carbon monoxide and hydrogen) using high temperatures and controlling the input of oxygen or steam. The resulting syngas can be used as a fuel to generate electricity, or can be further processed into Fischer-Tropsch fuels (see Chapter 2.6.3). The electricity generation pathway assumes a range of efficiencies typical in biomass boilers, from 32.1 to 43 percent, the high range representing an Integrated Gasification Combined Cycle (IGCC) biomass power plant [61]. Lower efficiency boilers are the option of choice for smaller scale and for distributed feedstock production. It is assumed that all feedstock production is done at industrial scale and therefore transportation to a centralized, capital-intensive facility is feasible and preferable for this pathway, and the conversion efficiencies take this design parameter into account. It is important to note that the high salt content of the salicornia straw and mangrove biomass may reduce the overall conversion efficiency of this process.

2.6.3 Fischer-Tropsch Synthesis

The Fischer-Tropsch (F-T) process utilizes the syngas generated from gasification of nearly any carbon-based feedstock converting it into green diesel, green jet fuel, and green naphtha. Green jet fuel, or F-T Synthetic Paraffinic Kerosene (SPK, or F-T Jet Fuel) is already approved for use in commercial aviation, but is not widely available [7]. Coal, natural gas, and biomass are all suitable feedstocks for this process. The feedstock is first gasified into syngas composed of mostly hydrogen and carbon monoxide which is then converted into the desired final product along the Fischer-Tropsch process [7]. Within the F-T process a hydrocracking step may be necessary to break down longer carbon chain products when cobalt catalysts are used for F-T diesel and F-T jet fuel [136]. The process efficiency is an important component of the F-T process that impacts the greenhouse gas emissions and net energy balance of the system and is defined as the ratio of the thermal energy of the fuel product over the sum of the original thermal energy content of the feedstock and the associated process energy. The energy and carbon balance of the F-T process can vary significantly depending upon the feedstock and source of the process energy. For the LCA, we have assumed that all of the process energy is from the biomass itself, thereby reducing the net fuel product output, but incurring no fossil energy or emission penalties. The F-T process produces a range of products depending upon the desired end product and the catalysts used, including F-T jet fuel, F-T diesel, and F-T naphtha, and in some cases, electricity for export to the local grid or for use onsite.

As defaults, the process efficiency assumptions from various sources were used [61], [137-140] ranging from 42 percent in the worst case to 52 percent [137] in the best case, with a baseline process efficiency of 45 percent [138], regardless of the feedstock or desired end products. The F-T process can technically be performed with minimal or no additional process energy input; the feedstock itself can be used to provide the process energy [138]. To calculate the quantity of fuel produced from the F-T process the energy of biomass input was multiplied by the process efficiency to determine the total energy in the fuel products. Under these assumptions, according to Gray et al. [139] and Kreutz et al. [137], the biomass to liquid (BTL) F-T process can yield electricity as a coproduct. The assumptions are based on the ratio of electricity produced per unit of biomass energy input examined in Gray's scenarios. However, not all of the literature supports the generation of electricity as a coproduct in a BTL facility. The NETL Report [141] calculates that only a coal based F-T process without carbon capture generates enough electricity that a portion of it can be exported. Hence, for our best and base default cases, we have assumed electricity is exported as per Gray's assumptions, and in our worst case we have assumed no net electricity is exported.

Not all of the biomass input can be converted into F-T Jet Fuel. According to ICAO [134], of the fuels produced from the F-T process, only 25 percent can be expected to be F-T jet fuel, with 55 percent F-T diesel and the remainder as naphtha. However, Gray et al. [139] estimates, based on differences in boiling fractions and chemical compositions, that up to 60 percent of the product slate could be jet fuel, with the remainder being naphtha. Naphtha is not typically used directly as a fuel but it can be converted into gasoline through catalytic reforming [135]. An additional use of parts of the naphtha produced through the F-T process, depending on its composition, can be used as a source for napthenes and aromatics that may in the future be used for blending with bio-SPK to meet aromatic requirements for 100 percent bio-derived jet fuel. The well-to-gate data in the NETL Report [141] was used to determine a carbon credit range for naphtha when depending upon the pathway under evaluation. Otherwise, the energy content of naphtha is used in the pathway calculations, as detailed in Appendix A.

It should be noted that the F-T process is suited for carbon capture and storage (CCS) due to the relatively pure stream of carbon dioxide emitted from the process [61], [139], [141]. In addition, it can be combined with concentrated power (CSP) plants to provide part of the process heat thus allowing for higher conversion rates of biomass to liquids [142]. However, we have not incorporated CCS or CSP for the purposes of this analysis primarily because the capital cost of implementation of F-T plants is already significant raising the difficulty of widespread commercial adoption of the process.

2.6.4 Pyrolysis

Slow pyrolysis is a process typically used to convert biomass into charcoal or bio-char [143]. Fast or flash pyrolysis produces liquid fuels or other liquid chemicals from biomass as a uniform, virtually ash-free liquid that has a significantly increased energy density compared to the input biomass. Pyrolysis is carried out in the absence of oxygen at atmospheric pressure and temperatures ranging from 300-600ºC [143], [144]. Both fast and slow pyrolysis require densifying the biomass by chipping or grinding prior to its entry into the reactor. Slow pyrolysis heats biomass to temperatures between 300ºC and 400ºC. Fast pyrolysis uses a high rate of particle heating to temperatures around 500ºC and a rapid cooling of vapors to condense the liquids [143]. Fast pyrolysis offers significant logistical and economic advantages over other thermal conversion processes because the liquid can be stored until required or readily transported for utilization elsewhere [145]. The resulting liquid is dark-brown with a heating value ranging from 16,000-19,000 MJ/MT, roughly equal to that of wood which is approximately half the heating value of fossil fuel oil [143], though Holmgren et al. [146] mentions that pyrolysis oil may be only about 36 percent the heating value of crude oil. The energetic yields of the fast pyrolysis process are approximately 55-60 percent [143]. It is important to note that the yields of char and gas increase significantly for higher ash contents in the biomass at the expense of bio-oil yields, with sodium and potassium having a large impact, see Figure 11 [143]. Oil yield can drop to below 50 percent by weight for biomass inputs with large ash content.

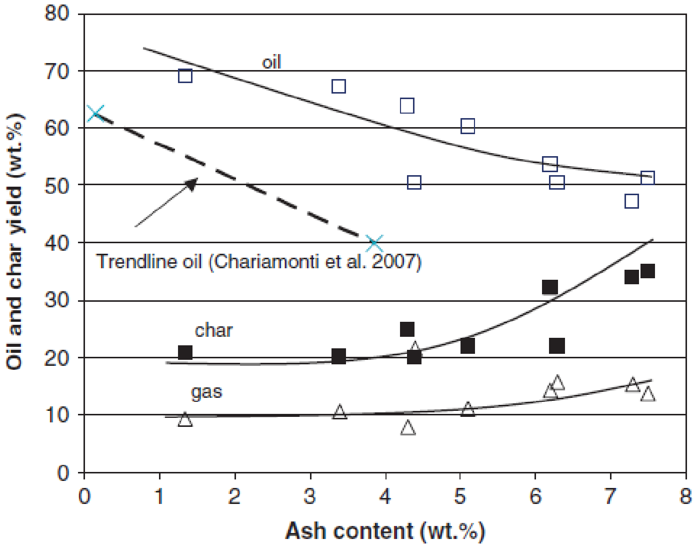

Figure 11 Impact of Ash Content on Oil and Char Yield [143]

Liquids used as fuels can be produced with longer vapor residence times of up to 6 seconds. However, most woods give maximum liquid yields of up to 80 percent by weight of the dry feed (with 64 percent weight organics and 16 percent weight water) at 500-520ºC with vapor residence times under 1 second [145]. Short residence times can result in a less homogenous liquid product, while longer residence times may reduce yield and adversely affect bio-oil properties. Additionally, biomass particles have to be very small to be able to be rapidly heated in the reactor to achieve high liquid yields [145]. There are widely variable claims relating particle size to liquid yields, all of which are highly dependent on ash and moisture content of the feedstock. Particle sizes from 2 to 6 mm have been used to achieve yields from 55 to 76 percent by weight of dry feedstock [145].

Bio-oil has been successfully fired for over 300 hours in a diesel test engine where it shows similar characteristics to conventional diesel in terms of engine parameters and emissions. Pyrolysis oil may also be able to be tailored to specific chemical compounds that could result in greater economic value than as a fuel, however, these processes and products are not yet well documented [145]. The pyrolysis process is illustrated in Figure 12.

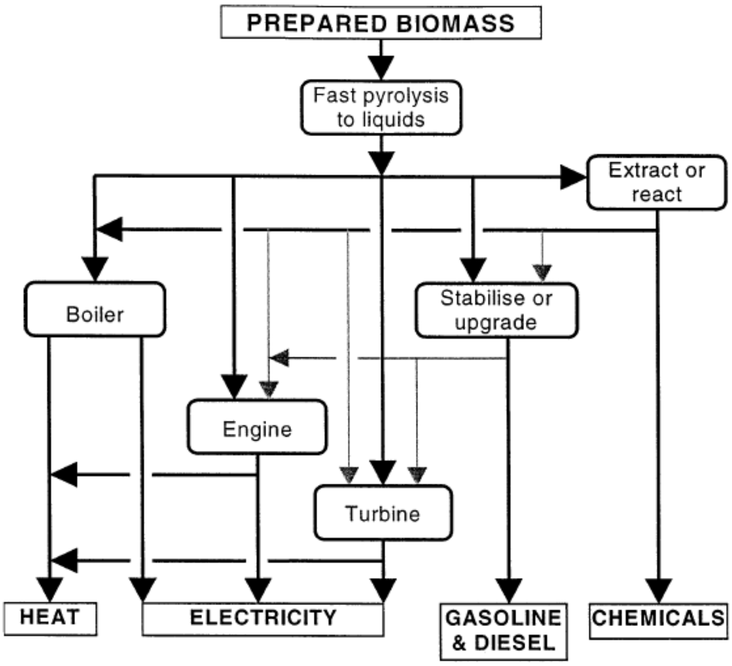

Figure 12 Diagram of Pyrolysis of Biomass [145]

Overall, using flash pyrolysis to process wood waste into pyrolysis oil to generate energy is relatively environmentally benign [144] and pyrolysis oil to gasoline has been shown to have less than half of the cradle-to-grave fossil CO_2 emissions when compared to ethanol [146] as well as having lower emission levels than petroleum fuels [147]. In fact, an LCA of a biomass-to-oil facility used to create pyrolysis diesel resulted in a reduction of 87.7 percent for the 100 year global warming potential compared to conventional diesel [148]. Roberts et al. [149] found that slow pyrolysis of corn stover, switchgrass, or yard waste into bio-char for use as a soil amendment all produced a surplus of energy and sequestered between 442 and 885 $kgCO_2e/MT$ of dry feedstock, although it should be noted that one type of switchgrass system evaluated acted as a carbon source, not sink.

2.6.5 Overall Biomass Processing Pathway Assumptions

Despite the wide variability and uncertainty with the several biomass processing technologies proposed herein, Table 6 provides a qualitative list of the assumptions used in the LCA model, with quantitative data provided in Appendix A.

Table 6 Biomass Processing Pathway Assumptions

Assumption	Applicable Pathway
The mass of salicornia and mangrove biomass is reduced by their respective salt content and	Gasification, Fischer-Tropsch, Pyrolysis
Fischer-Tropsch Average Product Slate used for all pathways	Fischer-Tropsch
Process efficiency used to calculate net fuel output based upon energy content of biomass	Gasification, Fischer-Tropsch
Biomass conversion into liquid fuel used to calculate net fuel output	Pyrolysis

2.6.6 Biofuel Pathway Analysis

The relative environmental impact of a given biofuel may be highly dependent upon the assumed use (or accounting) of its coproducts. This also makes it difficult to compare one feedstock to another because the allocation of emissions among the coproducts can significantly skew the results (further detail on allocation in Chapter 4.3). Salicornia is greatly impacted by this accounting mechanism due to the relatively high quantity of biomass harvested per hectare relative to the oil yield. As part of a related effort, several biofuel feedstocks were compared to one another along several fuel processing pathways using transportation distance traveled (pax-km) and avoided fossil fuel consumption (opportunity carbon benefit) as common metrics by which to make the comparison. Using this methodology it is possible to compare feedstocks used primarily to create ground transportation fuels with those used to create aviation fuels while concurrently accounting for all relevant coproducts. This analysis by Warshay et al. [8] compared seven crops along 18 different fuel production pathways, as shown in Table 7. This analysis revealed several interesting characteristics about the potential for large scale salicornia based biofuels.

Table 7 Feedstocks and Pathways Considered (adapted from [8])

Feedstock Type	**Oilseeds/Oil Crops**	**Starch/Sugar**	**Lignocellulosic**
Crops Considered	Salicornia (Sal) Jatropha (Jat) Palm Algae (Alg)	Corn Sugarcane (SC)	Switchgrass (SG)
Pathways	1 – Sal, Palm, Jat, Alg: HRJ-Gas 2 – Sal: HRJ-FTJ 3 – Sal, Palm, Jat: HRJ-Pyr 4 – Sal, Palm, Jat, Alg: HRD-Gas 5 – Sal: HRD-FTD 6 – Sal: HRD-Pyr 7 – Sal, Palm, Jat, Alg: BioD-Gas 8 – Sal: BioD-Cell 9 – Sal: BioD-Pyr	10 – Corn, SC : Eth-FTJ 11 – Corn, SC: Eth-FTD 12 – Corn, SC: Eth-Gas 13 – Corn, SC: Eth-Cell 14 – Corn, SC: Eth-Pyr	15 – SG: FTJ 16 – SG: FTD 17 – SG: Cell 18 – SG: Pyr
Definitions	Primary Processing Options: **HRJ** – Hydroprocessed Renewable Jet Fuel; **HRD** – Hydroprocessed; **Eth** – Ethanol from sugar; **Cell** – Cellulosic ethanol from hydrolysis of starch Coproduct Processing Options: Renewable Diesel Fuel; **FTJ** – Fischer-Tropsch Jet Fuel; **FTD** – Fischer-Tropsch Diesel Fuel; **BioD** – Biodiesel from transesterification of oil; **Gas** – Gasification (to generate electricity); **Pyr** - Pyrolysis		

Several of the salicornia pathways were relatively low compared to the other pathways in terms of total fuel produced (Figure 13) and roughly in the middle of the pack in terms of GHG emissions per unit of fuel (Figure 14) and process energy per unit of fuel produced (Figure 15). However, when it came to units of transportation per land area, salicornia ranked much higher (Figure 16, not including algae). Furthermore, all salicornia pathways had reduced GHG emissions per passenger-kilometer compared to the fossil fuel being replaced (Figure 17). The analysis reveals that, despite salicornia's relatively low oil yield per hectare, its high biomass yield makes it a potentially viable replacement for fossil fuels from a GHG emission and net energy perspective, comparable with other biofuel feedstocks. Additionally, the opportunity carbon benefit metric reveals that the most GHG emissions can be avoided by converting as much biomass as possible into liquid fuels as opposed to gasifying them to generate electricity. This is illustrated in Figure 17 by the replacement of many of the gasification pathways with liquid fuel pathways in the ranking (from left to right) when compared with Figure 13 to Figure 16. This is due to the biofuels being used to replace the relatively higher emission fossil liquid fuels used in combustion engines. This turns out to be a better use of the biomass from a GHG mitigation perspective in the transportation sector.

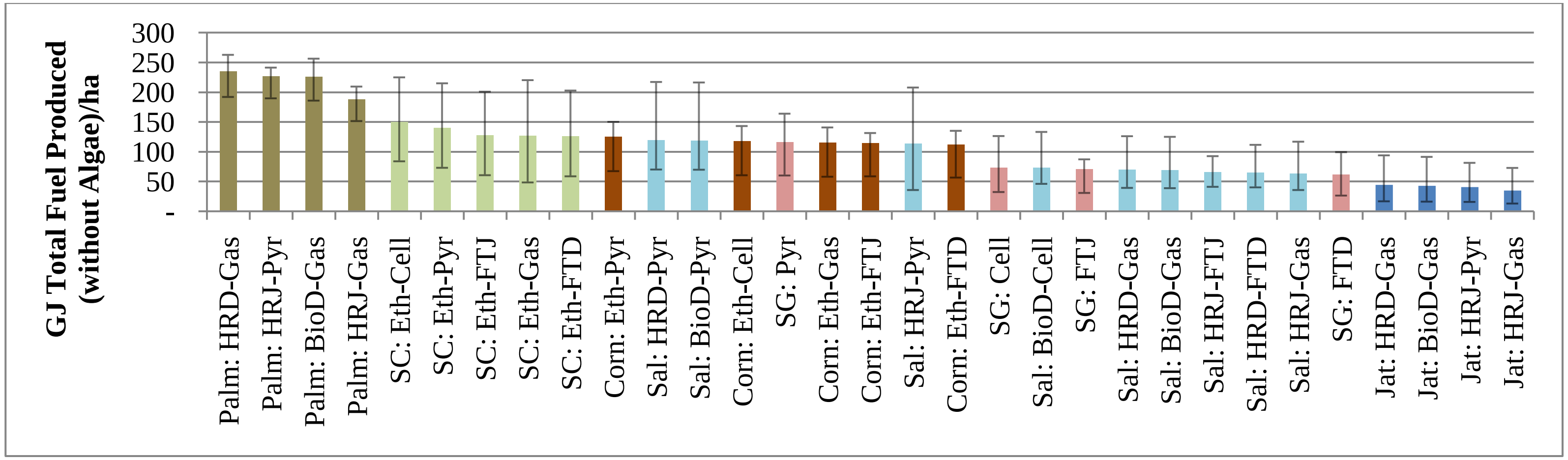

Figure 13 Total Fuel Produced per Hectare (excluding algae, adapted from [8])

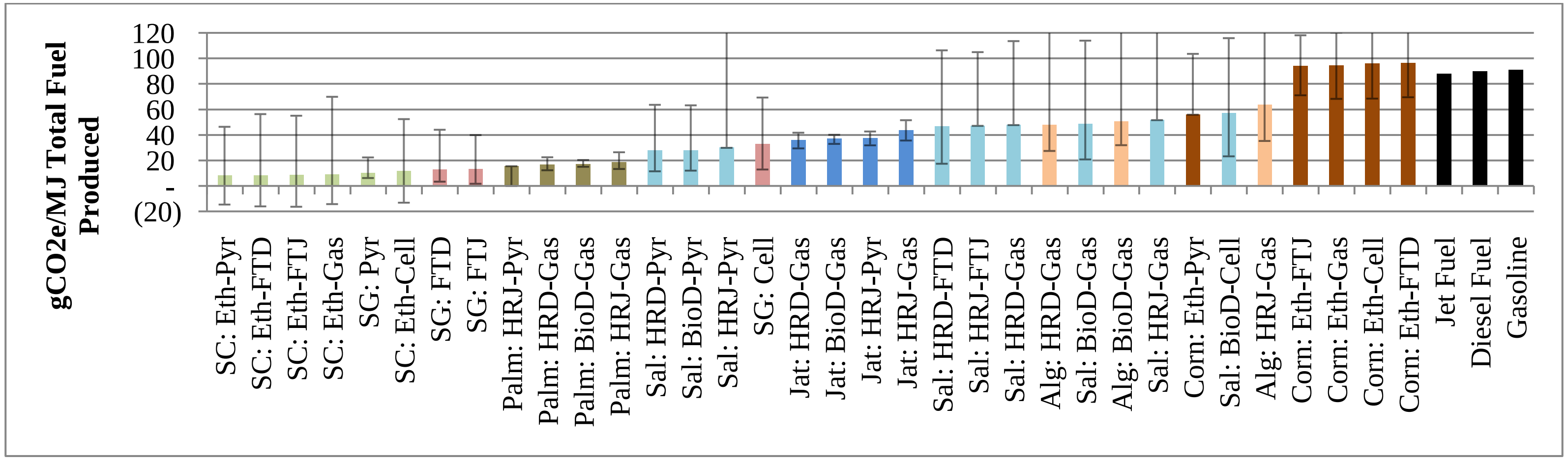

Figure 14 GHG Emissions per unit Biofuel Produced (adapted from [8])

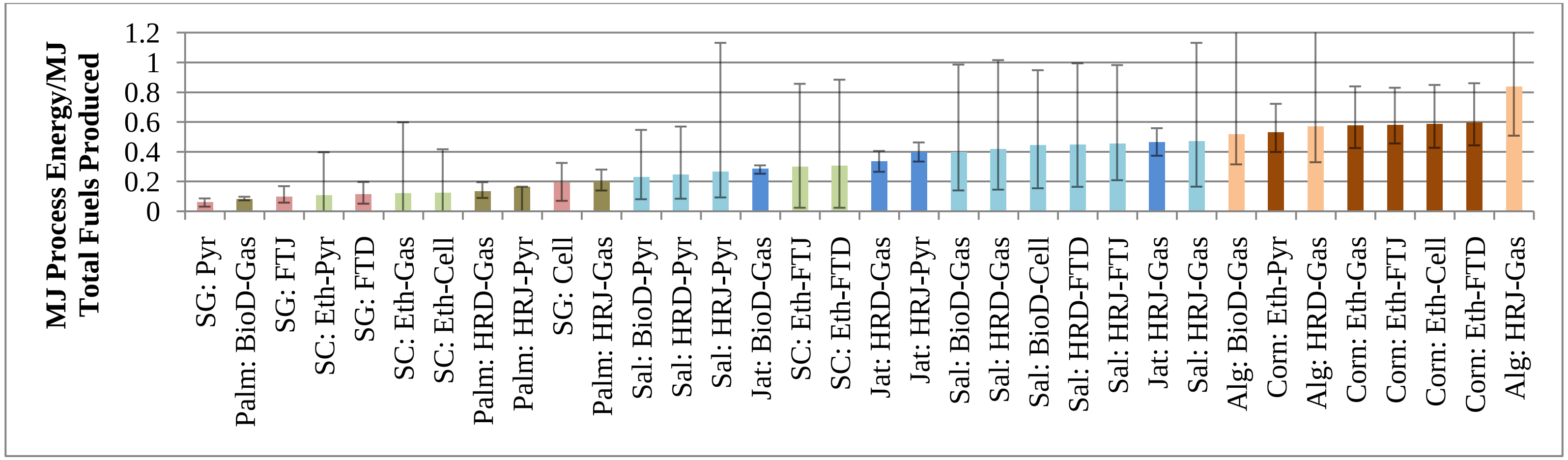

Figure 15 Fossil Process Energy input per unit Biofuel Produced (adapted from [8])

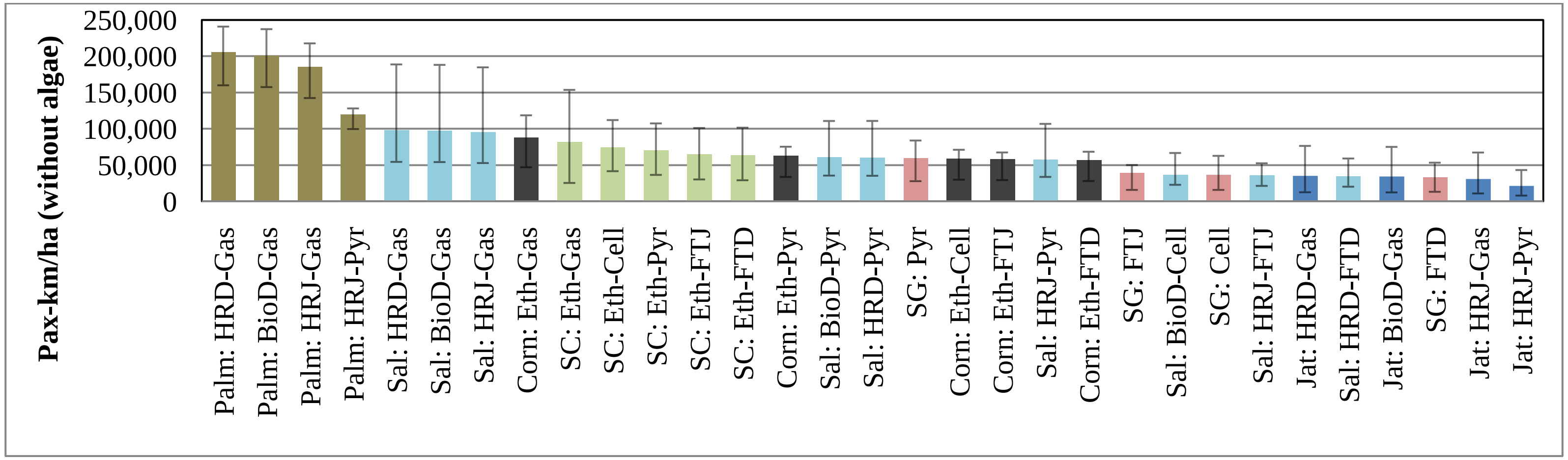

Figure 16 Transportation Service by Pathway per Hectare (excluding algae, adapted from [8])

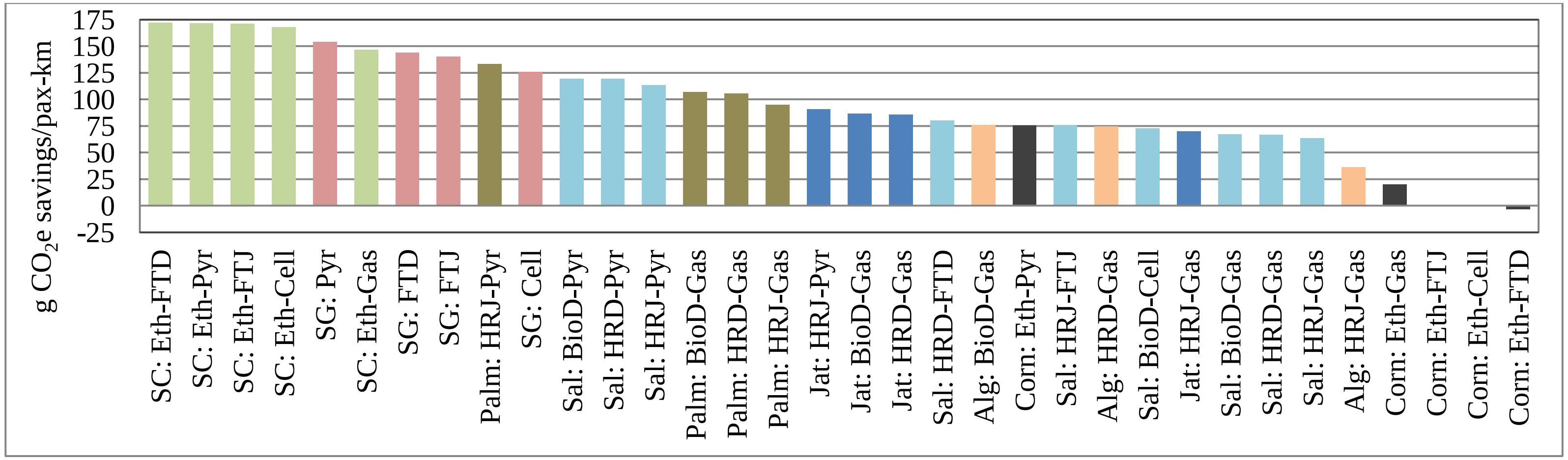

Figure 17 Life Cycle GHG Savings per Passenger-Kilometer through the replacement of Conventional Fossil Fuels with Biofuels (adapted from [8])

CHAPTER 3

3 Analytical Description of Physical ISAS System

This chapter describes the site morphology and characteristic requirements for the establishment of a large-scale commercial ISAS.

Glenn et al. [76] determined that there are 49.5 million hectares of usable coastal desert land for halophyte cultivation worldwide. Additionally, in less efficient irrigation districts, as much as 40 percent of the irrigated land is too salinized for traditional crops, but suitable for halophytes. These areas include northeast India, southeast Pakistan, and the sabkha flats along the Sea of Oman and the Arabian Gulf, the latter of which include Abu Dhabi.

3.1 Site Selection Criteria

Several key site selection criteria have been established for further study in the region prior to determining a suitable ISAS location. Data targeted for this study includes:

- Digital topographic maps at several resolutions (1:25,000 or 1:50,000 preferred);
- Soil maps of Abu Dhabi, including the soil type, elevations, permeability (K_{sat}, K_{dry}), and the soil depth and profile, when available;
- Land use maps;
- Geological maps;
- Vegetation maps;
- Satellite maps and imagery; and

- Access and infrastructural availability information (proximity to roads, ports, the electrical grid, etc.).

  Masdar Institute has been working towards compiling much of this data into the appropriate digital format for GIS software based on raw data provided by a recently released Environmental Agency of Abu Dhabi (EAD) soil mapping activity. Using the GIS software Masdar is using the following site selection criteria to determine area(s) in Abu Dhabi that may be suitable for small and large scale ISAS projects:

- Soil permeability (K_{sat});
- Soil pH;
- Soil profile from the surface to one meter below sea level;
- Existing site flora and fauna;
- Drainage and lateral flow of the soil;
- Water table depth;
- Evapotranspiration rate;
- Climatological data for the region;
- Tidal coastal areas and tidal model (bathymetry map of coast); and
- Salinity, conductivity, and coastal temperature of seawater.

Parameters for the aforementioned site selection criteria will be refined concurrently during the data and maps collection period.

3.1.1 Physical and Climatological ISAS Requirements

In order to evaluate the potential of operating an ISAS in the UAE additional research is required to identify suitable soils with proximity to seawater and to evaluate the most appropriate salicornia variety for the conditions available in this region.

One of the main challenges of a large-scale ISAS is the lack of literature with technical information about ISAS and salicornia yields in the region. Research showing salicornia yields obtained in other regions (e.g. Mexico, Eritrea) with different types of soils, climate, seawater salinity, and agricultural practices is available but does not provide enough data to justify commercial investment in a large scale system until the data is validated. Therefore, for the purposes of this Sustainability Assessment, the most recent and relevant information available will be used to establish a range of possible yields and other variables for the conditions in Abu Dhabi.

Previous research and experience has shown that oil and biomass yields are highly dependent on the following criteria, some of which were gathered from confidential discussions with a halophyte expert, except as noted otherwise:

- Climate – Night time temperatures below 18°C and above 5°C are recommended for a period of approximately 100 days immediately following planting, though this depends heavily on ecotype and breeding line. Nighttime temperatures in Massawa, Eritrea at Seawater Farms Eritrea were rarely below 25ºC, even in winter [34]. Mean daily temperatures of 12-20°C are ideal.
- Slope – Maximum slope of 5 percent.
- Evaporation rates – 2-3 meters per year, [150], [151].
- Water salinity – 10-40 ppt [152].
- Water temperature – Temperature ranges to be determined.
- Water table depth – Underground saline water tables are recommended to be at least 4 m below the surface with no freshwater aquifer below the site. Various irrigation strategies can be employed in areas with shallow saline water tables.
- Existing wildlife – Minimal existing flora and fauna habitats that could be impacted by ISAS construction and operation.

- Photoperiod – To be determined, though it may be a less important characteristic when using tropical ecotypes [34].
- Germplasm of seedstock – To be determined.
- Soil salinity – 10-75 ppt is recommended though it has been shown that salicornia can grow in soil with salinities between 80 and 120 ppt, see Chapter 2.3.2 [152].
- Soil type – sandy-loam to loam are best suited.
- Soil hydraulic conductivity – Soils should be leachable to control salinity, with soil infiltration rates of 20-100 mm per hour, though infiltration rates greater than 5 mm per hour can still work effectively [34].
- Planting period – For Abu Dhabi, plant around October and harvest before April [39].
- Sowing methods – To be determined.
- Irrigation methods – Flood irrigation is typically preferred, but overhead sprinklers have been shown to work well in some situations as well, [39].
- Fertilizer inputs – Varies depending on aquaculture effluent quality and quantity, [59].
- Harvesting methods – To be determined.

Many of the above criteria for Abu Dhabi are detailed in Chapter 3.1.2. However, several of these items cannot be addressed given the information available at this time. This missing data, and other data gaps identified in Chapter 6, may be provided after more research is completed. Future field experiments are currently being implemented in coordination with the International Center for Biosaline Agriculture [68].

3.1.2 Abu Dhabi Climatic, Physical, and Geographic Features

Abu Dhabi's climate is characterized by the harsh conditions of a tropical desert climate which combines extreme heat and low rainfall. Summer lasts from April through November, followed by a mild to warm winter with little rainfall between

December and March. February is the wettest month with about 24.4 mm of rainfall. Rainfall in summer is nearly zero. Evaporation rates in each month exceed rainfall many times over. The ratio of evaporation to rainfall is nearly 400:1 from May through August [153].

Abu Dhabi's climate is on the high range of what salicornia can tolerate (Figure 18). As a result, the growing season for salicornia in this climate is likely to be best from the fall through the spring with harvesting in April, at the latest [39]. However, Vandevivere [34] mentioned that harvesting may be able to take place as late as June in Abu Dhabi as it is occasionally necessary to allow the spikes to dry out prior to harvesting. High temperatures during the day (during the irrigation process) can increase evapotranspiration rates causing an increase in the salinity levels.

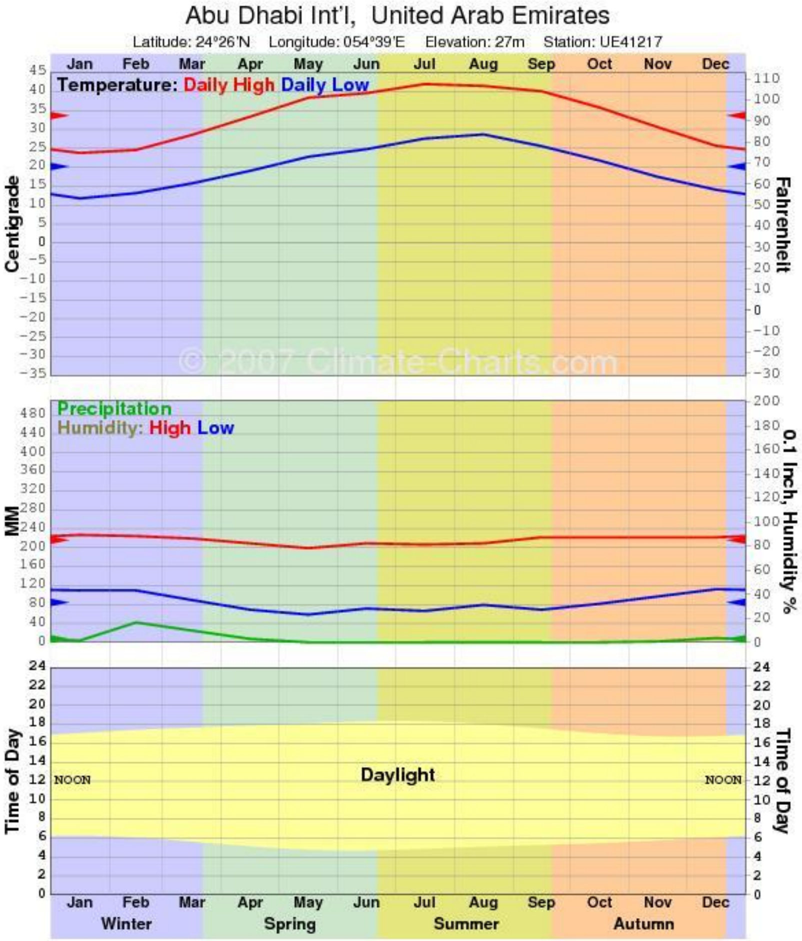

Figure 18 Temperatures in Abu Dhabi [154]

According to several experts, it is recommended that an ISAS should be located relatively close to the coastline to reduce infrastructure and pumping costs. However, site elevation above sea level is one of the key limitations due to the increased energy required to pump seawater. Soil infiltration rates of saline water into the soil should be 5-100 mm per hour [59]. According to ICBA [68], soil EC_e should be 16.8-23.5 ppt (25-35 dS/m) for sustaining a viable production system. It should also be noted that if the fields are close enough to the shoreline, irrigation will leach salts out into the groundwater and approach equilibrium with the seawater salinity. A majority of the UAE coastline has associated high soil salinity (Figure 19 and Figure 20).

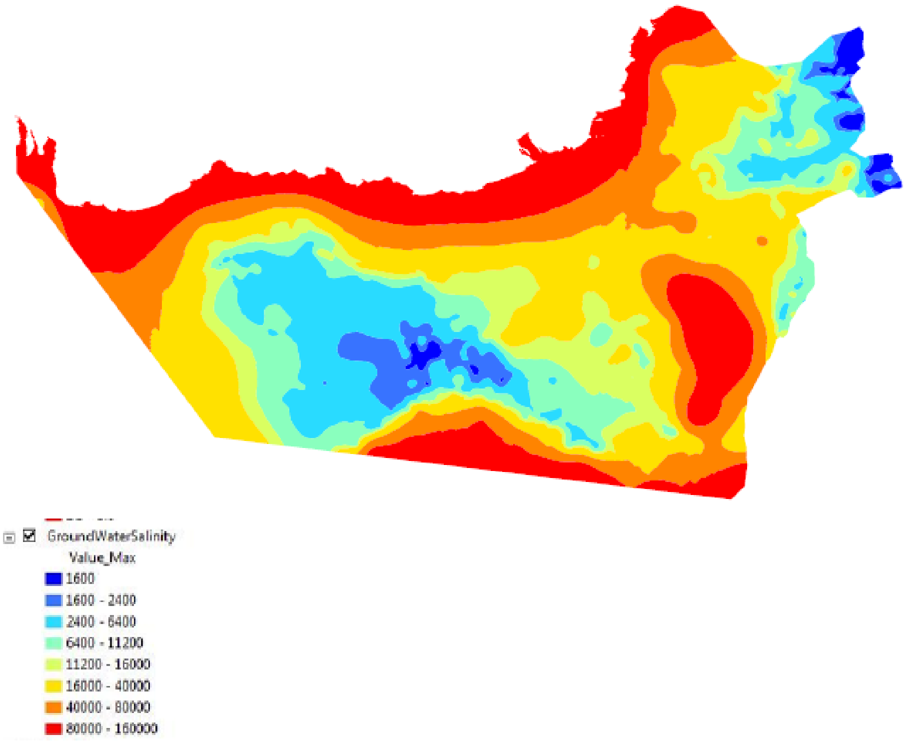

Figure 19 Groundwater Salinity on the Abu Dhabi Coastline [155], salinity in ppm

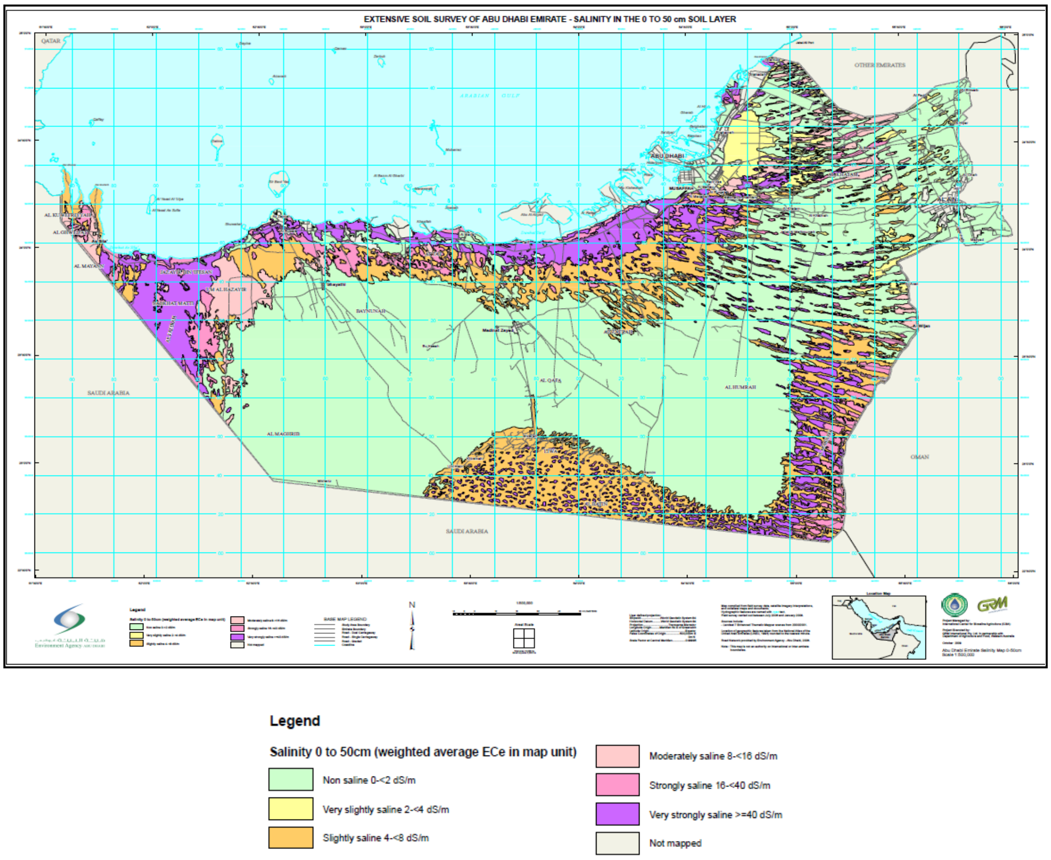

Figure 20 Soil Salinity along the Abu Dhabi Coast [155]

In the coastal regions, there are lower salinity regions but if the majority of them are to be used some soil remediation may need to be applied prior to cultivation. Areas further inland are more promising. The purple area is Figure 20 represents very strongly saline areas (greater than 40 dS/m, or ~27 ppt), though the data is limited because the figure does not specify the maximum soil salinity along the coast. According to Glenn [39], if other site parameters are within viable ranges and the soil salinity does not exceed 75 ppt, the relatively high soil salinity along Abu Dhabi's coast is not by itself a limiting factor for adequate salicornia growth. It may be necessary to flush the soil for a few weeks with seawater to reduce its salinity to that of the seawater being used to flush it. Energy inputs required for this process, if necessary, are not accounted for in the Sustainability Assessment because they are assumed to occur during site preparation and will only be required if the selected site has highly saline soil. Other site and soil factors, such as soil sodicity, are important for proper salicornia growth, but are not evaluated as part of this Sustainability Assessment.

Overall, local conditions may not be ideally suited for salicornia cultivation (high soil salinity, seawater salinity, high evaporation rates, and limited sandy-loam soils near the coast) but they are within the ranges at which the plant should be able to germinate and grow. Moreover, there are management strategies and technologies (pre-irrigation to decrease soil salinity, desalinization of seawater to reduce irrigation salinity, sprinkler irrigation, etc.) that can be used to mitigate some of the less appropriate local conditions. The impact of these management strategies will have to be weighed against their environmental, energy, and economic costs to the system and balanced against their capability to increase biomass and oil yields.

3.2 Aquaculture Process Description

Fish and shrimp are bred and processed onsite and packaged for sale to markets offsite. The hatcheries require freshwater supplied from the municipality. Breeding will likely take place over the summer at indoor facilities while the outdoor facilities are reconditioned. A significant portion of the feed will be imported from the market but processed and mixed onsite with salicornia seed meal. When the ponds are drained and harvested at the end of the season the fish are collected, brought to the onsite processing facility where they are mechanically cleaned, filleted (as appropriate for the species) and packaged either to be sold on the fresh or frozen market, as economics and logistics dictate.

3.3 Salicornia Cultivation Process Description

The nutrient-rich aquaculture effluent is pumped into nearby salicornia fields thus partially offsetting the chemical fertilizer requirement for salicornia while providing irrigation water to the salicornia fields. To achieve optimal salicornia growth, additional fertilizer may need to be purchased from offsite suppliers to supplement the effluent. Due to the high irrigation requirement of cultivating halophytes on relatively saline seawater, additional irrigation seawater may need to be pumped into the fields. Salicornia seeds are harvested mechanically and their seed oil is extracted and processed into HRJ (Chapter 2.6.1). The salicornia straw can be plowed back into the soil to build up organic matter and store carbon, gasified to generate electricity (Chapter 2.6.2), converted into synthetic jet or diesel fuel using the Fischer-Tropsch process (Chapter 2.6.3), or converted into pyrolysis oil for a variety of uses (Chapter 2.6.4). Salicornia straw can also be used to substitute a feed component for numerous types of livestock [74], [100], [102], [156] or even dried and used to create a sustainable fiberboard for construction [64], though this Sustainability Assessment only considers the use of biomass for energy or fuels. The high protein salicornia seed meal leftover from the oil extraction process can be used to partially offset a portion of the protein content in the fish feed mixed onsite [53], [54], with any remaining seed meal potentially sold to offsite markets.

3.4 Mangrove Silviculture Process Description

The ISAS is designed such that the irrigation water not taken up by the salicornia flows laterally underground or through channels towards a managed mangrove wetland. The soil and mangroves play a role in filtering out most of the remaining nutrients in the seawater, allowing it to flow back into the sea mitigating the risk of eutrophication [59], though the nutrient content of the salicornia drainage water and mangrove wetland will require close monitoring. The mangroves can be thinned and their biomass will be processed with the salicornia straw.

3.5 Biofuel Hydroprocessing

The oil from the salicornia seeds can be mechanically extracted in a similar way to established processes used for extracting oil from soybeans. Mechanical pressing or chemical extraction using n-hexane can be employed. Once extracted, the oil can be processed using established hydroprocessing technology as described in Chapter 2.6.1.

3.6 Biomass Processing

Salicornia straw can be mechanically separated from the seeds at the harvest. The leftover straw and mangrove trimmings can be used to generate energy or fuels using one of three pathways, gasification, Fischer-Tropsch synthesis, or pyrolysis, described in further detail in Chapters 2.6.2 to 2.6.4. It is assumed that now all of the salicornia straw can be captured mechanically. Therefore, 10 percent of the salicornia straw is assumed to be plowed back into the soil after each harvest, with a portion of its biogenic carbon entering long-term storage, as calculated by Equation 11 and Equation 12.

In this system the primary materials exported are fish and biofuels with the primary imports being fish feed and fertilizer. The salicornia and mangroves sequester carbon and, in some cases, electricity or other alternative biofuels are exported (depending upon the salicornia straw and mangrove trimming biomass pathway employed).

CHAPTER 4

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4 Life Cycle Assessment Methodology

The most widely recognized approach for life cycle assessments follows the International Organization for Standardization (ISO) guidelines 14040 and 14044 for conducting an LCA [157], [158]. The four phases identified by the ISO guidelines include:

- Goal and scope definition;
- Inventory analysis;
- Impact assessment; and
- Interpretation.

A typical LCA is iterative and evolves as the practitioner gathers data, fills in information gaps, and evaluates periodic results [158]. For the purposes of this Sustainability Assessment, a goal and scope have been defined with a variety of design assumptions. The sensitivity and pathway analysis following the initial results will help define the most energy and carbon intensive operations in the ISAS as well as allow for future optimization of the system based upon tradeoffs associated with advanced management and technological improvements (e.g. desalination of seawater, irrigation methodology, plowing of salicornia straw back into soil, etc.). The ranges of results presented in Chapter 7 are based upon the assumptions and pathways proposed herein and detailed in Appendix A. As more empirical data become available from experimental analysis the LCA tool, calculations, and results will be refined. It should be noted that an LCA is only as valid as its data. Given the highly uncertain nature of much of the data used in this Sustainability Assessment and the high dependence upon a few key sources, it is important to realize that the results presented herein require further confirmation and validation for a commercial scale ISAS operating in the region.

4.1 Goal and Scope

As defined in Chapter 1 the goal of this research is to develop an LCA-based tool for evaluating the feasibility of producing biojet fuel through an ISAS process, quantifying energy and fuel yields, net GHG emissions (or sequestration), energy return on fossil energy invested, resource consumption, and other relevant environmental or land use impacts. The tool should identify key processes within the system of high concern (disproportionately high environmental impact), the relative uncertainty of the data sources, and areas for further research. For the present study, a hypothetical ISAS configuration is proposed based on the best available data in the literature and from experts. In this context, the tool has been created to estimate the range of potential impacts given a variety of inputs and process efficiencies, under various ISAS configurations, management strategies, and biomass processing pathways. If detailed data for a specific ISAS design is obtained the LCA tool could be modified to compare the design options that ISAS owners may consider.

The scope of the Sustainability Assessment includes the life cycle of each component of the ISAS process relative to its contribution to the development of the biojet fuel, from raw material acquisition through the biofuel production process. Due to the complexity of the ISAS and the numerous coproducts produced in the process, the primary focus of the ISAS is assumed to be the production of biojet fuel, but the lifecycle impact of all other known coproducts are also accounted for.

The goal and scope of the study are aligned with the Roundtable on Sustainable Biofuels (RSB) publication, Version Two, which provides standards to ensure that biofuels are developed more sustainably than the conventional fossil fuels they are designed to replace [2]. This LCA can be compared to other biofuel production processes to aid decision makers with determining the most appropriate biofuel approach for a given fuel need and region. The applicability of RSB criteria to the ISAS is described in Chapter 8.

4.1.1 Geographic Boundary

The ISAS under evaluation is based as much as possible on regional data for the Middle East, and, more specifically, that of Abu Dhabi, when available. When this data is not available, other global data was used to supplement it until empirical research becomes available to verify or refine the data used in this first evaluation. All local infrastructural norms were assumed to be from Abu Dhabi, including assuming that grid electricity is from natural gas fired power plants and that any freshwater comes from centralized desalination plants.

4.2 Functional Unit

The ISAS is a unique system for producing bio-jet fuel, especially when compared to conventional vegetable oil feedstocks (such as soybean or jatropha oil), because significantly more salicornia and mangrove biomass is produced than the oil used to create the primary product, HRJ. An accurate comparison to other bio-jet fuel feedstocks would require several assumptions relating to the allocation of the numerous ISAS coproducts (detailed further in Chapter 4.3). To maintain consistency and transparency with the results presented herein, and to avoid unnecessary assumptions when the data being used incurs a high degree of uncertainty, the allocation of emissions among the numerous coproducts was primarily avoided.

Due to the complexity of the ISAS compared to typical biofuel production systems and conventional fossil jet fuel, the initial results presented in Chapter 7 are evaluated using a functional unit of greenhouse gas emissions per unit land area of ISAS, or gCO_2e/ha ISAS. This unit allows for an accurate comparison between the different pathways and management alternatives evaluated herein. A hectare of ISAS is considered to be a representative unit value of land area that hypothetically contains all three systems (aquaculture, halo-agriculture, mangrove silviculture) in the proportions shown in Appendix A as well as including marginal land area for all infrastructure and facilities that may be required for the commercial scale ISAS, assuming that the ISAS takes advantage of all economies of scale that would occur on a commercial size facility. This allows the LCA tool to be scaled up to any commercial size system by simply multiplying the results of the unit land area analysis by the number of hectares of the proposed system. However, this functional unit does not allow for a comparison to other biofuels or fossil jet fuel.

Therefore, the results are also illustrated using a functional unit of the greenhouse gas emissions (emitted or sequestered) per megajoule of bioenergy produced ($gCO_2e/MJ_{bioenergy}$). A megajoule of bioenergy can come from HRJ, green electricity from the gasification of biomass, Fischer-Tropsch fuels, pyrolysis oil created from biomass, or any other energy or fuels created in one of the ISAS processes. Other intermediary results, such as the net energy benefit of the system (net energy output/fossil process energy input) and the yields of each coproduct per hectare of ISAS, are also provided in the results (Chapter 7).

To provide for a comparison to other biofuels or fossil jet fuel, and to follow the guidelines of the RSB, an economic allocation was also carried out which made it possible to use the functional unit of $gCO_2e/MJ_{jet\ fuel}$. This procedure is described in more detail in Chapter 4.3.1 with results presented in Chapter 7.1.4

4.3 Allocation

The ISAS has the potential to produce numerous fuels and materials, depending upon the management strategy and biomass processing pathway chosen. To make a more appropriate comparison to other biofuel production systems, it is sometimes helpful to distinguish the coproduct emissions from the primary product emissions. In this case, as described in more detail in Chapter 4.6.1, the primary product of the ISAS is jet fuel. When the emissions are divided across all coproducts based on a specified weighting scheme it is known as allocation. Due to the imprecise nature of determining a weighting scheme, ISO 14044 [158] recommends against allocation whenever it is possible to disaggregate the unit processes into sub-processes or expand the system boundaries to include the avoided emissions associated with the coproducts. System expansion is the primary methodology undertaken in this study. The ISAS is evaluated from a system perspective and any fuels or coproducts that can be kept within the system and used onsite are assumed to be used onsite first with any excess exported to the market (e.g. aquaculture effluent, salicornia meal, F-T diesel, electricity, etc.). However, when allocation cannot be avoided, ISO 14044 [158] recommends that the inputs and outputs of the system be partitioned between the different products or functions in a way that reflects the underlying physical relationships between them. Otherwise, when a physical relationship cannot be established, the allocation between the coproducts should reflect other relationships between them, such as their economic value.

Several allocation options have been evaluated to appropriately quantify the net emissions and energy outputs of the ISAS. The products leaving the system (tilapia, shrimp, salicornia meal, electricity, F-T fuels, pyrolysis oil) could be accounted for based on their desired function. The fish and salicornia meal are valued for their mass and economic value. It is also possible to offset their conventional production elsewhere, and therefore their production in the ISAS displaces the production of fish or salicornia meal elsewhere (though if this option was employed soy meal may be used as a proxy because of the lack of data on the salicornia meal market). Electricity and F-T fuels leaving the system could be valued for their energy content and perhaps their economic value as well, especially if renewable electricity or green diesel is valued at a premium in Abu Dhabi. As with the material products, the electricity and F-T diesel can also displace the production of fossil electricity (from natural gas) and diesel (from petroleum) elsewhere.

The allocation of emissions among the many coproducts that are valued for different properties (energy, money, mass) is difficult to do consistently as the coproducts produced in the ISAS are valued for different properties. Economic allocation is difficult when comparing the cost of goods in different regions and fuels that have highly dynamic prices. Mass allocation becomes skewed with coproducts that have high mass but low energy densities or value. It may be misleading to perform a mass allocation because the emissions allocated to the HRJ may end up disproportionately low due to the relatively small quantity of oil produced relative to biomass. As a result, the material exports (salicornia meal, fish, and shrimp) are excluded from the initial results of Chapter 7.1, which are based only on the energy and fuel products produced in the ISAS.

For the purposes of this Sustainability Assessment, and to attempt to follow as closely as possible the ISO guidelines, the results are analyzed on a systemic basis by evaluating one hectare of ISAS operations to determine if the system as a whole provides a net GHG and energy surplus or deficit for the several pathways. The initial GHG emissions per megajoule of fuels produced are determined without any allocation or displacement to maximize the transparency of the results. The primary assumption from this methodology is that the energy of each fuel (electricity, jet fuel, diesel, naphtha, mixed propane gas, pyrolysis oil) is treated identically based upon its energy density (MJ/kg or MJ/liter). All fuels produced by the ISAS are assumed to produce no net emissions when they are combusted as they are produced using biomass that absorbed carbon from the atmosphere. The fossil process energy input required to produce the feedstock and process the fuels is accounted for separately within the LCA. Additionally, fuels such as naphtha and mixed propane gas are considered for their energy content, not for any proposed function or use (e.g. naphtha may eventually be refined into gasoline or used as chemical industry feedstock). Any carbon sequestration that is accounted for in the LCA is only from carbon taken up by the biomass (salicornia or mangroves) and then assumed to enter long-term storage underground, as in Equation 11 and Equation 12 using data from Appendix A.

4.3.1 Economic Allocation

Though the primary results of this analysis are determined without any allocation, for illustrative purposes it is helpful to perform some type of allocation to be able to compare the biofuels produced by the ISAS to those produced under different biofuel production schemes. The Roundtable on Sustainable Biofuels GHG Calculation Methodology [159] requires the use of economic allocation for all coproducts. However, not all coproducts produced by the ISAS are sold in a typical market. To account for this uncertainty, surrogate prices were used for unconventional coproducts according to Table 8. To maintain consistency across different price estimates, a single source (the U.S. Energy Information Administration, EIA) was used to identify prices for as many of the fuel coproducts as possible [160]. For material coproducts, Index Mundi price data and National Oceanic and Atmospheric Administration (NOAA) data was used [161], [162]. For those fuels or coproducts not included explicitly in this source, their relative value to fuels listed in this source was used from other sources, as detailed in Appendix A.

Table 8 Coproduct Price Surrogates

ISAS Product	Price Surrogate (if applicable)	Source
Jet Fuel (HRJ or F-T)	Jet Fuel	EIA [160]
Mixed Propane Gas	Liquid Propane Gas (LPG)	EIA [160]
Diesel	Based on its relative value to the Residual Fuel Oil price	EIA [160]
Pyrolysis Oil	Based on its energy content relative to that of Residual Fuel Oil	EIA [160]
Naphtha	Based on its relative value to Diesel	EIA [160]
Electricity exported to grid	Retail Electricity	EIA [160]
Shrimp	Shrimp	Index Mundi [162]
Tilapia	Tilapia	NOAA [161]
Salicornia Meal	Soybean Meal	Index Mundi [162]

The economic allocation was determined by calculating the percentage contribution of each material or fuel to the total revenue per hectare of ISAS. This was done using dollars per megajoule prices for all fuels and both dollars per megajoule of material coproducts (using the calorific value or shrimp, tilapia, and salicornia meal) and price per unit mass ($/MT) of shrimp, tilapia and salicornia meal. The economic allocation was also performed excluding the material coproducts. It is important to note that to remain conservative the economic allocation was performed assuming no carbon sequestration in the salicornia and mangrove biomass. This provided a worst case set of emissions per unit fuel or product produced. This assumption was made because under certain pathways the total ISAS emissions are negative due to carbon sequestration in the biomass. Any negative emissions would clearly be beneficial from a GHG perspective for the HRJ produced, thereby eliminating the need to even perform this allocation. The results of the economic allocation are provided in Chapter 7.1.4. The generic formula used to perform the economic allocation is provided in Equation 5.

Equation 5 Economic Allocation Calculation

$$[[CoP(i) \times Price(i)] \div \sum_{i=1}^{n} (CoP(i) \times Price(i))] \times GHGsys \div CoP(i) = GHG(i)$$

CoP(i): Coproduct *i* yield per hectare for *n* coproducts (MJ/ha or grams/ha)

Price(i): Price per unit yield for coproduct *i* ($/MJ or $/gram)

GHGsys: System wide total emissions for a given pathway (gCO_2e/ha ISAS)

GHG(i): Emissions allocated to coproduct *i* (gCO_2e/MJ or gCO_2e/gram product)

4.4 Limitations

The LCA model is limited by its dependence on a number of key variables and their data sources as well as the calculation methodology used. Certain variables, such as the salicornia water and fertilizer requirements, actually vary throughout the year and are highly dependent on the weather and soil conditions at the ISAS site. Aquaculture feeding rates and water requirements also vary throughout the year. We aggregate the yearly consumption requirements so that the annual operational total quantities of materials, water, and energy and their resulting emissions are captured in the model.

4.5 Assumptions

Due to the complexity of the ISAS process and the lack of actual operating ISAS system data, it is necessary to make certain underlying assumptions and design decisions to carry out a useful LCA. Therefore, the following baseline assumptions are based on readily available information and numerous discussions with the project stakeholders and are common to all pathways within this Sustainability Assessment in order to compare them to one another. It is important to note that, though much of the data is based on peer reviewed published literature, this Sustainability Assessment is not evaluating the validity or accuracy of the data gleaned from the literature. The data presented is assumed to be useful for the purpose of defining ranges of parameter values for this LCA and conflicting data sources and caveats to certain design assumptions are noted throughout the document. Uncertainty is addressed further in Chapter 4.6 and the pathway analysis in Chapter 7. Assumptions for each of the pathways, as well as the actual values used for the assumptions detailed below, are provided in Appendix A. For each pathway the baseline data in Appendix A is the same, except as noted for each pathway description in Chapter 7.1, but not all values in Appendix A are used in each pathway. For example, the yields for the Mexican and Eritrean varieties of salicornia are both provided in Appendix A, but only one variety can be chosen for each pathway evaluation, as defined by the assumptions for the given pathway. Other data gleaned from the research is provided in Appendix A but not all are used in the current model.

The following subchapters define the assumptions used in the model. These are broken down into inputs and system assumptions. A detailed list of all assumptions and their values for the main scenarios is shown in Appendix A.

4.5.1 General System Wide Assumptions

- **Location** – The ISAS under evaluation is a hypothetical 100,000 hectare (ha) operation in Abu Dhabi, UAE.
- **Prior Land Use** – The land use prior to cultivation is desert with minimal prior vegetation and negligible stored soil carbon.
- **Timeframe** – The Sustainability Assessment is for one year of steady-state operations. This implies that the ISAS has been in operation for several years prior to this analysis and therefore assumes that the system has been optimized to achieve the yields, products, and energy slate desired by the operator.
- **Scalability** – The LCA calculations are based on a theoretical one hectare ISAS operation with the land allocation between aquaculture, mangroves, and salicornia. The one hectare of ISAS is conceptually a single plot of land divided amongst the three land uses (with the footprints for buildings and roads assumed to be negligible). However, the operations on this one hectare plot are designed as if they were for a fully functioning 100,000 ha facility, therefore taking into account all operational efficiencies and economies of scale of an ISAS of that size. The one hectare plot approach was employed to make the model more robust against future design changes.
- **Transportation** – Transportation of materials (shrimp, tilapia, salicornia meal, F-T diesel, HRJ) to the market and materials from the market brought onsite (fertilizer, fish feed, diesel, other chemicals) will be the same for each pathway.
- **Capital Goods** – Capital goods (building materials), initial site construction, and start-up operations are not included, primarily due to their small footprint relative to the long lifetime of the proposed ISAS operations.

- **Pumping –** Seawater pumps for aquaculture and irrigation are powered by electricity. If the gasification pathway is chosen, the electricity generated is first used for all onsite aquaculture and salicornia irrigation pumping needs (split evenly between the two processes), with any surplus exported to the grid and any deficit provided by the grid.
- **Pipe Friction** – Frictional energy loss from lateral water transmission in the horizontal pipes or channels used for transporting seawater to the fields is currently ignored. Only the energy required for lifting the water to the elevation of the aquaculture ponds or salicornia field is accounted for. In effect, this means that the only factor impacting the pumping energy is the elevation of the ISAS above sea level, not distance from the coast.
- **Grid Electricity** – All grid electricity is assumed to be from natural gas fired power plants.
- **Desalination** – All desalination is assumed to be from a centralized Reverse-Osmosis (RO) facility using electricity from the grid, unless otherwise specified [163], [164].

4.5.2 Aquaculture Assumptions

- **Aquaculture Species –** Tilapia and shrimp are cultivated in the aquaculture portion of the ISAS, with yields that can be expected from semi-intensive methods using open ponds aquaculture, described in more detail in Chapter 2.2.1;
- **Aquaculture Facilities –** Tilapia and shrimp hatcheries, post-harvest processing center, and feed production facility will be onsite within the footprint allocated to aquaculture.
- **Harvests –** Two shrimp harvests and one tilapia harvest will occur per operational year.

- **Operations** – Operations are assumed to take place only for the portion of the year specified in Appendix A.

4.5.3 Salicornia Halo-Agriculture Assumptions

- **Salicornia Processes –** All halo-agriculture processes will occur onsite, including seed germination and breeding.
- **Salicornia Seeds –** Enough viable salicornia seeds will be available to allow the ISAS to be self-sufficient in terms of providing its own seeds for the annual crop of salicornia. The quantity of seeds required to reseed the field each year is subtracted from the total seed yields for each pathway.
- **Salicornia Straw –** Ten percent of salicornia biomass yield is assumed to be left on the fields each harvest, as it is unlikely that all of the straw can be harvested and leaving a percentage of the straw on the field contributes to building up soil organic matter in the soil and a portion of long-term carbon storage.
- **Growing Period –** Salicornia is assumed to have a growing period to parallel that of the aquaculture system and as noted by Vandevivere [59].
- **Farm Equipment –** For the baseline pathway the farm equipment runs off of conventional diesel from offsite sources. When the salicornia straw and mangrove biomass are processed along the Fischer-Tropsch pathway into F-T diesel, the diesel is first used onsite to supplement this diesel fuel requirement, with any remaining exported offsite to market.

4.5.4 Mangrove Assumptions

- **Mangrove Cultivation –** Once the mangrove forest is established it is assumed that any management and thinning will be performed by manual labor, thereby ignoring any fossil fuel inputs. No artificial fertilization or chemical inputs are assumed to be required for mangrove cultivation.

- **Carbon Sequestration –** The carbon removed in the biomass harvested for further processing is separate from the carbon assumed to be entering long-term storage in the mangrove forest.

4.5.5 Biomass and Biofuel Processing Assumptions

- **Biomass Usage –** Excess salicornia straw and mangrove biomass (collectively biomass, as opposed to salicornia seeds, oil, or meal) will be treated the same way in terms of their processing for each pathway (except for the salicornia straw assumed to be plowed back into the soil). The three pathways under evaluation are gasification, Fischer-Tropsch synthesis, or pyrolysis, with an option to plow a percentage of the salicornia straw back into the soil to build up organic matter and facilitate long-term carbon sequestration (see Chapter 2.3.10). When more accurate information becomes available regarding the salt content of the salicornia straw and its impact on the biomass processing pathway, it may be determined that the straw requires pressing and rinsing to reduce its salt content. However, this additional processing step is currently not accounted for in the analysis.
- **Biomass Processing –** All biomass post-harvest processing and biofuel production will occur onsite, including oil extraction, hydroprocessing of salicornia oil, and either gasification, Fischer-Tropsch synthesis, or pyrolysis of the biomass;
- **Hydrogen Production for Hydroprocessing –** Hydrogen will be produced offsite from the steam reformation of natural gas in Abu Dhabi and piped or trucked to the ISAS. This transportation is currently assumed to be negligible, unless otherwise specified. Future pathways may evaluate the feasibility of producing the hydrogen onsite via electrolysis using electricity from the gasification of biomass, but are not currently within the scope of this LCA.

Several diagrams have been created to illustrate the various components of the ISAS and to help visualize the LCA and system structure. These diagrams are used to guide the preliminary construction of the LCA model and will be refined concurrently with the quantitative components of the model as more data becomes available.

Figure 21 is a Process Flow Diagram describing the entire ISAS system. A process flow diagram shows the unit processes within a system and illustrates their inter-relationships to define where the unit process begins, the nature of the operations that occur, and the destination of the intermediate or final products [158]. Figure 22 to Figure 27 are Sankey diagrams that shows the material, energy, greenhouse gas, and cash flows quantitatively throughout the ISAS in the base case Gasification pathway.

Figure 28 is a System Boundary Diagram that illustrates the processes and materials that will be considered as part of the life cycle assessment, as well as those associated processes and materials with environmental impacts that will not be considered in this system. At this stage in the LCA the system boundaries have been expanded to attempt to account for the many flows and materials and to internalize the use and impact of as many of the numerous coproducts as possible. The infrastructure requirements for interconnection, transmission, and distribution to the electricity grid are outside of the system boundaries because their construction would be required for a similar amount of electricity generation from traditional, non-renewable sources. Additionally, labor is not accounted for in this study because most of the agricultural practices will be mechanical and when this LCA is compared to conventional petroleum production processes for jet fuel, they do not typically include labor in their calculations. Carbon dioxide from the atmosphere will be accounted for when it is sequestered in the biomass and soil systems by the salicornia and mangroves, but not accounted for when it is taken up by biomass but then re-emitted after the biofuels are consumed by industrial processes.

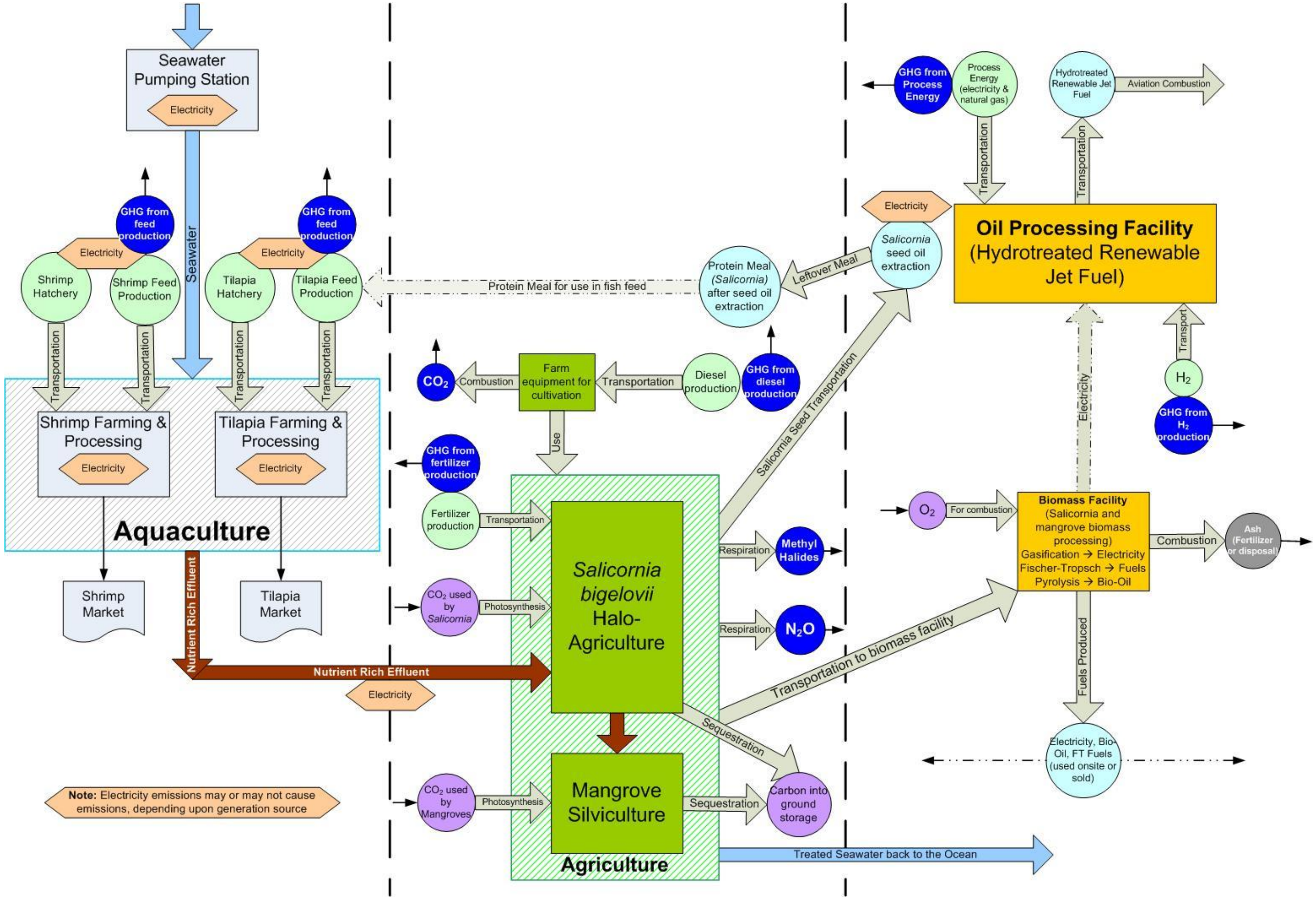

Figure 21 ISAS Process Flow Diagram

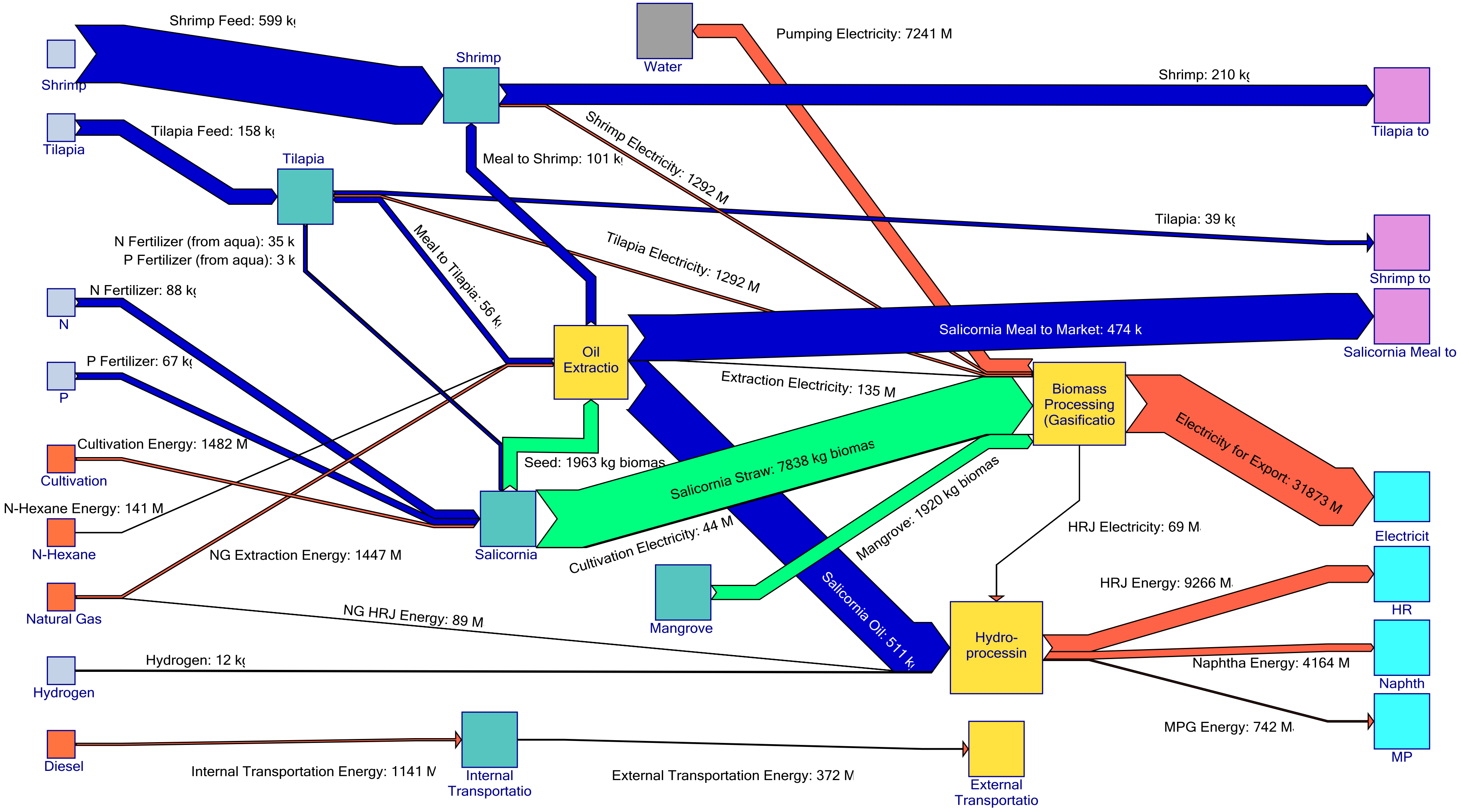

Figure 22 ISAS Sankey Diagram of Mass and Energy flows for the Base Case Gasification Pathway

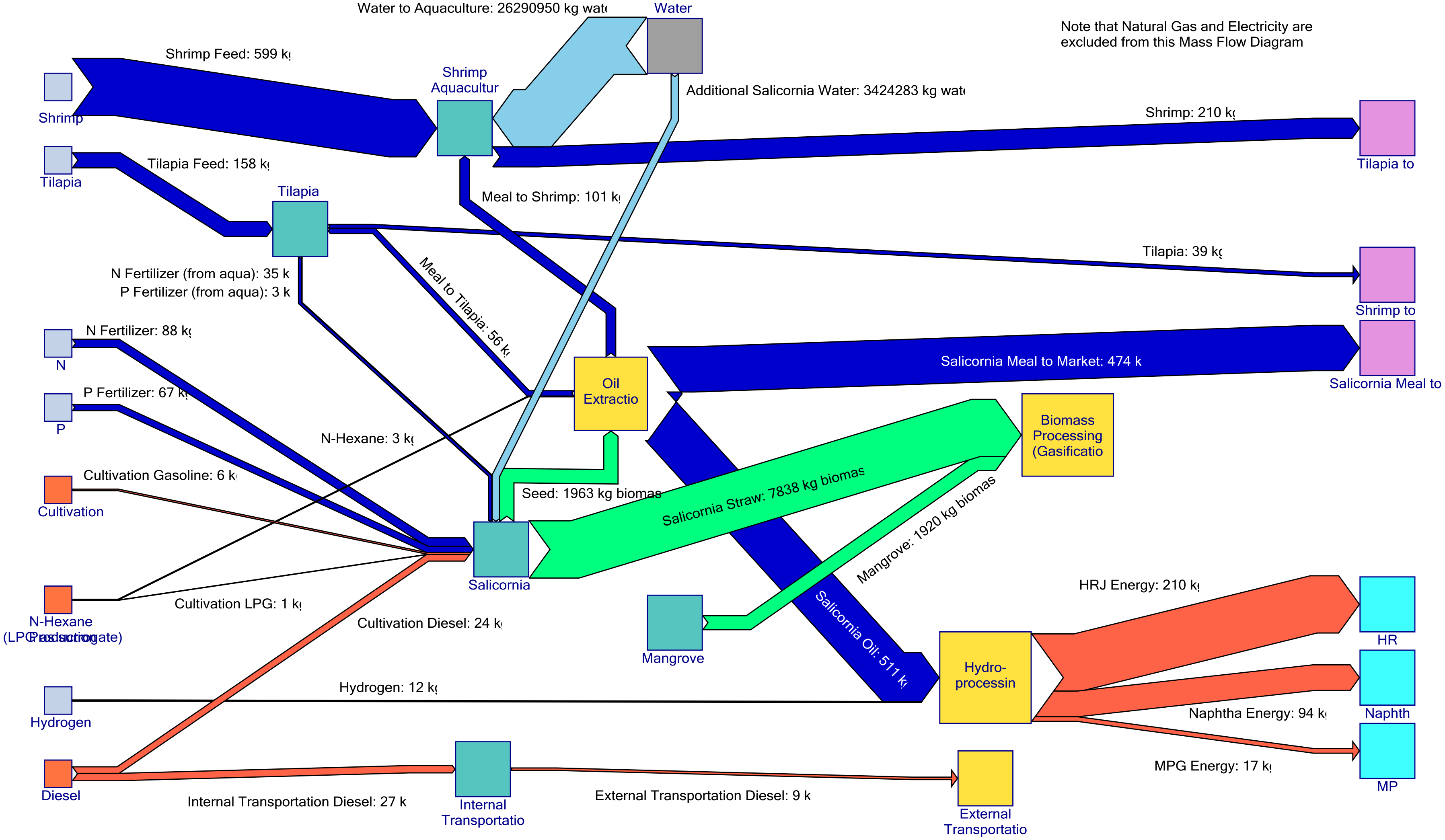

Figure 23 ISAS Sankey Diagram of Mass Flows for the Base Case Gasification Pathway

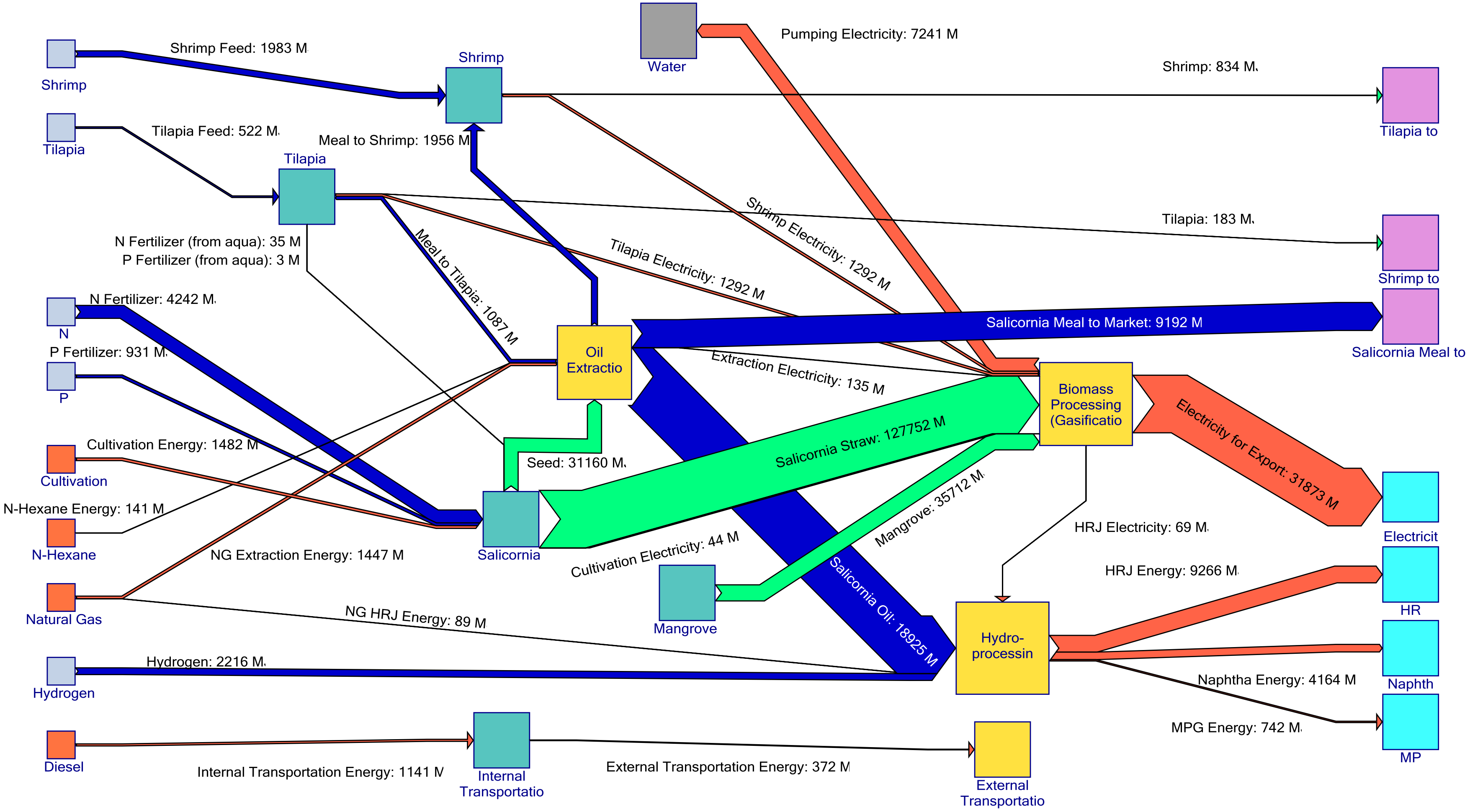

Figure 24 ISAS Sankey Diagram of Energy Flows for the Base Case Gasification Pathway

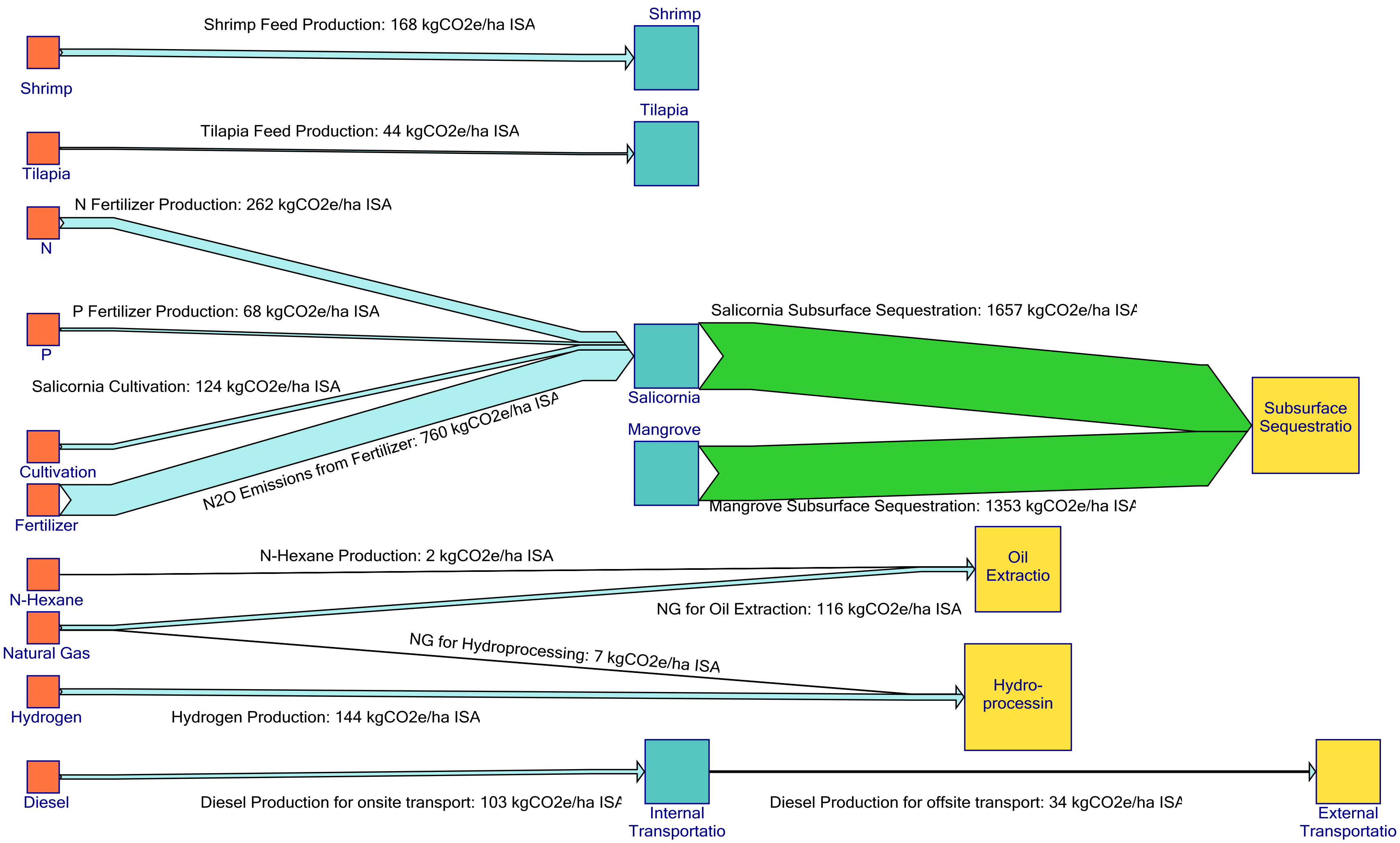

Figure 25 ISAS Sankey Diagram of Greenhouse Gas flows for the Base Case Gasification Pathway

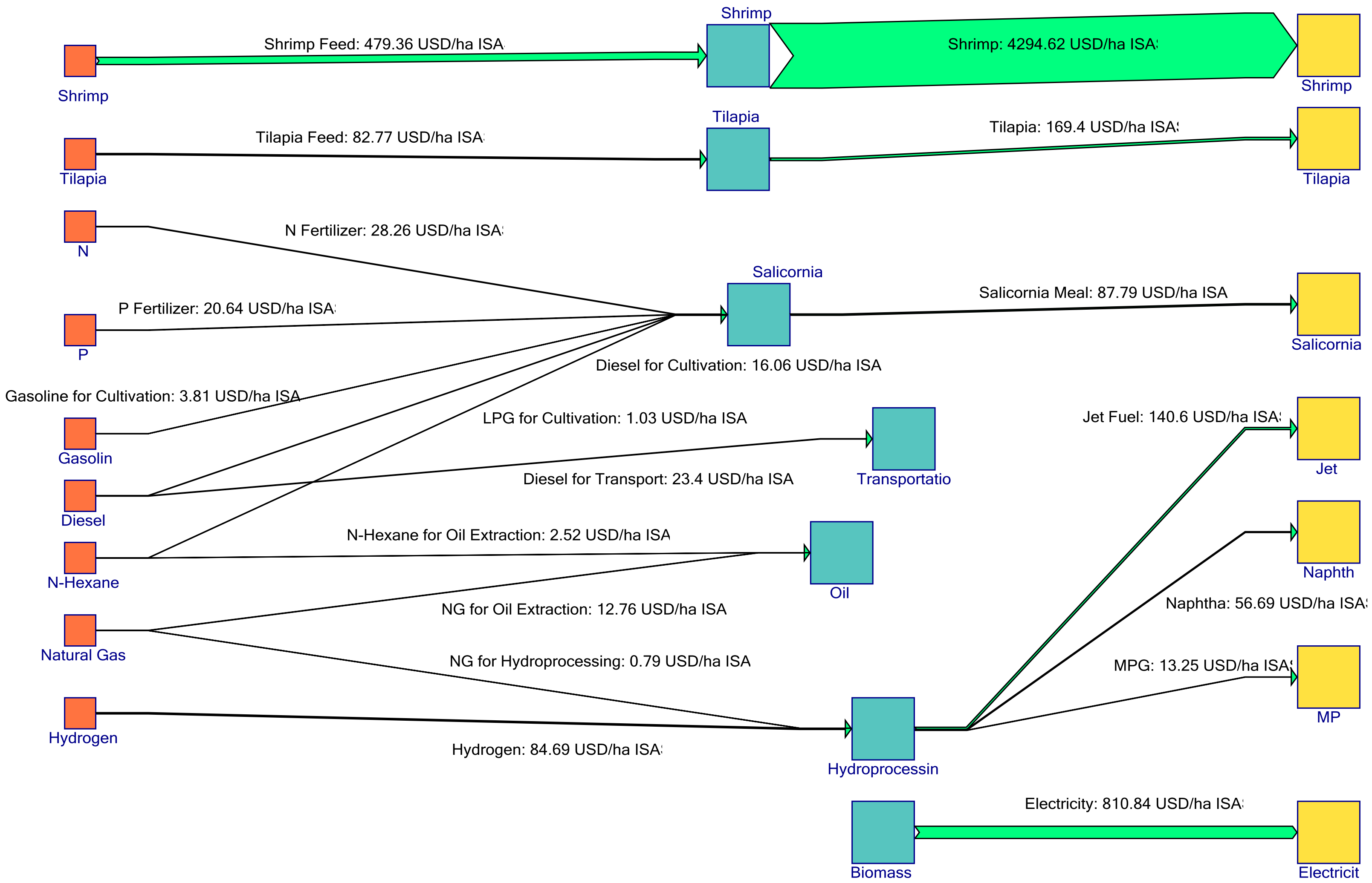

Figure 26 ISAS Sankey Diagram of Costs and Revenue Flows for the Base Case Gasification Pathway

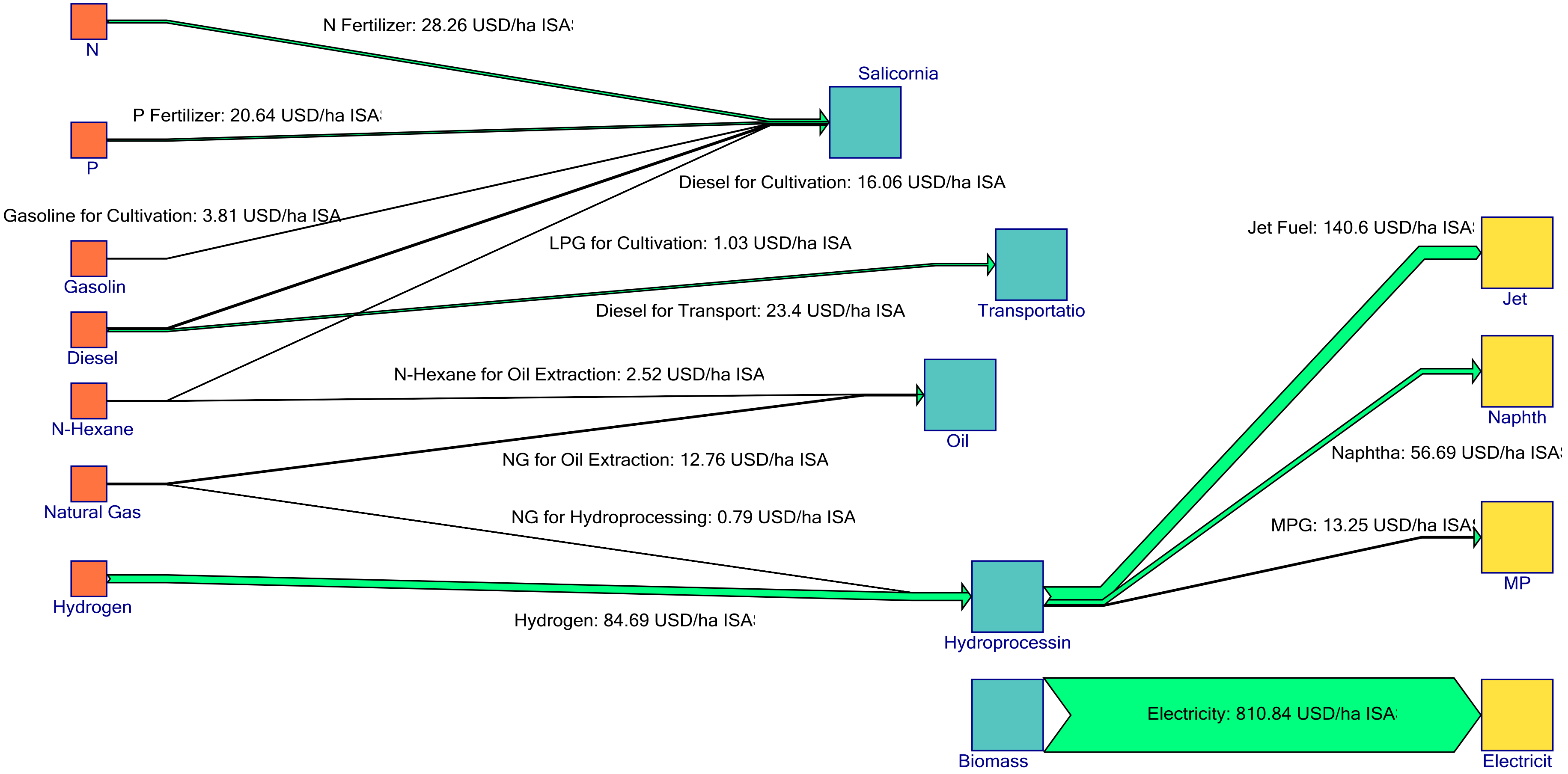

Figure 27 ISAS Sankey Diagram of Costs and Revenue Flows for the Base Case Gasification Pathway (Fuel Only)

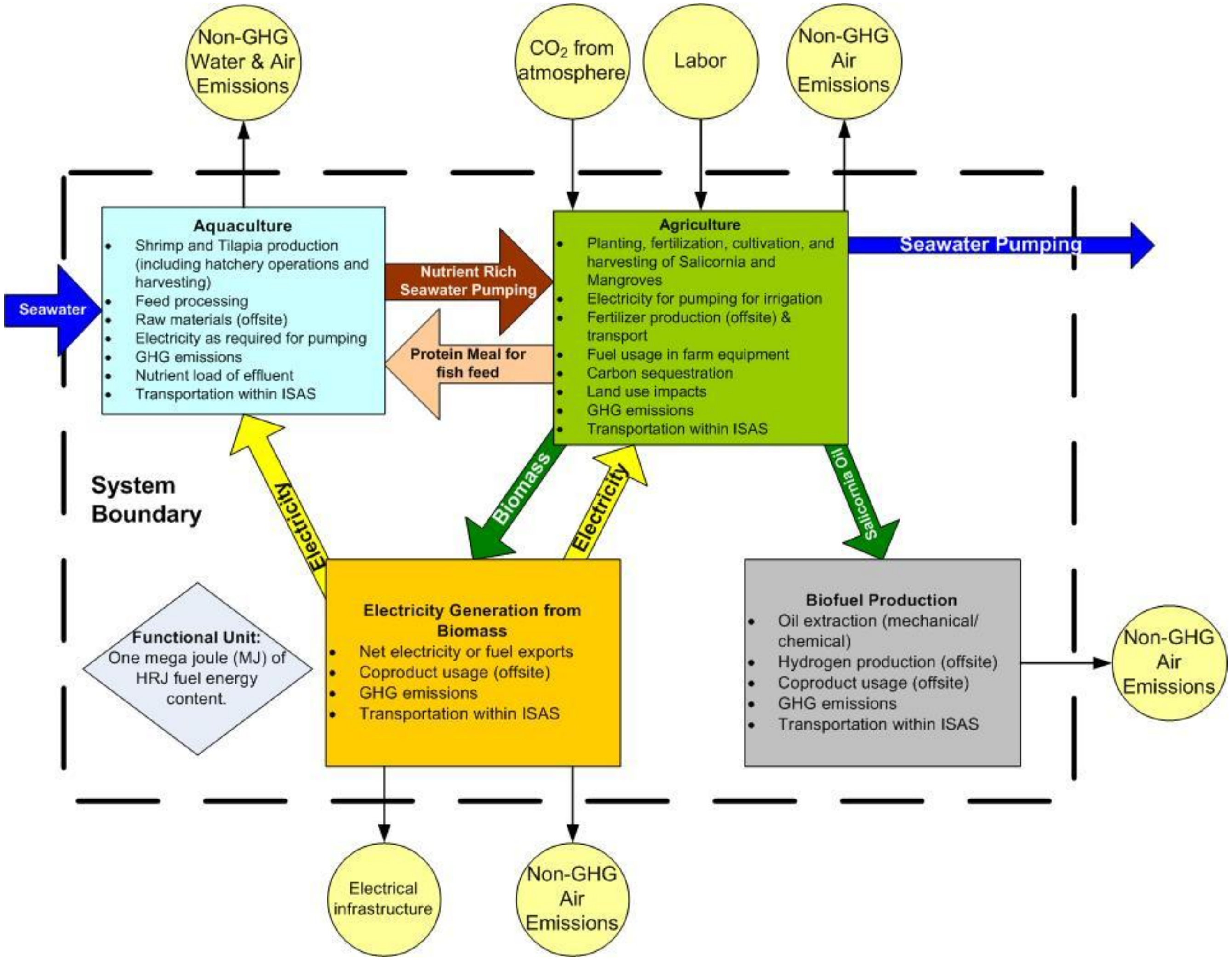

Figure 28 System Boundary Diagram

4.6 LCA Calculation Methodology

Due to the limited empirical data available for salicornia halo-agriculture, mangrove silviculture, and ISAS operations, this LCA is based upon the best available literature data and opinions and recommendations from specific industry experts (see Chapter 2.1), but still includes substantial uncertainty as to the practicality and potential successful implementation of a commercial scale ISAS in Abu Dhabi. There is also considerable uncertainty at this time as to what the final design of the ISAS will consist of, including, but not limited to, the ratio of pond area to shrimp versus tilapia, the seed variety and yield of salicornia, the irrigation regime for salicornia, and the biomass conversion pathway. To evaluate this wide range of uncertainty, this LCA was designed according to the baseline assumptions explained in Chapter 4.5. In addition to the baseline assumptions, there are numerous other parameters and variables that are detailed in Appendix A. The quantitative data used in the LCA are presented in Appendix A (with their respective sources) and therefore are omitted from this chapter. This chapter provides a qualitative overview of the LCA methodology employed for each process within the ISAS.

The baseline assumptions in Chapter 4.5 and specific set of options are assigned to a Baseline Pathway. For example, a pathway option may be deciding which salicornia seed variety to plant, which biomass conversion pathway to follow (gasification, Fischer-Tropsch, pyrolysis), or how much salicornia straw is plowed back into the soil. Within the scope of this Sustainability Assessment the Baseline Pathway will be used to compare to other options (see Chapter 7.1).

4.6.1 Establishing Worst, Base, and Best Cases

Due to the lack of definitive data, a range of values for most of the data inputs was used such that each pathway evaluated produced a range of results, assuming a Best, Base, and Worst Case. The parameter inputs for each of the three cases, detailed in Appendix A, were chosen according to the following three prioritized criteria:

1. **Maximize Jet Fuel:** The primary goal of the theoretical ISAS is to maximize fuel yields, specifically the yield of Jet Fuel, the priority fuel product of the ISAS. Therefore, the Best Case parameters have been chosen based on maximizing the oil yields and the amount of HRJ that can be derived from the oil. This criteria, however, falls within the constraint of the land area allocation (e.g. The most HRJ yield would result from an ISAS with 100 percent of its land area devoted to salicornia; however this would defeat the purpose of the ISAS).
2. **Minimize GHG Emissions:** The secondary goal of the ISAS is to minimize the environmental footprint of the ISAS, though the net GHG balance is the primary metric for this goal. An ideal ISAS would sequester more atmospheric carbon than the fossil carbon (or other GHG) emitted to operate it. If a parameter does not contribute to the objective of maximizing jet fuel, for example the feed conversion ratio for the fish and shrimp, then the parameter with the lowest net GHG impact is chosen for the best case. This secondary objective leads to choosing parameters with the least fossil energy inputs as well.
3. **Maximize Production:** The tertiary goal is to maximize the overall production in each of the three systems within the ISAS. Therefore, so long as the first two objectives are not violated, parameters chosen relating to production are maximized. These parameters include fish yields, salicornia straw yield, and mangrove biomass yield.

It is important to note that the three objectives and the parameters are decoupled such that changing one baseline parameter does not necessarily impact other parameters unless they are directly related. For example, from the literature the fertilizer requirement for optimal salicornia growth is unclear. But it is known that some fertilizer is required to achieve commercially viable salicornia yields. Therefore, the Best Case parameter for fertilizer requirement is chosen to be the least amount of fertilizer reported in the data and the Worst Case parameter for fertilizer requirement is chosen to be the largest amount of fertilizer reported in the data, with the Base Case falling in between. This is because chemical fertilizer production requires a high input of fossil energy to produce and therefore has high GHG emissions and a significant fossil energy input (this is only for additional fertilizer required to make up for the shortfall not accounted for by the nutrient rich aquaculture effluent). Intuitively, however, more fertilizer should produce higher salicornia yields. Because the parameters are decoupled from one another, this is not the case. The Best Case fertilizer parameter has the lowest fertilizer requirement but the highest salicornia yields. Though this decoupling produces a wide range of results, it is most appropriate for representing the uncertainty in the data and illustrating the significant difference between the Best and Worst Cases.

Additionally, due to this decoupling, the first criteria, maximizing HRJ yield, may conflict with the other criteria. For example, maximizing the HRJ yield requires using the highest salicornia oil yields in the Best Case. However, the more oil that needs to be processed into HRJ, the more energy and material inputs are required for transport and processing. As a result, a process may not have the lowest carbon emissions or process energy per acre of ISAS, but the Best Case will always have the lowest net GHG emissions per unit energy produced and highest net energy ratio for each process.

4.6.2 Water Pumping LCA Methodology

The water pumping requirement for the ISAS is based upon water exchange requirements for the aquaculture process and the irrigation requirements of the salicornia. Additionally, the salinity of the aquaculture water and of the aquaculture effluent needs to be managed to maximize both fish and salicornia growth while minimizing pumping requirements necessary to dilute the water (due to high evaporation rates in the region and the large surface area of the open aquaculture ponds). Frictional loss associated with horizontal water flow with the same elevation is ignored. Though the irrigation method used for salicornia may significantly impact the overall energy consumption of the system, the most effective methodology for the region has not yet been confirmed. Flood irrigation is likely to be used, though mechanical irrigation with booms have been used effectively as well [55]. Due to this uncertainty, only the water quantity required for the salicornia is assumed to be provided, ignoring the method used to deliver the water to the fields, aside from pumping the water up to the elevation of the fields. Only head calculations are used to determine the pumping energy required for the aquaculture and salicornia operations[7].

Aquaculture Water Requirement: The Aquaculture Water Requirement is the amount of seawater needed to be pumped into the aquaculture facility in one year of operations. This variable is dependent upon the Evaporation Rate and either the Exchange Requirement of the ponds required for fish health or the Salinity Requirement, whichever is higher for a given pathway or set of parametric assumptions. The Exchange Requirement is based on the percentage of the water that needs to be exchanged each day to maintain fish health, based on expert interviews

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[7] Note that all numerical data is provided in Appendix A.

and other sources provided in Appendix A. The Salinity Requirement is dependent upon the seawater salinity and the desired salinity of the aquaculture ponds. Evaporative losses each day will cause an increase in salinity. To counter this salinity increase, more seawater needs to be pumped into the ponds to maintain a desired salinity level slightly above that of seawater, but below what would occur if there was no additional seawater pumped in. Equation 6 was used to calculate the Exchange Requirement and Equation 7 was used to calculate the Salinity Requirement.

Equation 6 Exchange Requirement

$$[(ExP \times PV) + \frac{(ER \times PA)}{DiY}] \times OP = ExR$$

ExP: Exchange Percent, the minimum percent of pond water necessary to exchange each day, on average, to maintain fish health

PV: Pond Volume (m^3)

ER: Evaporation Rate (meters per year)

PA: Pond Area (m^2)

DiY: Days in a year, 365

OP: Operating period (days per year aquaculture facilities are in operation)

ExR: Exchange Requirement (m^3 of seawater intake per hectare per year, which can be converted into mass by the seawater density conversion factors listed in Appendix A)

To calculate the Salinity Requirement, a mass balance was used:

Equation 7 Salinity Requirement

$$(SWS \times SR) + (PWS \times PW) = DPS \times TPW$$

$$(SWS \times SR) + (PWS \times PW) = DPS \times [SR + PW]$$

To find the SR, the equation is transformed into:

$$\frac{[(SWS \times SR) + (PWS \times PW) - (DPS \times PW)]}{DPS} = SR$$

SWS: Seawater salinity (%)

SR: Salinity Requirement (kg of seawater intake per hectare per year necessary to maintain the DPS, see below)

PWS: Pond Water Salinity (%)

PW: Pond Water after Evaporative Losses, from Equation 6, (m^3 converted into kg of pond water per hectare per year):

$$PW = [\frac{ER \times PA}{DiY}] \times OP$$

DPS: Desired Pond Water Salinity (%)

TPW: Total Pond Water, includes Pond Water after Evaporative Losses and Salinity Requirement, representing the total amount of water in the ponds[8] (kg of pond water):

$$TPW = SR + PW$$

The greater of the Salinity Requirement (SR) and the Exchange Requirement (ExR) is used to determine the quantity of water needing pumping, on average, each day into the aquaculture facility. Using this methodology, both the minimum water exchange is met and the salinity is maintained at an appropriate level.

Aquaculture Pump Energy Requirement: The Aquaculture Pump Energy Requirement is the amount of pumping energy required to move the amount of seawater determined by the Aquaculture Water Requirement. It is based solely on moving seawater up an elevation. Because specific design parameters have not yet been determined, horizontal flow and pipe friction have been neglected from this calculation, shown in Equation 8.

Equation 8 Aquaculture Pump Energy Requirement

$$\frac{(AWR \times G \times El)}{PE} = APER$$

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[8] Note that although the TPW may be greater than the total pond volume, the pond outflow can be regulated to ensure that no overflowing occurs. Additionally, these calculations are made on a daily basis when in reality the seawater inflow and outflow will be continuous. The calculations are only to determine the minimum amount of seawater intake required to maintain the desired salinity of the pond water throughout a given day to calculate annual pumping requirements over the season.

AWR: Aquaculture Water Requirement (kg of seawater intake per hectare per year)

G: Gravity

El: Elevation about seawater of the aquaculture ponds (meters)

PE: Seawater pump efficiency (%)

APER: Annual Pumping Energy Requirement (Joules per hectare of aquaculture)

Salicornia Water Requirement: The additional seawater required for salicornia irrigation is the difference between the water requirement for salicornia and the aquaculture effluent provided from the aquaculture system. If more effluent is provided than required by the salicornia, that water can be bypassed directly to the mangrove wetland. For the purposes of this analysis, only annual averages are factored into the calculations to account for pumping requirements. However, in reality, the flow rates at different times of year may not align between the aquaculture and salicornia systems, potentially requiring additional seawater to be pumped into the salicornia fields. The calculations contained herein only deal with annual average flows.

Salicornia Pump Energy Requirement: The Salicornia Pump Energy Requirement is calculated in the same way as the Aquaculture Pump Energy Requirement, Equation 8. The effluent from the aquaculture system is pumped up the specified elevation to the salicornia fields. Any additional Salicornia Water Requirement is assumed to be pumped up from sea level, which is the sum of the elevation of the aquaculture system and the elevation of the salicornia fields above the aquaculture system.

4.6.3 Aquaculture LCA Methodology

The aquaculture components of the ISAS system were based upon data from the literature and expert interviews [37]. The following are variables and equations used to determine the operational characteristics and environmental impacts of the aquaculture operations:

- Hatcheries require freshwater (or very low salinity water as described in Chapter 2.2.1); This freshwater requirement is provided by the local municipality, assuming the necessary infrastructure is in place, and the energy consumption and emissions resulting from the production the freshwater from centralized desalination plants is calculated into the overall energy and emission balance of the ISAS.
- The quantity of feed required remains constant in each pathway, though the Feed Conversion Ratio (FCR) varies according to several sources. The yields of fish is then calculated according to Equation 9.

Equation 9 Feed Conversion Ratio and Fish Yield

$$\text{Feed}/\text{FCR} = \text{Yield}$$

- Composition of the feed for the shrimp and tilapia vary according to several sources and the life stage of each species (e.g. young fry and fingerlings require diets higher in protein than adults in later stages).
- Salicornia meal is incorporated into the feed compositions according to the protein composition requirement of the feed and the protein content of the meal. This salicornia meal offsets a portion of other plant proteins typically incorporated in commercial feeds.
- Energy (and resulting emissions) from onsite feed production is incorporated into the system calculations.
- Harvesting is mostly manual labor and therefore omitted in terms of energy and GHG emission impact.
- Post-harvest processing of the fish (filleting, freezing, packaging) is factored into the overall aquaculture system impacts.

- Due to the limited outdoor aquaculture growing cycle (see Chapter 2.2.1) summer months can be used to drain and recondition ponds. The sediment at the bottom of the ponds is nutrient rich and is assumed to be collected and spread onto salicornia fields each summer, providing a slow release fertilizer prior to the start of each growing season in the fall. The nutrient levels in this sediment is estimated and factored into the salicornia fertilizer requirement calculations.

4.6.4 Salicornia LCA Methodology

Yields: Salicornia yields may be dependent upon fertilization, soil type, irrigation regime, climate, seed strain, time of planting, and numerous other biological and physical factors. However, due to the wide range and limited empirical data for salicornia's yield in the region, the various factors contributing to growth are assumed to vary independently for the purpose of the LCA calculations. As a result, yields for salicornia are provided from different sources identified in Appendix A. Total biomass yields for two different salicornia varieties are provided, one based on results of test plots at Puerto Peñasco, Mexico [12] and the other calculated from results obtained by Seawater Farms Eritrea[9] [69]. A range of seed yields, seed oil content, reseeding requirements, and ash contents were obtained from the literature such that the oil yield, seed meal yield, straw yield, and ash yields (per ha of salicornia) could be obtained. Typically, only total biomass yields and seed yields were provided. Therefore, salicornia straw yield was calculated by subtracting the seed yield from the total biomass yield.

Oil yield was calculated by subtracting the seeds needed to reseed the subsequent year's crop of salicornia from the total seed yield and multiplying that quantity by the seed oil content, as in Equation 10.

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[9] Massawa, Eritrea is located at 15º37'N, 39º27'E [69]. Abu Dhabi, UAE, is located between 22º29'N and 24º53'N and 56º10'E and 51º37'E [153].

Equation 10 Oil Yield

$$[SY - RR] \times SOC = OY$$

SY: Seed Yield (MT/ha)

RR: Reseeding Requirement (MT/ha)

SOC: Seed Oil Content (%)

OY: Oil Yield (MT/ha)

Several sources explained that salicornia biomass yields may be reduced at irrigation salinities above 10 ppt while other sources mentioned no yield reduction at full strength seawater or higher (see Chapter 2.3). To account for this uncertainty an additional option was factored into the LCA that reduces the total biomass yield of salicornia by a percentage according to the salinity of the irrigation water, according to Figure 29.

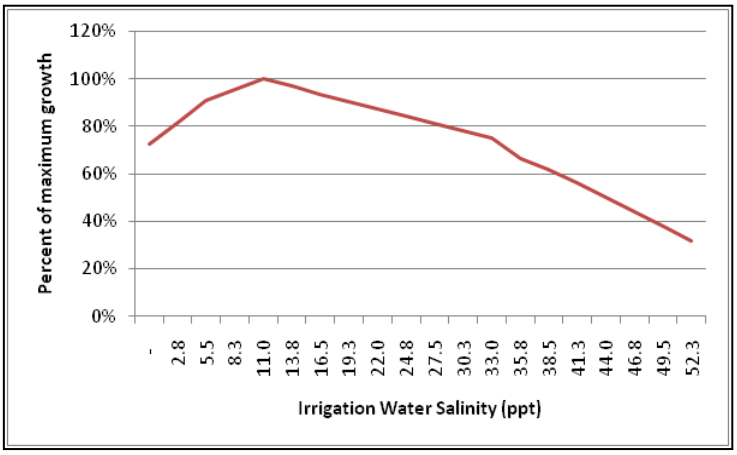

Figure 29 Curve Used to Evaluate Salinity versus Salicornia Biomass Growth [79], [93][10]

Cultivation Energy: There is little reliable information on the farming energy required to cultivate salicornia, other than that it can be accomplished using conventional farming machinery with some modifications [12]. Glenn et al. [76], assuming all farming energy (including pumping, see Chapter 2.3.10) is provided by fossil diesel assumes that 22.5 to 30 percent of the harvested carbon (in salicornia

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[10] Several data sources were used for the creation of Figure 29 resulting in a curve that is not entirely smooth.

biomass) results from fossil inputs. However, it was determined (in part using calculations from Stratton et al. [61]) that this results in an energy input significantly larger than that for conventional crops, even factoring in the pumping requirements. To provide a better basis for comparison, salicornia cultivation inputs (notwithstanding the pumping requirements explained in Chapter 4.6.2) were based upon those from several peer reviewed published papers on soybean farming, which should require similar farming methods and machinery to salicornia farming when the irrigation requirements are omitted. The irrigation requirements are calculated separately based on the water pumping requirements identified previously in this chapter. The sources and data used for these calculations are identified in Appendix A.

Salicornia Carbon Sequestration: An area of high uncertainty, and high importance in this LCA, is the potential of long-term carbon sequestration from salicornia (see Chapter 2.3.10). Excluding the aboveground biomass, Equation 11 determines the amount of carbon that enters long-term storage each year:

Equation 11 Carbon Storage of Belowground Salicornia Roots

$$TBY \times PBR \times CCB \times LTC \times CNV = CSroots$$

TBY: Total Biomass Yield, the total aboveground salicornia biomass yield (MT/ha), including straw and seeds

PBR: Percentage Biomass in the Roots, an approximation for the quantity of root biomass, as a percentage of the TBY (%)

CCB: Carbon Content of the Biomass (%)[11]

LTC: Long-Term Carbon storage, the percent of carbon in the roots that is assumed to enter into long-term storage (%)

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[11] This is assumed to be the same as the carbon content of the aboveground biomass.

CNV: Conversion of stored carbon into carbon dioxide equivalent, 44/12 (dimensionless)[12]

CS_{roots}: Carbon Storage of salicornia roots, the amount of carbon dioxide equivalent entering long-term storage each year due to belowground biomass (MT CO_2e/ha)

However, some of the salicornia straw is plowed into the soil each year. A portion of this straw may enter long-term storage, according to Equation 12, using several of the same factors from Equation 11.

Equation 12 Salicornia Straw Plowed into Long-Term Carbon Storage

$$TBY \times PSP \times CCB \times LTC \times CNV = CSstraw$$

PSP: Percentage of salicornia Straw Plowed back into the soil each year (%)

CS_{straw}: Carbon Storage of salicornia straw, the amount of carbon dioxide equivalent entering long-term storage each year due to aboveground biomass plowed into the soil (MT CO_2e/ha)

Nitrogen Volatilization: Estimates for emissions of N_2O from salicornia agriculture were calculated using IPCC Tier 1 methodology which accounts for the combined direct and indirect conversion rate for nitrogen from synthetic fertilizers [61], [165] according to Equation 13.

Equation 13 IPCC Tier 1 Methodology for Calculating N_2O Emissions [13]

$$\left(\left(\frac{gNitrogenFertilizer}{kgSeed}\right) \times 0.01325\right) \times \left(\frac{44gN2O}{28gN}\right) = N2O\ Emissions$$

Fertilizer Requirements: The required amount of fertilizer for salicornia is shown in Appendix A. The nutrients provided by the aquaculture are calculated according to the nutrient characteristics of the feed, primarily nitrogen (N) and phosphorous (P) (Figure 3). The aquaculture and salicornia growth cycles complement one another

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[12] 44/12, or 3.67, is a factor used to convert a mass of stored carbon into a mass of carbon dioxide equivalent (CO_2e) for comparison purposes with GHG emissions. It is the ratio of the mass of a molecule of CO_2 to a molecule of carbon.

[13] Note that Nitrogen Fertilizer in this equation is the entire nitrogen requirement for salicornia, not just the additional chemical fertilizer required in excess of the aquaculture effluent. This is to remain conservative in the calculations and may be revised if it is determined that there is minimal nitrogen volatilization from the aquaculture effluent or fertilizer application.

because they are expected to begin and end approximately at the same time. As the aquaculture feeding rate increases as the fish grow more nutrients will leach into the effluent. At the same time, the salicornia will be growing larger and may require more nutrients for its continued growth. However, according to the literature, the nitrogen and phosphorous requirements for salicornia are constant throughout its growth cycle. In reality it may be necessary to map the curve for the aquaculture feeding requirements over time to determine the net additional fertilizer requirement for salicornia at any given time throughout the fish and salicornia growth cycles. However, for the purposes of this analysis, an average N and P load in the effluent is calculated on an annual basis and is assumed to be identical from both the shrimp and fish, despite differing feed compositions and rates.

Nutrient Load in Effluent: The N or P load in the effluent is based on both the N or P content of the feed and the ability of the fish to uptake the nutrients from the feed that they consume. Some of the feed becomes particulate matter that may end up in the sediment of the ponds. This sediment can be collected at the end of each season and laid on the fields as a slow release fertilizer [59]. The general formula for the calculation of the N and P load of the effluent and the N and P composition of the sediment is in Equation 14.

Equation 14 Effluent and Sediment Nutrient Composition

$$(F \times NComp) - (F \times NComp \times PDx) = Nload$$

F: Feed provided (MT/ha of aquaculture)

N_{Comp}: Nutrient Composition, the amount of N or P in the feed (%)

PD_x: Percent Distribution, the percent of N or P that is dissolved in the water (PD_{dislvd}, which is assumed to go into the effluent) or the amount of N or P that is particulate matter (PD_{part}, which is assumed to settle into the sediment that can be spread on the fields each year)

4.6.5 Salicornia Oil Hydroprocessing

The salicornia oil is converted into HRJ, Mixed Propane Gas, and Naphtha on a per unit mass basis using the process energy as is shown in Table 5.

4.6.6 Biomass Processing

Leftover biomass (salicornia straw and mangrove trimmings) can be processed along one of three pathways:

- **Gasification**: Creating syngas from the biomass and burning it to generate electricity. The gasification process can have different process efficiencies depending on the technology employed and the energy content of the biomass (Chapter 2.6.2).
- **Fischer-Tropsch**: Creating either green diesel or green jet fuel from the biomass (the product slate from the Fischer-Tropsch process can yield different ratios of green diesel, green jet fuel, and naphtha). The Fischer-Tropsch process can have different process efficiencies depending on the technology employed and the energy content of the biomass (Chapter 2.6.3).
- **Pyrolysis**: Creating bio-oil from biomass. Different process efficiencies and product yields depend upon the energy content of the biomass and the ash content of the biomass (Chapter 2.6.4).

One of the main causes of uncertainty in the processing pathways is how the salt content of the salicornia and mangrove biomass will impact the ability of the biomass to be converted along each pathway. As such, the salt content (or ash content), by mass, is assumed to pass through each of the pathways unchanged. Therefore, to remain conservative, the energy content of the biomass for each pathway is scaled down according to its ash content. Both the Gasification and Fischer-Tropsch pathways are calculated using Equation 15. All three pathways are assumed to be self-sustaining, meaning that the process energy necessary to drive the reactions comes from the biomass input into the system. Therefore, there are no net emissions, but the quantity of fuel produced as a result of each of these pathways is reduced by the biomass energy required to drive the process.

Equation 15 Gasification and Fischer-Tropsch Processing Pathway

$$BEC \times BAA \times PE = FE$$

BEC: Biomass Energy Content, energy content of salicornia or mangrove biomass (MJ/MT biomass)

BAA: Biomass Ash Adjusted, salicornia or mangrove biomass, adjusted to factor out ash content (MT/ha)

PE: Process Efficiency (Gasification or Fischer-Tropsch), the percent of fuel output relative to the biomass input from the pathway (%)

FE: Fuel Energy, the fuel energy output, in electricity (for Gasification) or in the product slate identified (for Fischer-Tropsch), in MJ/ha for each salicornia and mangrove; the relative quantities per hectare of ISAS can then be scaled based on the land area allocation

The Pyrolysis pathway is calculated according to Equation 16 because more data was available on pyrolysis oil yields rather than the pyrolysis process efficiency. In addition, it is assumed that salicornia straw is rinsed and pressed to reduce its salt content (Chapter 2.3.7).

Equation 16 Pyrolysis Processing Pathway

$$\begin{aligned}&(Bsal \times BECsal \times OYsalt \times LAAsal)\\ &\qquad + (Bmgv \times BECmgv \times OYsalt \times LAAmgv) = PO\end{aligned}$$

Bsal/mgv: Biomass, salicornia or mangrove, including ash content, though for salicornia the ash content is that after rinsing and pressing to reduce the overall ash content (MT/ha)

BECsal/mgv: Biomass Energy Content, energy content of salicornia or mangrove biomass (MJ/MT)

OYsalt: Using the curve in Figure 11 [143], the oil yield based on the assumed salt content of each salicornia and mangrove (%)

LAAsal/mgv: Land Area Allocation, the percent of a hectare of ISAS allocated to each salicornia and mangrove production (%)

PO: Pyrolysis Oil output (MJ/ha ISAS)

Electricity Usage: If the gasification pathway is used the electricity will be used onsite for water pumping and any other needs, with any remaining electricity exported to the grid. However, if it is more economically beneficial to export all of the electricity directly to the grid (for example if there was a renewable energy premium policy in place) then grid electricity could be used onsite and a significant quantity of revenue could be generated, though it is possible that the carbon benefits of using renewable electricity onsite might be lost. For simplicity in this analysis, it is assumed that all electricity generated will be first used onsite with excess exported to the grid, avoiding the use of natural gas fired electricity generated in the UAE.

4.6.7 Transportation Methodology

The mass of the products from each process is calculated and the transportation requirements both within the ISAS, from the ISAS to market (for those products leaving the system), and from the market to the ISAS are factored into the LCA based upon distances within the ISAS (assuming all facilities are centrally located to minimize transportation) and to market as detailed in Appendix A. Energy consumption and emissions are based on the mass of each product and the assumed distance traveled, using ton-kilometers as the metric.

4.7 Model User Interface

The Microsoft Excel LCA model uses life cycle data from a variety of sources, including the literature and other LCA software. All of the data assumptions are provided in a single tab within the model, the “Input” worksheet. This worksheet contains almost entirely hardcoded data that make up the underlying assumptions for the calculations and results determined by formulas in other worksheets linking to these inputs. The “Inputs” worksheet is provided as Appendix A.

There are numerous other worksheets linked to the “Inputs” worksheet where the actual calculations are performed according to the assumptions and equations provided throughout Chapter 4. Each of these worksheets represents a process, sub-process, or calculation needed within the ISAS, as follows:

- **Shrimp**: Shrimp production and feed data;
- **Tilapia**: Tilapia production and feed data;
- **Hatcheries**: Water pumping, freshwater requirement, feed requirement, and production of shrimp and tilapia from breeding until transfer to the outdoor ponds;
- **Feed Production**: Process energy related to producing feed onsite using some materials imported from offsite along with salicornia seed meal produced onsite;
- **Fish Processing**: Process energy related to filleting, freezing, and packaging shrimp and tilapia onsite;
- **Water**: All of the pumping and desalination requirements (if applicable) for aquaculture seawater and salicornia irrigation, including the use of electricity when the ISAS is evaluated under the gasification pathways;
- **Salicornia**: Yield data, cultivation requirements, nitrogen emissions from fertilization, fertilizer requirements and production assumptions, and fertilizer offset by aquaculture effluent;

- **Mangroves**: Yield data, carbon sequestration, and mangrove wood energy content;
- Gasification, F-T, & Pyrolysis: These three worksheets each use the yield data calculated in the “Salicornia” and “Mangrove” worksheets and assumptions from the “Inputs” worksheet to determine the fuel types and yields resulting from biomass processing;
- **HRJ**: Hydroprocessing of the salicornia oil into HRJ using the assumed process energy, with the associated emissions and coproduced fuels;
- Transportation: Includes all onsite and offsite transportation quantities and distances;
- **Calcs Worksheets**: There are also calculation worksheets that have data inputs used in other process worksheets, including:
- o **DesalCalcs**: Lookup table used when the user decides upon incoming seawater salinity the requires desalination (as the higher the salinity of the incoming water, the more energy required for desalination)
- o **SalinityCalcs**: Lookup table used to create the curve in Figure 29 and factored into calculations when the user decides that the salinity of the irrigation water for salicornia will impact its growth, as described by Ayala and O’Leary [79] and Miyamoto [166]
- o **EffluentNutrientCalcs**: Calculations used to determine the amount of available nitrogen and phosphorous present in the aquaculture effluent flowing into the salicornia fields to offset artificial fertilizer requirements
- o **MethyHalideCalcs**: Calculations for the data used in Table 9
- **Outputs**: Displays the results in a table for the active user selected pathway, including the energy inputs, fuels produced, net energy balance, carbon balance, and materials for sale (shrimp, tilapia, salicornia meal) produced by the ISAS, as shown in Table 10;

- **GHGSpecies**: Categorizes the emissions from each process by its GHG constituent (carbon dioxide, methane, or dinitrogen monoxide); and
- **Results**: Filters the results from the "Outputs" worksheet into tables linked with the figures presented in Chapter 7.

4.7.1 Outputs Worksheet

This worksheet is the heart of the user interface, assuming the underlying data assumptions in the "Inputs" worksheet do not need to be changed. The "Outputs" worksheet allows the user to formulate any unique pathway under different operational or yield assumptions. The user has the option to change and test the impacts of any or all of the following parameters, though the default parameter for each option is specified below:

- **Biomass Processing**: Gasification (default), Fischer-Tropsch, or Pyrolysis for biomass processing;
- **Water Salinity**: The user can enter in different assumptions for the desired or anticipated salinity concentrations in the different components of the ISAS to evaluate the pumping impact, although salinities are decoupled from aquaculture and salicornia yields, thereby assuming that the salinities entered into the model are the maximum allowable that will not impact yields. The following data can be entered by the user, although default values are provided:
  - Incoming seawater salinity (default in Appendix A)
  - Desired aquaculture pond water salinity (default in Appendix A)
  - Desired salicornia irrigation water salinity (default in Appendix A)
- **Desalination for salicornia germination**: The user can decide if freshwater is required for the first month after salicornia planting to ensure germination (default is that salicornia can be germinated with saline irrigation water);

- **Fischer-Tropsch Slate**: Due to the uncertainty surrounding the possible fuel yields from the Fischer-Tropsch process, the user can select from three fuel slates that may result after the biomass is processed along the Fischer-Tropsch pathway, from a High Jet Fuel Slate, Average Slate (default), or Low Jet Fuel Slate based upon different sources provided in Appendix A;
- **Cultivation Energy**: Due to the uncertainty surrounding the energy required to cultivate salicornia, two alternatives are provided to the user:
  - Soybean equivalent: The cultivation energy requirements mirror that of conventional soybean production (default)
  - Glenn equivalent: The cultivation energy requirements are taken from Glenn et al. [76] but are adjusted to not include water pumping, which is calculated elsewhere
- **Salicornia Yields**: Due to uncertainty surrounding the potential yields of salicornia in the UAE, the user may select to use the yields from field experiments in Mexico (default) or the yields from the experimental ISAS developed in Eritrea, which has lower total biomass yields but equivalent oil yield to the Mexican variety;
- **Salinity Irrigation Water Impact**: Due to the uncertainty regarding the yield of salicornia using relatively highly saline irrigation water, the user can choose to have the salicornia yields scaled down according to the curve in Figure 29, although the default is not to have any impact (default) from the salinity of the irrigation water because there ISAS operator should be able to mitigate impacts through best management practices;
- **Salicornia Straw Burial**: The user can enter the percentage of salicornia straw that is buried after each harvest, a portion of which will enter long-term storage according to Equation 12 (default 10 percent); and

- **Mangrove Carbon Sequestration**: Due to uncertainty relating to the ability of a managed mangrove ecosystem to sequester atmospheric carbon for the long-term, the user can select either the base carbon sequestration rate (default) or the high carbon sequestration rate, detailed explicitly in Appendix A.

These options allow the user to test the sensitivity of the ISAS LCA model outputs to different assumptions, uncertainties, designs, and management practices. Each set of choices determined by the user define a pathway. Due to the numerous possible permutations between these options, several key assumptions were defined and tested, with the results presented in Chapter 7.

CHAPTER 5

5 Potential Risks

There are numerous risks associated with the wide range of variable components inherent to the ISAS as well as the limited availability of recent, reliable, and relevant data. There are risks both to the project (business case risks) and to the environment (environmental risks). Several of the key risks associated with the development of a commercial scale ISAS are listed below with several described in more detail in Chapters 5.3-5.5:

5.1 Business Risks

- According to some of the published literature, the high salinity of the Arabian Gulf water could markedly reduce the yield of salicornia.
- Salicornia oil, as well as the plant tips, can potentially be used as a food source. Using these products for fuel production does eliminate this potential food supply. However, the market for these edible products is small and the development of saline agriculture very limited. It is very unlikely that there would be any competition for land between edible saline agriculture and ISAS in the near future.
- Uncontrollable variables such as temperature, rainfall, pathogens, and erratic weather could change the commercial feasibility of an ISAS.
- Operational costs and impacts of a commercial scale ISAS have not yet been quantified.

- Lack of local management expertise and laborer skill in the region could make it difficult or expensive to recruit capable farmhands.
- Enough suitable land may not be available in the region for a commercial scale ISAS.
- Intellectual property rights associated with the seed procurement and subsequent breeding will need to be clearly stated prior to large-scale implementation.
- Contamination of aquaculture facilities resulting in a large-scale die-off is always a possibility with aquaculture, though the risk can be minimized with best management practices.
- Though there are few known pathogen risks to salicornia, a large-scale monoculture ISAS could be prone to infection.
- A commercial scale ISAS of up to 100,000 ha has never been successfully implemented anywhere in the world, therefore presenting potential operational and logistical risks heretofore unaccounted for.
- Supply chain for materials, machinery, water, and energy to operate the ISAS may be difficult to establish and maintain in the region.

5.2 Environmental Risks

- Improperly managed ISAS can result in hypersalinization of the soil, rendering the land relatively unusable for any future agricultural purpose.
- Aquaculture and irrigation water effluent, if improperly managed, could pose a eutrophication risk to marine wildlife on the coast.
- The environmental impact of constructing the ISAS is not well known without a detailed design and could adversely impact the overall life cycle environmental impact of the ISAS.

5.3 Methyl Halides

It has been found that some halophyte marsh plants naturally emit methyl halides into the atmosphere (also known as halogenated methanes which are volatile halogenated organic compounds (VHOCs)). Though salt marshes, a typical environmental for *Salicornia bigelovii*, make up only 0.1 percent of the global surface area, coastal salt marsh plants are estimated to produce 10 percent of the total flux of atmospheric CH_3Cl and CH_3Br [167]. These compounds (methyl chloride (CH_3Cl), methyl bromide (CH_3Br), and methyl iodide (CH_3I)) are important due to their ability to reach the lower stratosphere where they have the potential to destroy ozone [168]. It was determined that *Salicornia bigelovii*, in a coastal salt marsh environment, emits 2,400 mg/m^2/year of CH_3Cl [167]. However, this is orders of magnitude greater than what was recorded for other species of *Salicornia.* Manley et al. [168] evaluated the methyl halide emissions from *Salicornia virginica* in situ in California and determined that, relative to a control of soil and mud, *S. virginica* emitted only 12 mg/m^2/yr of CH_3Cl, 3.2 mg/m^2/yr of CH_3Br, and 2.0 mg/m^2/yr of CH_3I. Valtanen [169] performed a similar study on *Salicornia europaea* that yielded only 4 mg/m^2/yr of CH_3Cl.

Gebhardt [170] illustrates the relative rates of methyl halide emissions from wetlands and salt marshes compared to overall global emissions (note that CH_3I is not accounted for in Table 9).

Table 9 Methyl Halide Emissions from Selected Ecosystems [170]

Methyl Halide	Range	Salt Marsh (Gg/yr)	Wetland (Gg/yr)	Global Total (Gg/yr)	Average Salt Marsh & Wetland Emissions as Percent of Global Total[14]
CH_3Cl	Min	65	48	1,743	~3.9%
	Max	440	48	13,578	
CH_3Br	Min	7	2.3	77	~12.8%
	Max	29	9.2	293	

These results indicate that large scale global conversion of desert into salt marshes or wetland ecosystems has the potential to impact global methyl halide emissions. However, using the data from Rhew et al. [167], a 100,000 ha ISAS consisting of 70 percent *Salicornia bigelovii* by land area may only emit as much as 1.68×10^6 kg/year, or 1.68 Gg/year of CH_3Cl, which is less than 0.1 percent of the global total CH_3Cl emitted each year. Using the data from Manley [168] for CH_3Br emissions from *S. virginica*, 70,000 ha of salicornia agriculture would contribute only 2,240 kg/year, or 0.00224 Gg/year of CH_3Br each year, less than 0.005 percent of the global total.

It is important to note that these compounds, the mechanism for their biogenic production, and their interactions within the atmosphere, are still not very well known. Large ranges of uncertainty still exist for the emissions of methyl halides from various ecosystems. Additionally, the in situ measurements performed in the studies noted above were on salt marsh plants in their natural ecosystem, not in an agricultural environment, which may significantly alter the methyl halide emissions.

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[14] This column is calculated by dividing the average Salt Marsh and Wetland emissions by the average Global Total emissions, e.g. for CH_3Cl [((65+440)/2) + ((48+48)/2)]/((1743+13578)/2) = 0.0392. This data is for illustrative purposes only because the range of uncertainty is very large.

Further, there is limited data regarding the methyl halide emissions from conventional terrestrial crops and the oil industry to compare to the unconventional farming and fuel production systems proposed for the ISAS.

5.4 Radiative Forcing due to Surface Albedo Change

A potential side effect of planting large swaths of green plants on an existing desert is the radiative forcing that results from converting a large area of light colored, highly reflective sand (relatively high albedo) with less reflective green plants (lower albedo). Rotenberg and Yakir [171] performed a 9-year study on a semi-arid forest that showed that the substantial carbon sequestration of a new forest is counteracted by longwave radiation suppression, doubling the forestation shortwave albedo effect. The result was that several decades of carbon accumulation are required to balance the longwave and shortwave effects. In fact, the authors report that desertification has actually contributed a net negative forcing at the Earth's surface, moderating global warming trends. Though this research pertains to a semi-arid forest, it may be applicable to the large area of land potentially 'greened' in the ISAS, and warrants further research to quantify the potential radiative forcing of planting a large area of salicornia for a portion of the year in Abu Dhabi.

5.5 Invasive Species

Salicornia bigelovii is not native to Abu Dhabi or the UAE but has shown its ability to thrive in similar climates and ecosystems. This brings up the potential risk of more robust selectively bred strains of salicornia escaping into the surrounding regions where it may not be desirable. It should be noted, though, that after several years of pilot scale testing at Seawater Farms Eritrea there was no reported salicornia invasion in nearby land, nor has salicornia been reported as an invasive species. It should also be noted that although salicornia is non-native that does not imply that it is also invasive [172]. Typical characteristics of invasive species include perennial growth, rapid and high aboveground biomass growth, tolerance to drought, low fertility soils, or saline soils, and a lack of resident pathogens or pests. Salicornia exhibits on a few of these characteristics (tolerance to drought, low fertility soils, and saline soils) but in this cursory analysis does not seem to pose a serious invasive threat to the region. In fact, the United States Department of Agriculture (USDA) performed a pest risk assessment to examine the plant pest risks associated with the importation of fresh salicornia tips grown in Mexico [173]. It was determined that salicornia was not listed in any literature as a potential weed and happened to be indigenous to certain areas of the United States, and as such was not considered a potential pest risk. However, prior to large-scale implementation, this issue warrants further research for Abu Dhabi and the UAE.

CHAPTER 6

6 Data Gaps

One of the key results of this Sustainability Assessment is the identification of data gaps in the literature and design assumptions associated with the ISAS that pose operational or environmental risks for the viability and ultimate success of the system. These are areas for further research that will be critical for the effective implementation of a commercial scale ISAS in the future. There are two categories of data gaps, those directly related to the site chosen and its final design and general knowledge gaps due to insufficient research or literature sources. These data gaps are identified in Chapters 6.1 and 6.2.

6.1 Site-Specific and General Data Gaps

This chapter lists the gaps in site-specific data that will be determined when an appropriate site and design is chosen for the ISAS.

- **Construction** – Energy and material flows, machinery required for infrastructure, buildings, and land shaping are required to assess the capital goods associated with the aquaculture component of the ISAS is currently ignored.
- **Transportation** – Transportation to and from the ISAS and within the ISAS is based on rough, but conservative, approximations.
- **Pumps** – Energy consumption is based on the potential energy required to pump water up assumed elevations with a pumping efficiency range, but is not based actual pump specifications.

- **Friction from Water Flow** – The losses associated with friction when pumping the seawater is currently ignored as the ISAS is assumed to be located close to the coast and use mostly large diameter channels with seawater.
- **Long–Term Impacts –** The long-term soil and environmental impacts of operating a commercial scale ISAS in Abu Dhabi have not been quantified or included.
- **Coastal Area Available for Mangroves –** As mentioned in Chapter 2.4, mangroves in the UAE seem to best adapted for growth 0–2 meters from the sea water line. Currently, healthy growth of mangroves are present along the near shore islands and lagoons of Abu Dhabi (2,500 ha), Umm Al Qaiwain (200 ha), Khor Kalba (150 ha), Ras Al Khaima (20 ha), and Ajman (20 ha) [118]. This is less than 3,000 ha of existing mangroves in the UAE. It has not yet been determined if there is sufficient coastal area for 10,000–20,000 ha of contiguous mangrove wetlands, as intended in a commercial scale ISAS. However, it is possible that the mangroves will be able to grow at elevations higher than 2 meters if their roots can intercept salicornia leachate below the surface [34].
- **Social, Aesthetic, and Ecotourism Considerations –** Once the key quantitative environmental and economic impacts of the system are evaluated it will be important to further address the social benefits of implementing a large-scale ISAS in Abu Dhabi, specifically the jobs created, technology development opportunities, and knowledge building for the local community. Additionally, the ISAS provides an opportunity for what many may consider the beautification of the desert by greening it. It is difficult to quantify this benefit, but it may well be able to be captured in the potential ecotourism opportunities promoted by afforesting the coastline with mangrove swamps that are likely to increase biodiversity and fishing opportunities in the region.

6.2 Knowledge Gaps

This chapter details specific data gaps in the available research for the processes employed in a large-scale ISAS. These gaps can be targeted for future research projects and experiments.

6.2.1 Aquaculture Data Gaps

- **Species** – Though it is likely that the shrimp and tilapia species identified in Chapter 2.2 will be appropriate for an ISAS in the region, this choice requires testing and verification.

6.2.2 Salicornia Halo-Agriculture Data Gaps

- **Yields** – Assumed yields for salicornia are taken from the literature and adjusted based on seawater salinity and local climate, but are not based on empirical data of growing salicornia in Abu Dhabi. Additionally, there have been some issues with salicornia spikes maturing at different times from one another, making mechanical harvesting difficult and potentially reducing overall achievable yields [69].
- **Nitrogen Volatilization** – IPCC Tier 1 methodology is currently used to account for nitrogen volatilization from the salicornia fields (as in Stratton et al. [61]). This may not be an appropriate methodology for the irrigation and fertilization methods used for salicornia farming and results in a significant GHG contribution in the halo-agriculture process, as shown in Figure 33Figure 34 and Figure 35.
- **Farm Machinery Usage** – Farming energy is assumed to be similar to that used in soybean farming until better information becomes available. Though it has been shown that typical farming equipment (such as irrigation booms or combines) can be slightly modified to be used to cultivate salicornia [55] there have been some issues with lodging (when seed spikes do not stay erect) which can significantly impact the yields obtained through mechanical methods [69].

- **Salicornia Carbon Sequestration** – The carbon sequestration data for salicornia (root and straw, if plowed back into the soil) is unverified (see Chapter 2.3.10).
- **Seedling production** – Associated energy flows and inputs and outputs for salicornia seedling production is ignored, except for the planting of salicornia seeds mechanically. Additionally, the viability of germinating salicornia seeds in situ using seawater or diluted seawater need to be addressed such that best practice methods can be developed and implemented.
- **Chemical Usage –** Pesticide or herbicide usage is ignored in this sustainability assessment as it is expected to be minimal but this needs to be verified.

6.2.3 Mangrove Silviculture Data Gaps

- **Seedling production** – Associated energy flows and inputs and outputs for mangrove seedling production is ignored.
- **Yields** – Assumed yields for mangroves are taken from the literature but are not based on empirical data of growing and managing mangroves in Abu Dhabi.
- **Salt Content** – It is likely that the mangrove biomass has a high salt content (ash content). However, accurate data on this quantity is not readily available in the literature. The amount of salt content in the mangrove biomass could significantly reduce the quantity of usable energy and fuel produced from the processing of the mangrove biomass into electricity, Fischer-Tropsch fuels, or pyrolysis bio-oil.
- **Mangrove Cultivation** – No information is yet available for mangrove cultivation or harvesting.
- **Mangrove Carbon Sequestration –** Minimal verifiable information is available on the carbon sequestration potential of mangroves (see Chapter 2.4). Additionally, the amount of carbon that enters long-term sequestration versus the quantity of biomass harvested for biomass processing requires further research and validation.

- **Mangrove species** – It is assumed that *Avicennia marina* will be grown, but this has not yet been confirmed by a mangrove expert.
- **Farm Machinery Usage** – Farming energy for the mangroves is assumed to be minimal and mostly manual labor intensive.
- **Harvesting –** The harvesting process for mangroves has not been explicitly defined. It may require a large quantity of manual labor as it did in Eritrea.

6.2.4 Salicornia and Mangrove Biomass Conversion Data Gaps

- **Salt Content** – Salicornia straw can have a high salt content which may impact its ability processed into fuels. It may be possible to rinse and press the straw to reduce its salt content, but energy flows required for this process have not yet been reliably obtained.
- **Energy Content –** Salicornia straw and mangrove biomass energy content is taken from the literature, but may not be applicable to the ISAS operations under the conditions described using full strength seawater for irrigation.
- **Biomass Conversion Processes –** Gasification, Fischer-Tropsch process, and the pyrolysis pathways are extremely simplified and untested with salicornia straw and mangrove biomass.

Though many of these data gaps may have a limited impact on the overall life cycle assessment results, it will be important to address them empirically and locally with field experiments.

CHAPTER 7

7 ISAS LCA Results

Perhaps the most important results obtained in this Sustainability Assessment are the identification of the risks in Chapter 5 and data gaps in Chapter 6. The numerical results presented in Chapter 7.1 are important but must be taken within the scope of this study as illustrative at best, representing the highest and lowest (hence the best and worst case analysis) *potential* impacts of an ISAS described herein being implemented on a large scale in the UAE. Should a viable site be found and the technological hurdles overcome, the ISAS shows tremendous promise as a more sustainable system for producing food and fuel, even under several alternative management practices or yield assumptions.

7.1 Pathway Result Comparisons

Due to the uncertainty with the ISAS design, potential site characteristics, and yields of the various processes within the ISAS, several pathways have been identified for comparison. The ISAS produces numerous marketable coproducts, including fish, salicornia meal, and various fuels, depending on the pathway selected. Therefore results can be interpreted in various ways depending on the data presented and the allocation of emissions among the coproducts, as mentioned in Chapter 4.3. To accurately and transparently present the results of this data, unallocated pathway results are provided on a per hectare of ISAS basis.

7.1.1 Pathway Identification

Eight pathways were identified to compare different assumptions to one another as well as different ISAS design options. The first three pathways evaluate the impact of different pathways on biomass processing, namely gasification, Fischer-Tropsch synthesis, and pyrolysis. For simplicity, the remaining pathways are all modifications of the baseline Pathway 1, Gasification. They are as follows:

1. **Gasification Pathway (Gas) –** Salicornia and mangrove biomass harvested is gasified to generate electricity. The electricity is used onsite to power the pumps for aquaculture and salicornia irrigation. Excess electricity is transmitted to the grid to avoid using natural gas fired power plant electricity.
2. **Low Biomass Yields (Low Mass)** – Similar to the Gasification Pathway except that the yield of salicornia biomass is assumed to be similar to that achieved in by the Eritrean seed variety bred and developed by Seawater Farms Eritrea and described by Zerai et al. [69]. The Eritrean Strain has a reduced biomass yield but comparable oil yields to the Mexican Strain.
3. **Salinity Yield Reduction (Salt Red) –** Similar to the Gasification Pathway except that the yields of salicornia are reduced by the curve in Figure 29 depending upon the salinity of the irrigation water.
4. **Salicornia Straw Burial (Burial) –** Similar to the Gasification Pathway except that 50 percent of the yield of salicornia straw is plowed back into the soil with a portion of it entering long-term sequestration (instead of 10 percent as in all other pathways).
5. **High Carbon Sequestration (High C) –** Similar to the Gasification Pathway except that the GHG sequestration data for the mangroves described by Poynter [127] is used instead of those provided by the USEPA [129], explicitly stated in Appendix A.

6. **RO Use** – Similar to the Gasification Pathway except that the first month of salicornia cultivation is assumed to require freshwater for seed germination. The freshwater is assumed to come from desalinated seawater using Reverse-Osmosis technology at a centralized facility at sea level. It may be possible to use less RO water if salicornia seeds are germinated in a greenhouse because the irrigation could be more efficiently applied. The seedlings may then be transplanted mechanically to the field using a similar technique to those used in some rice paddies [59]. However, this method is untested with salicornia and therefore an area for further research, but not calculated in this analysis.
7. **Fischer-Tropsch Pathway (F-T) –** All salicornia and mangrove biomass harvested is converted via the Fischer-Tropsch process into a slate of FT Jet Fuel, FT Diesel, and FT Naphtha. FT Diesel is used onsite in farm equipment to avoid using fossil diesel. Excess fuels are sold to the market.
8. **Pyrolysis Pathway (Pyr) –** All salicornia and mangrove biomass harvested is converted via pyrolysis into bio-oil. Bio-oil can be used to replace a portion of diesel fuel (by mixing), though it has a reduced energy content than diesel, which is accounted for.

7.1.2 Per Hectare Pathway Comparisons

The following results are on a per hectare of ISAS basis, and are most easily compared to one another to evaluate the several pathways internally from a greenhouse gas and net energy benefit perspective. It is important to note that these results do not include any allocation of emissions or energy among the coproducts, they are an absolute measurement of the data indicated scaled to a single hectare of ISAS operations, which would include aquaculture, salicornia, and mangrove processes according to the land area allocation identified in Appendix A. These results are presented in Figure 30. Figure 31 illustrates the net fuels produced per MJ of fossil fuel input.

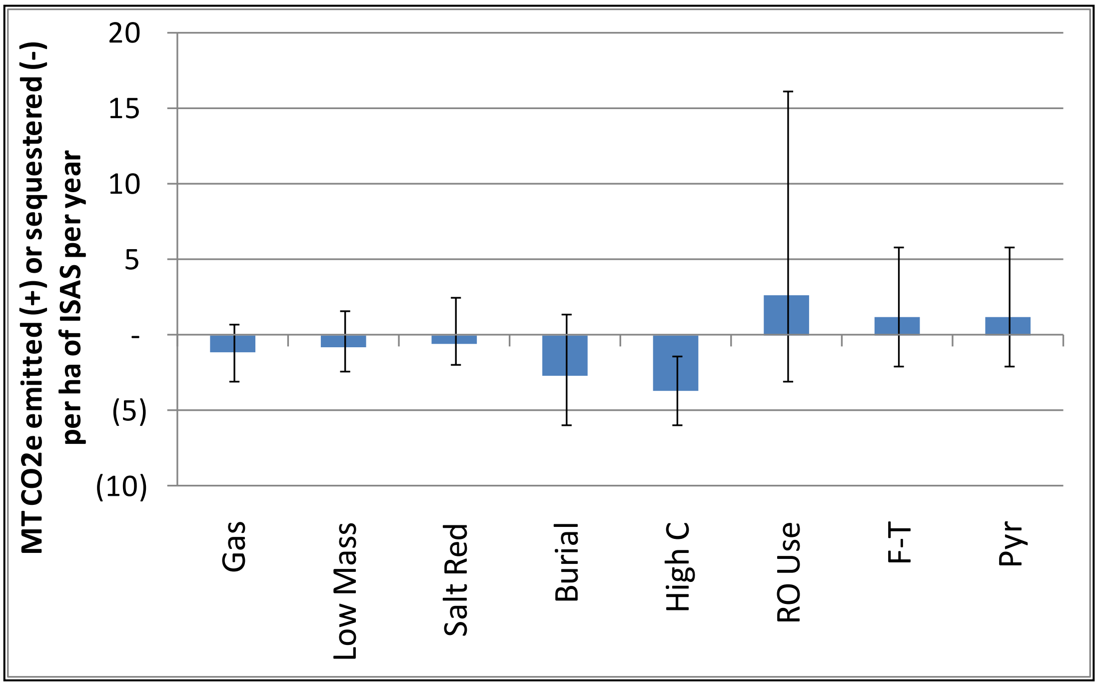


Figure 30 Per Hectare Pathway Comparison of Net GHG Sequestration

It is worth noting that the Fischer-Tropsch and Pyrolysis pathways do no show a net sequestration of carbon dioxide in their base cases primarily because of the large amount of electricity required for the aquaculture water pumping and salicornia irrigation water pumping requirements that are offset by the electricity produced and used onsite in the gasification pathways. Using desalinated water to germinate salicornia seeds in situ for the first month of cultivation results in a substantial increase in process energy required and GHG emissions.

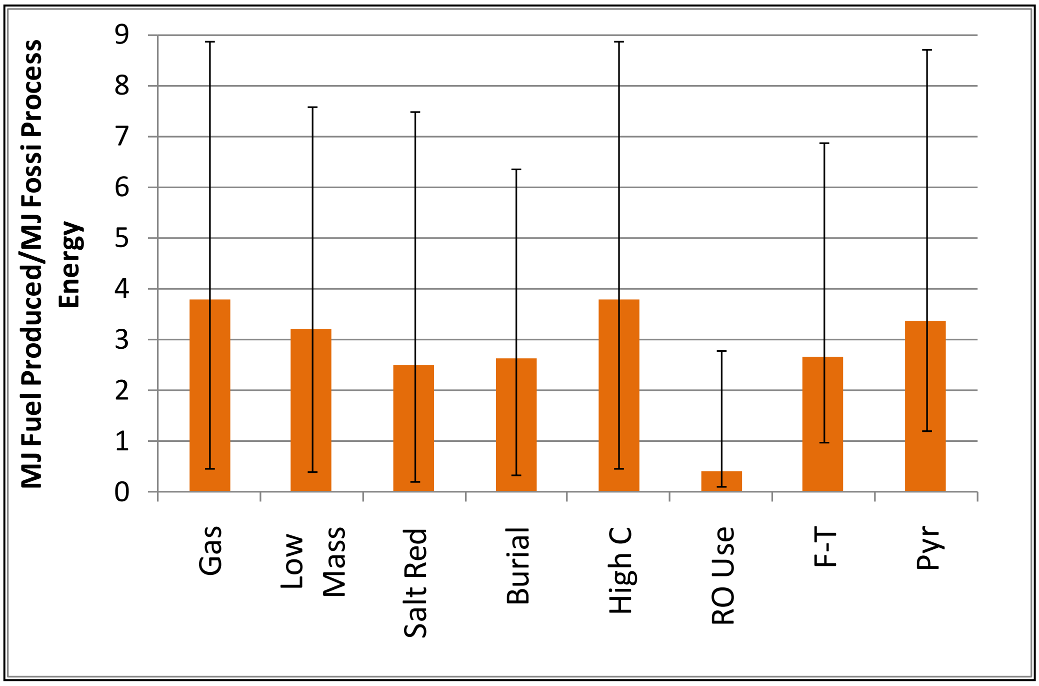


Figure 31 Net Fuel Produced per Fossil Process Energy Input

All of the pathways selected can have net energy balances greater than one in their best cases and net energy losses in their worst cases. Except for the RO Use case, the base cases for each pathway produce a net surplus of fuel energy relative to the fossil energy input. The high and low uncertainty bars indicate the wide range of data used in the best, base, and worst case scenarios for each of the pathways. It is anticipated that these uncertainty bars can be reduced with further research identified by the Data Gaps in Chapter 6.

Each of the pathways identified has differing amounts of process energy and emissions required for each production process (e.g. aquaculture, salicornia halo-agriculture, mangrove silviculture, etc.). These results are indicated in Figure 32 and Figure 33. When the gasification pathway is employed and the electricity is used onsite, it is assumed to be evenly distributed to the aquaculture and salicornia processes for water pumping. Any excess electricity is used for desalination, if applicable. It is otherwise exported to the grid.

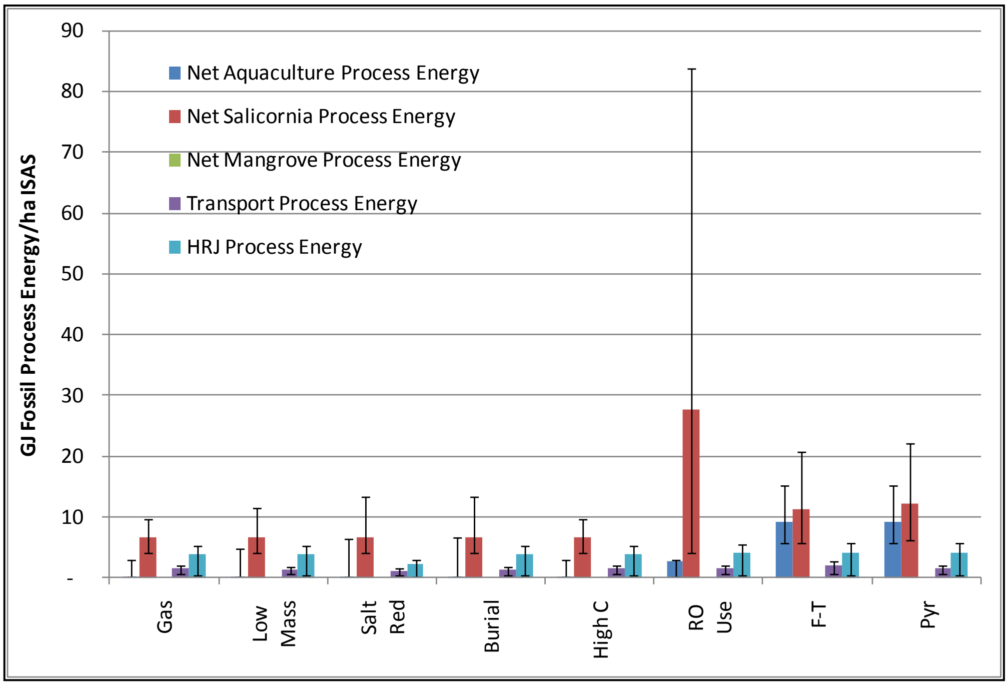


Figure 32 Fossil Process Energy per Production Process

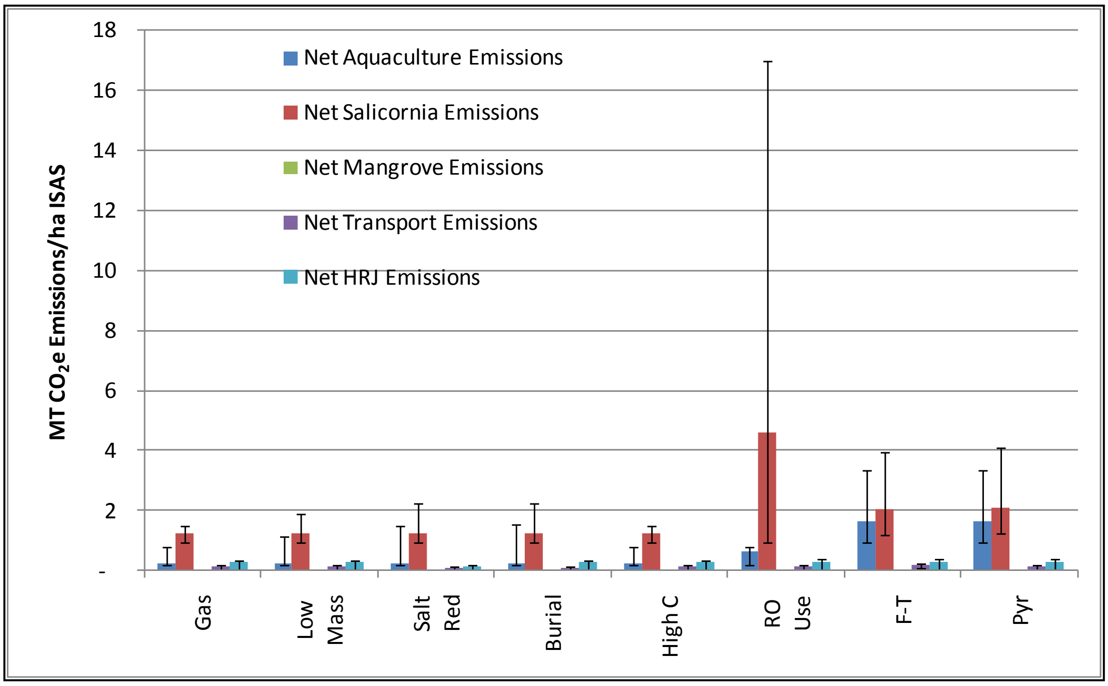


Figure 33 GHG Emissions per Production Process

It is also important to evaluate which of the three primary greenhouse gases (CO_2, N_2O, CH_4) evaluated in this study are emitted from each of the processes to identify the processes with the highest potential for improvement. The six main processes from the Gasification pathway are illustrated in Figure 34 and Figure 35, both on an absolute and percentage contribution scale. The Gasification Pathway was evaluated for illustrative purposes only as it is used as the baseline for five of the eight pathways evaluated. The relative GHG emission contributions for each of the processes remains relatively stable in the Fischer-Tropsch and Pyrolysis pathways (not shown) except that the Water Pumping process has substantial GHG emissions, primarily from CO_2, due to the grid supplied electricity used for this process when gasification is not employed.

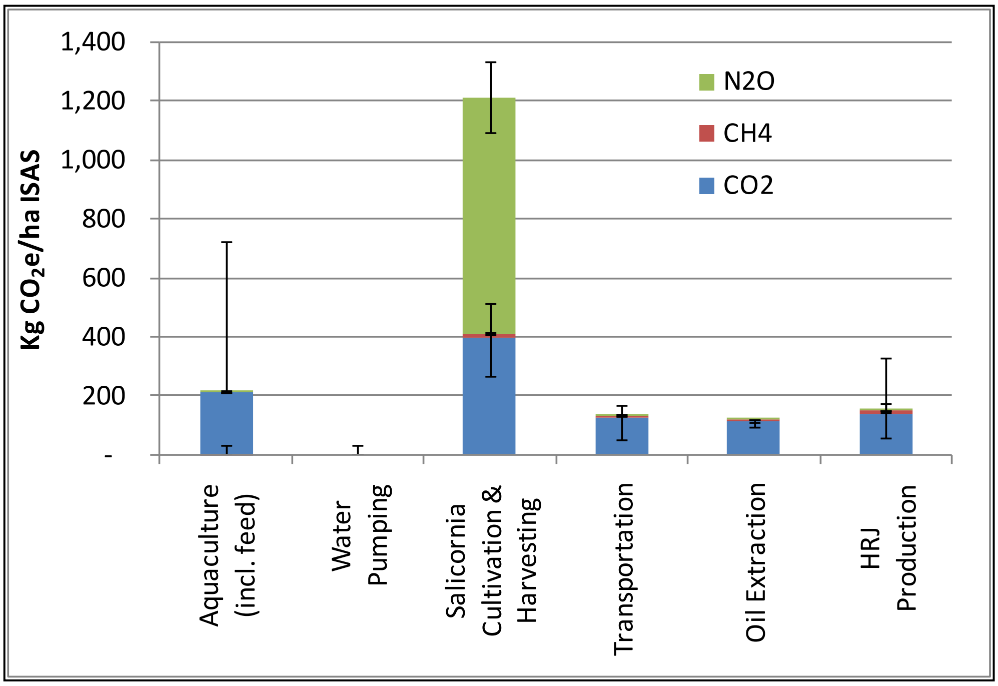
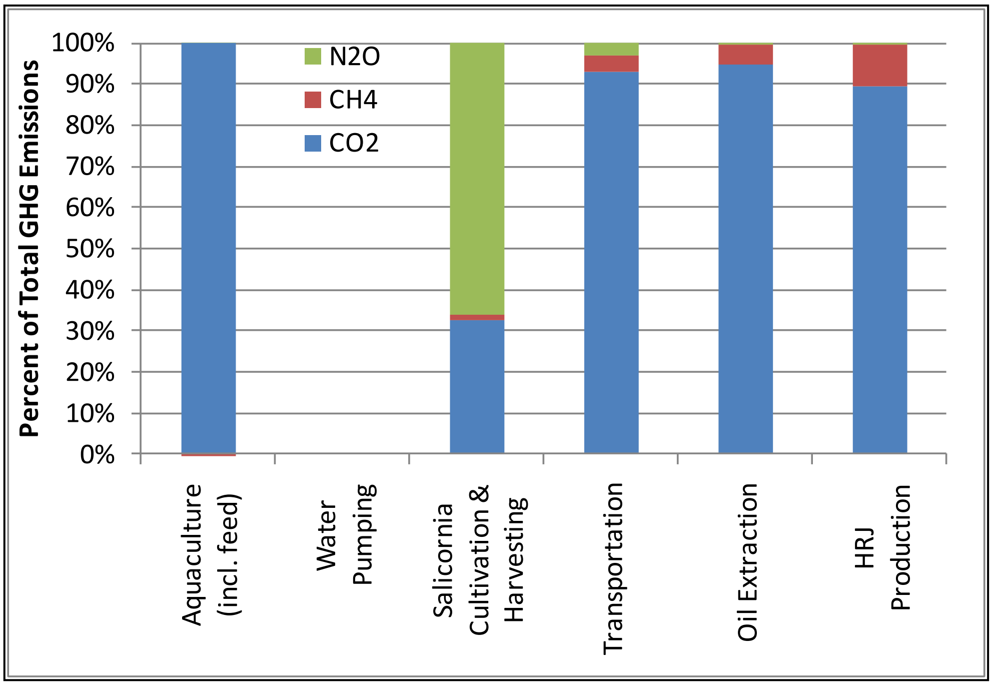


Figure 34 GHG Emissions by Process and GHG Gas, Gasification Pathway



Note: Water Pumping has no related GHG Emissions in the Base Case of the Gasification Pathway because all of the pumping electricity requirements are assumed to be accounted for by green electricity generated from the gasification of salicornia and mangrove biomass.

Figure 35 Base Case GHG Emissions by Process and Gas, as a Percentage of Total GHG for Gasification Pathway

Both salicornia and mangroves sequester carbon in their biomass. These quantities vary according to the pathway selected and the assumptions about biomass carbon sequestration detailed in Appendix A. Though not examined here, it is also possible to make assumptions about the potential for the fuels produced in the ISAS to offset their fossil fuel counterparts. These GHG offsets can be used in alternate displacement or allocation pathways not examined in this analysis. If fossil fuels were displaced by the fuels produced along the various pathways, it would be according to the following methodology:

- **HRJ and F-T Jet Fuel** – Credited against fossil jet fuel according to the results from Skone and Gerdes [26], [174].
- **Naphtha** – Naphtha can be used to create other fuels, such as gasoline. Several references were used (detailed in Appendix A) to provide the offsets for naphtha.

- **Electricity** – Credited against grid electricity in Abu Dhabi produced using natural gas.
- **Mixed Propane Gas** – Credited against electricity that could be produced from it if it is gasified according to the same process efficiencies as those in the gasification pathway. The electricity offsets grid electricity produced from natural gas.
- **F-T Diesel** – Credited against fossil diesel according to the results from Skone and Gerdes [175].
- **Pyrolysis Oil** – Credited against fossil diesel according to the results from Skone and Gerdes [175]. Pyrolysis oil has been successfully used in diesel test engines where it shows similar characteristics to conventional diesel in terms of engine parameters and emissions [145]. The reduced energy content of pyrolysis oil relative to fossil diesel should be accounted for.

For illustrative purposes, the potential biomass carbon sequestration and fuel offsets are shown in Figure 36.

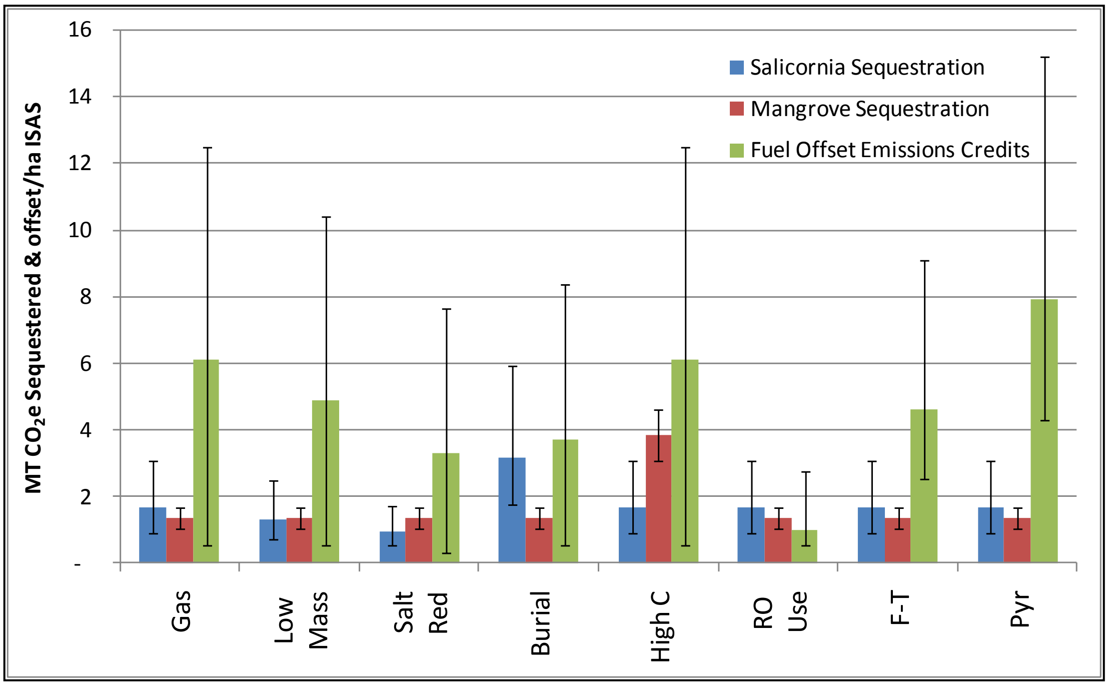
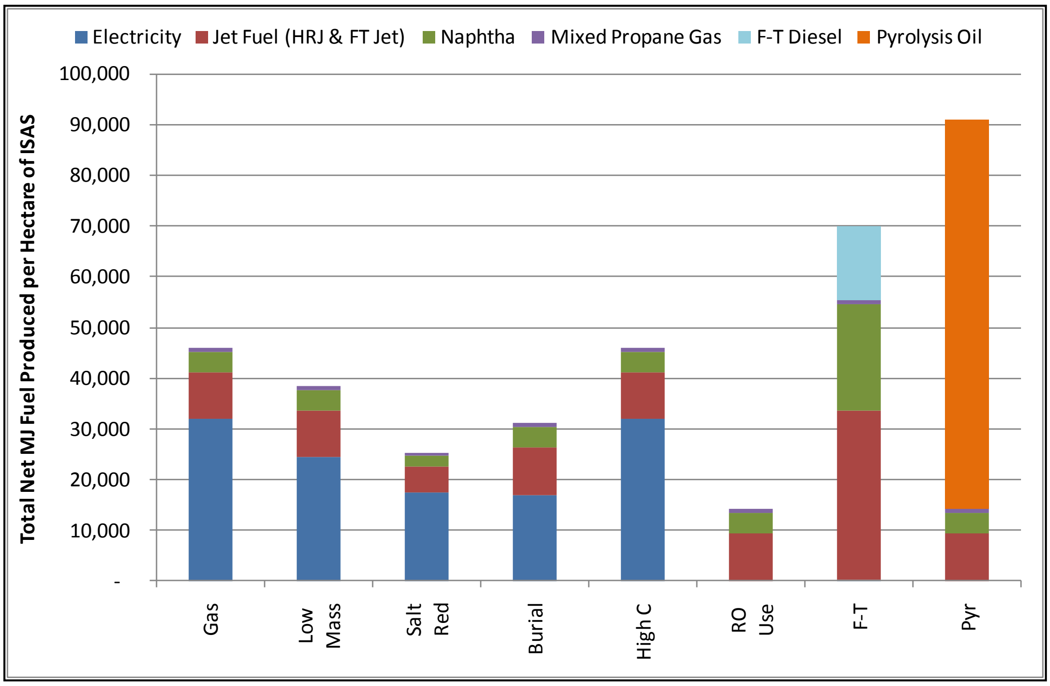


Figure 36 Carbon Sequestration or Offset per Production Process

We also examined each pathway for the potential fuel produced along each pathway as well. The net fuel produced in each pathway is the fuel that can be exported offsite after any of it that can be used onsite is used. This primarily applies to electricity produced in the gasification pathways that is used for water pumping and the Fischer-Tropsch Diesel fuel used onsite for farming operations. The gross fuel produced per hectare of ISAS is also illustrated in Figure 37 if it is more cost effective or beneficial to the system to export 100 percent of the green fuels produced onsite at the ISAS.



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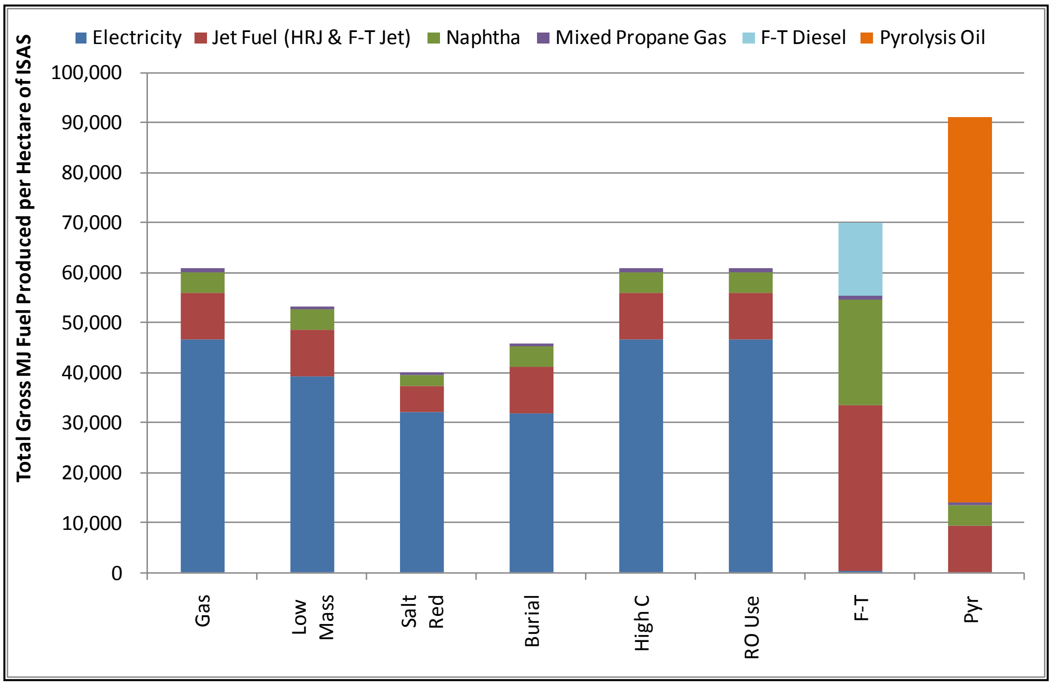

B

Figure 37 Net (A) and Gross (B) Fuel Slates Produced per Hectare ISAS

7.1.3 GHG Emissions per Fuel Production

To compare the net GHG emissions of the ISAS to other biofuel feedstock production processes and to that of fossil jet fuel it is necessary to examine the emissions from the system per unit fuel produced. Due to the nature of the system and the numerous coproducts for each produce pathway, the results are most transparently illustrated without any allocation (see Chapter 4.3), as shown in Figure 38 and Figure 39. Note that the data in Figure 38 and Figure 39 are identical. The uncertainty bars are removed in Figure 39 to provide a better visual representation of the base case results for each of the pathways.

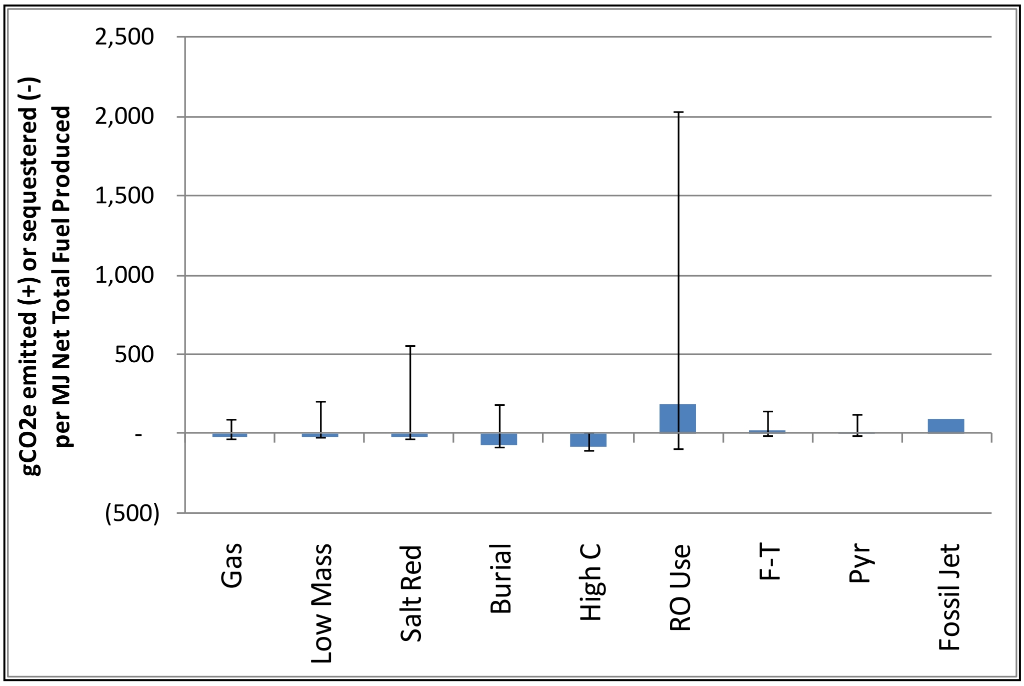

Figure 38 Emissions per MJ Fuel Produced (Fossil Jet Fuel data from Skone and Gerdes [175])

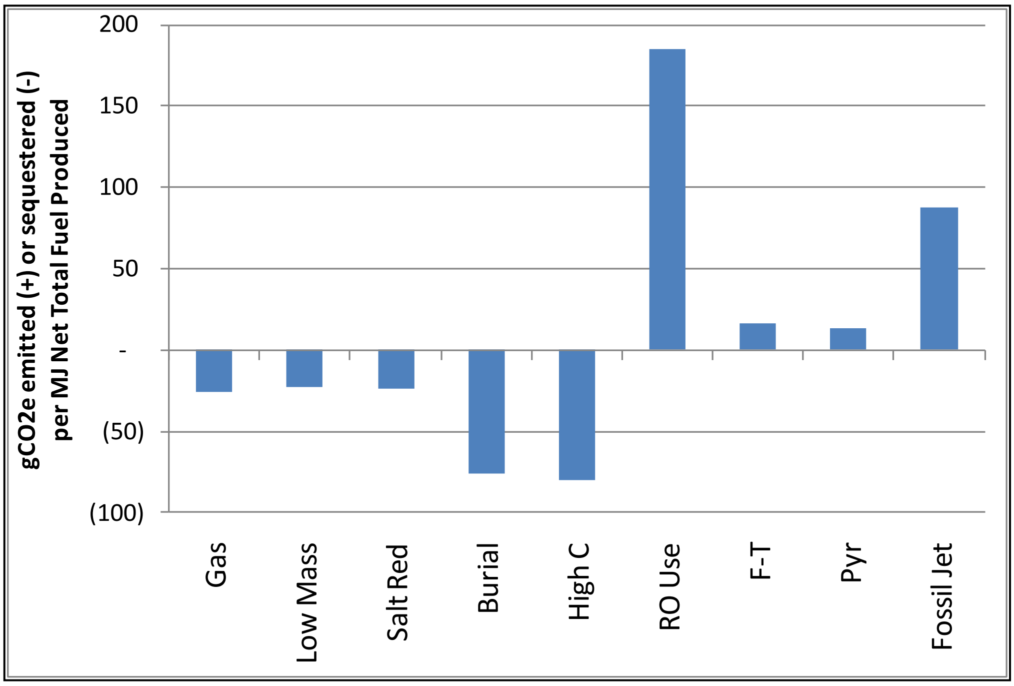

Figure 39 Base Emissions per MJ Fuel Produced, for Illustrative Purposes Only (Fossil Jet Fuel data from Skone and Gerdes [175])

The total net GHG emissions (or sequestration) are divided by the total net energy of the entire fuel slate produced in each pathway, resulting in the mass of GHG emissions per MJ of fuel produced in the ISAS. It is possible to compare these results to the GHG emissions from fossil jet fuel taken from Skone and Gerdes [175] because each type of fuel produced has the same unit GHG emissions per MJ. The results indicate that seven of the eight ISAS pathways have a strong potential to produce fuels with significantly lower net GHG emissions than those of fossil jet fuel. However, it is important not to overlook the wide uncertainty bars that illustrate the importance of acquiring more accurate data to narrow the range of uncertainty. More detail for each pathway's results is provided in Table 10.

7.1.4 Economic Allocation Results

Due to the relatively high value of the shrimp relative to the other coproducts produced in the ISAS, representing over 80 percent of the revenue per unit land area of ISAS (see Figure 40), the GHG emissions per gram of coproduct was used instead of GHG emissions per metric ton.

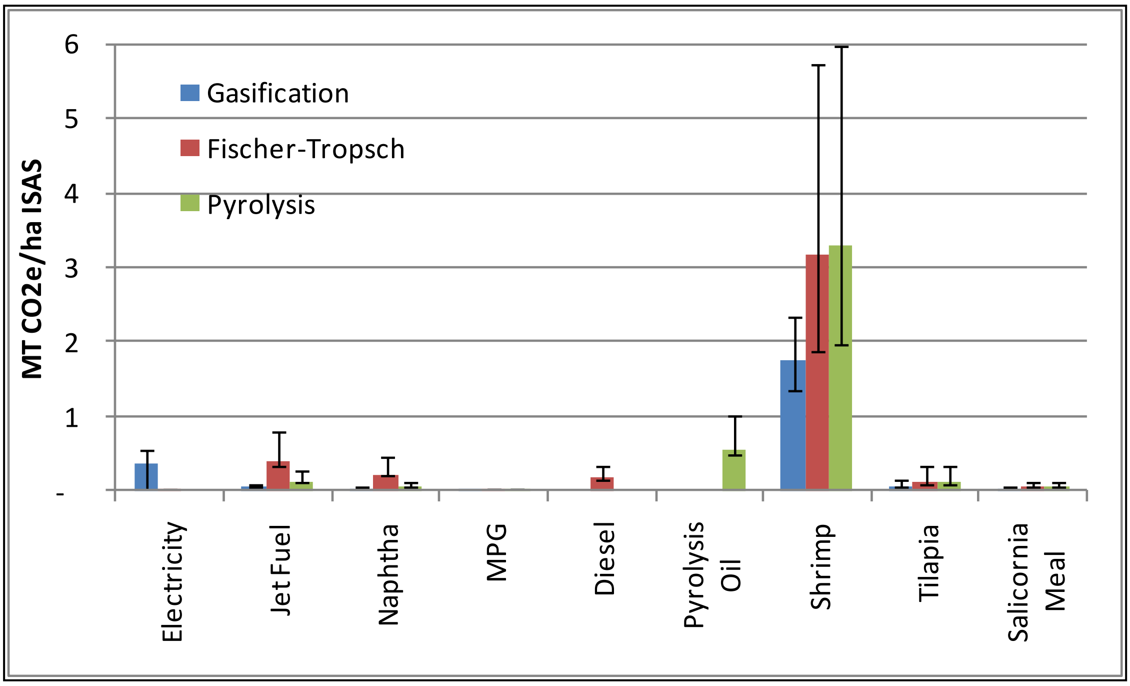

Figure 40 Emissions per Coproduct based on Revenue per Hectare

Even assuming that there is no net carbon sequestration in the biomass, jet fuel produced by the ISAS has substantially lower net emissions compared to fossil jet [175]. Due to the relatively subjective nature of this economic allocation, only the three main pathways were evaluated against one another to provide an approximate basis for comparison to jet fuel, as in Figure 41.

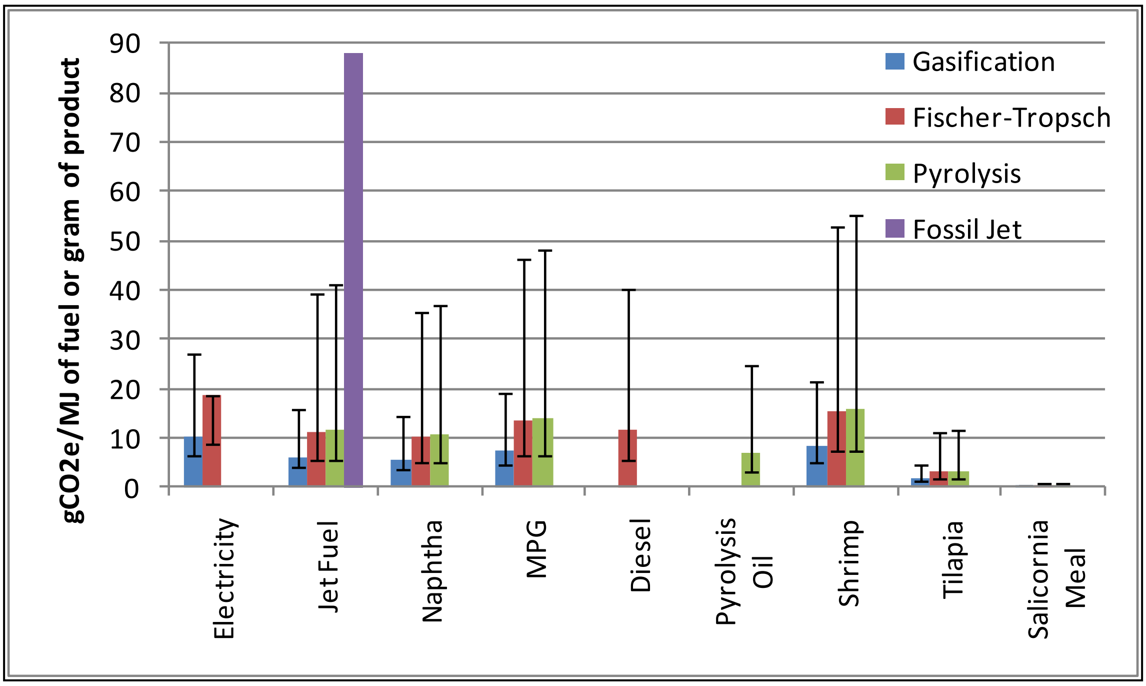

Figure 41 Economic Allocation Results

When the material coproducts are ignored, however, the results differ significantly, although the jet fuel produced in all three pathways still remains below that of jet fuel for the base case, though the worst case scenarios could result in significantly higher emissions compared to fossil jet fuel, see Figure 42.

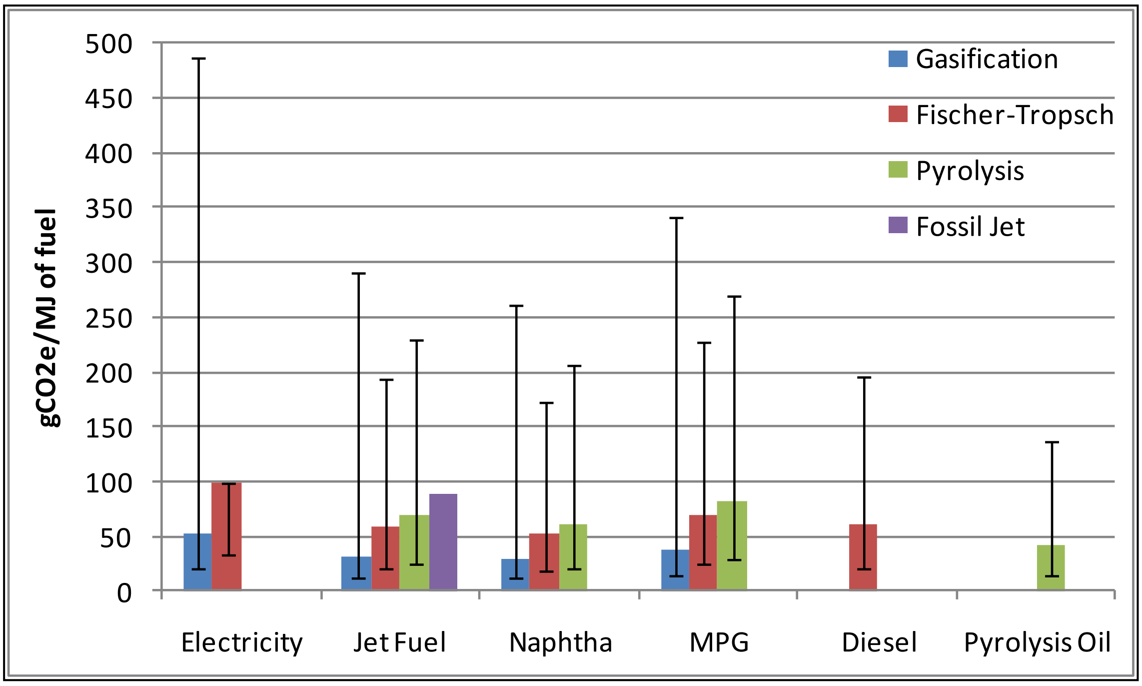

Figure 42 Economic Allocation Results without Shrimp, Tilapia, and Salicornia Meal

The economic allocation among the other five pathways does produce marginally different results from those presented in Figure 41 and Figure 42, but not noticeably different from the three pathways presented herein, except in the case of the RO Use pathway which has a significant impact on the overall GHG and energy balance of the system, resulting in higher emissions than fossil jet fuel when using this allocation methodology.

Table 10 Pathway Results

		1			2			3			4		
		Gas			**Low Mass**			**Salt Red**			**Burial**		
		Worst	Base	Best	Worst	Base	Best	Worst	Base	Best	Worst	Base	Best
Aquaculture Energy Inputs	MJ/ha ISAS	2,864	179	153	2,864	179	153	2,864	179	153	2,864	179	153
Salicornia Energy Inputs	MJ/ha ISAS	9,434	6,654	4,067	9,434	6,654	4,067	9,434	6,654	4,067	9,434	6,654	4,067
Mangrove Energy Inputs	MJ/ha ISAS	-	-	-	-	-	-	-	-	-	-	-	-
Transportation Energy Inputs	MJ/ha ISAS	1,991	1,513	568	1,836	1,357	496	1,554	1,124	402	1,680	1,204	426
Water Pumping for Aquaculture Energy	MJ/ha ISAS	-	-	-	1,802	-	-	3,577	-	-	3,644	-	-
Salicornia irrigation: Pumping to fields (and desal if necessary)	MJ/ha ISAS	173	-	-	2,014	-	-	3,790	-	-	3,857	-	-
HRJ Process Energy	MJ/ha ISAS	2,557	3,894	7,482	2,597	3,894	7,482	1,439	2,171	4,190	2,597	3,894	7,482
Net Process Energy (+/-)	MJ/ha ISAS	17,019	12,241	12,270	20,546	12,085	12,198	22,657	10,129	8,812	24,075	11,932	12,128
Net Electricity produced, after onsite usage in pumping/desalination	MJ fuel/ha ISAS	-	31,873	81,774	-	24,334	65,715	-	17,311	50,894	-	16,949	50,178
HRJ	MJ fuel/ha ISAS	5,363	9,266	17,565	5,363	9,266	17,565	2,971	5,166	9,837	5,363	9,266	17,565
F-T Jet	MJ fuel/ha ISAS	-	-	-	-	-	-	-	-	-	-	-	-
Naphtha	MJ fuel/ha ISAS	2,410	4,164	7,912	2,410	4,164	7,912	1,335	2,321	4,431	2,410	4,164	7,912
Mixed Propane Gas	MJ fuel/ha ISAS	182	742	1,436	182	742	1,436	101	414	804	182	742	1,436
Net F-T Diesel produced, after onsite usage in farm equipment	MJ fuel/ha ISAS	-	-	-	-	-	-	-	-	-	-	-	-
Pyrolysis Oil	MJ fuel/ha ISAS	-	-	-	-	-	-	-	-	-	-	-	-
Total Fuel Energy Production	MJ fuel/ha ISAS	7,955	46,045	108,686	7,955	38,506	92,628	4,407	25,212	65,966	7,955	31,121	77,091
Net Energy Benefit	MJ output/MJ input	0.47	3.76	8.86	0.39	3.19	7.59	0.19	2.49	7.49	0.33	2.61	6.36
Aquaculture Emissions	gCO2e/ha ISAS	764,167	212,034	208,320	764,167	212,034	208,320	764,167	212,034	208,320	764,167	212,034	208,320
Salicornia Emissions	gCO2e/ha ISAS	1,455,671	1,214,757	956,250	1,455,671	1,214,757	956,250	1,455,671	1,214,757	956,250	1,455,671	1,214,757	956,250
Mangrove Emissions	gCO2e/ha ISAS	-	-	-	-	-	-	-	-	-	-	-	-
Transportation Emissions	gCO2e/ha ISAS	179,309	136,271	51,137	165,288	122,201	44,642	139,894	101,215	36,230	151,259	108,419	38,359
Water Pumping for Aquaculture Emissions	gCO2e/ha ISAS	-	-	-	375,866	-	-	746,263	-	-	760,236	-	-
Salicornia irrigation: Pumping Emissions	gCO2e/ha ISAS	36,088	-	-	420,231	-	-	790,629	-	-	804,602	-	-
HRJ Process Energy Emissions	gCO2e/ha ISAS	199,038	268,979	505,549	207,316	268,979	505,549	114,855	149,962	283,126	207,316	268,979	505,549
Total Emissions	gCO2e/ha ISAS	2,634,274	1,832,041	1,721,256	3,388,539	1,817,971	1,714,762	4,011,479	1,677,968	1,483,926	4,143,251	1,804,189	1,708,479
Salicornia Sequestration	gCO2e/ha ISAS	925,473	1,656,555	3,078,075	742,376	1,328,819	2,469,103	521,630	933,695	1,734,915	1,779,756	3,185,683	5,919,375
Mangrove Sequestration	gCO2e/ha ISAS	1,019,333	1,353,000	1,686,667	1,019,333	1,353,000	1,686,667	1,019,333	1,353,000	1,686,667	1,019,333	1,353,000	1,686,667
Credit from Naphtha	gCO2e/ha ISAS	20,570	49,698	121,347	20,570	49,698	121,347	11,396	27,708	67,958	20,570	49,698	121,347
Credit from electricity	gCO2e/ha ISAS	-	5,108,608	10,653,288	-	3,900,248	8,561,201	-	2,774,560	6,630,303	-	2,716,574	6,537,142
Credit from Jet Fuel	gCO2e/ha ISAS	472,210	815,858	1,546,618	472,210	815,858	1,546,618	261,609	454,859	866,162	472,210	815,858	1,546,618
Credit from MPG (assumed to be gasified into electricity)	gCO2e/ha ISAS	37,911	118,929	187,065	37,911	118,929	187,065	21,003	66,305	104,763	37,911	118,929	187,065
Credit from F-T Diesel	gCO2e/ha ISAS	-	-	-	-	-	-	-	-	-	-	-	-
Credit from pyrolysis oil (offsets diesel use, adjusted for energy content	gCO2e/ha ISAS	-	-	-	-	-	-	-	-	-	-	-	-
Total Sequestered or Avoided	gCO2e/ha ISAS	4,420,304	12,112,203	22,037,800	4,054,110	10,248,372	18,727,769	3,375,936	7,896,821	14,512,350	6,128,870	12,778,424	23,604,254
Net Carbon Balance (+/-) with displacement except for Jet Fuel	gCO2e/ha ISAS	(630,986)	6,454,749	14,005,185	(1,568,348)	4,932,723	11,310,620	(2,438,116)	3,477,301	8,740,680	(1,285,680)	5,619,694	12,743,116
Net Carbon Balance (+/-) with no displacement	gCO2e/ha ISAS	(689,467)	1,177,514	3,043,485	(1,626,830)	863,848	2,441,008	(2,470,516)	608,727	1,937,655	(1,344,162)	2,734,494	5,897,563
Shrimp	MT/ha ISAS	0.11	0.21	0.26	0.11	0.21	0.26	0.11	0.21	0.26	0.11	0.21	0.26
Tilapia	MT/ha ISAS	0.03	0.04	0.05	0.03	0.04	0.05	0.03	0.04	0.05	0.03	0.04	0.05
Salicornia meal	MT/ha ISAS	0.15	0.28	0.58	0.15	0.28	0.58	0.02	0.09	0.25	0.15	0.28	0.58

		5			6			7			8		
		High C			**RO Use**			**F-T**			**Pyr**		
		Worst	Base	Best	Worst	Base	Best	Worst	Base	Best	Worst	Base	Best
Aquaculture Energy Inputs	MJ/ha ISAS	2,864	179	153	2,864	2,763	153	2,864	2,763	2,607	2,864	2,763	2,607
Salicornia Energy Inputs	MJ/ha ISAS	9,434	6,654	4,067	9,434	6,654	4,067	8,178	5,722	3,662	9,434	6,654	4,067
Mangrove Energy Inputs	MJ/ha ISAS	-	-	-	-	-	-	-	-	-	-	-	-
Transportation Energy Inputs	MJ/ha ISAS	1,991	1,513	568	1,991	1,513	568	2,589	1,910	689	1,991	1,513	568
Water Pumping for Aquaculture Energy	MJ/ha ISAS	-	-	-	-	-	-	12,349	6,446	3,058	12,349	6,446	3,058
Salicornia irrigation: Pumping to fields (and desal if necessary)	MJ/ha ISAS	173	-	-	74,379	20,978	-	12,562	5,569	1,986	12,562	5,569	1,986
HRJ Process Energy	MJ/ha ISAS	2,557	3,894	7,482	2,464	3,964	7,482	2,653	4,157	7,869	2,653	4,157	7,869
Net Process Energy (+/-)	MJ/ha ISAS	17,019	12,241	12,270	91,132	35,872	12,270	41,195	26,567	19,870	41,854	27,103	20,154
		-	-	-	-	-	-	-	-	-	-	-	-
Net Electricity produced, after onsite usage in pumping/desalination	MJ fuel/ha ISAS	-	31,873	81,774	-	-	7,052	-	327	1,211	-	-	-
HRJ	MJ fuel/ha ISAS	5,363	9,266	17,565	5,363	9,266	17,565	5,363	9,266	17,565	5,363	9,266	17,565
F-T Jet	MJ fuel/ha ISAS	-	-	-	-	-	-	13,969	23,933	46,152	-	-	-
Naphtha	MJ fuel/ha ISAS	2,410	4,164	7,912	2,410	4,164	7,912	12,270	21,057	40,490	2,410	4,164	7,912
Mixed Propane Gas	MJ fuel/ha ISAS	182	742	1,436	182	742	1,436	182	742	1,436	182	742	1,436
Net F-T Diesel produced, after onsite usage in farm equipment	MJ fuel/ha ISAS	-	-	-	-	-	-	8,039	14,744	29,540	-	-	-
Pyrolysis Oil	MJ fuel/ha ISAS	-	-	-	-	-	-	-	-	-	41,789	76,866	148,357
Total Fuel Energy Production	MJ fuel/ha ISAS	7,955	46,045	108,686	7,955	14,171	33,965	39,822	70,069	136,393	49,743	91,037	175,270
		-	-	-	-	-	-	-	-	-	-	-	-
Net Energy Benefit	MJ output/MJ input	0.47	3.76	8.86	0.09	0.40	2.77	0.97	2.64	6.86	1.19	3.36	8.70
		-	-	-	-	-	-	-	-	-	-	-	-
Aquaculture Emissions	gCO2e/ha ISAS	764,167	212,034	208,320	764,167	626,214	208,320	764,167	626,214	528,063	764,167	626,214	528,063
Salicornia Emissions	gCO2e/ha ISAS	1,455,671	1,214,757	956,250	1,455,671	1,221,882	956,250	1,329,646	1,128,352	918,070	1,455,671	1,221,882	958,771
Mangrove Emissions	gCO2e/ha ISAS	-	-	-	-	-	-	-	-	-	-	-	-
Transportation Emissions	gCO2e/ha ISAS	179,309	136,271	51,137	179,309	136,271	51,137	233,091	171,951	62,060	179,309	136,271	51,137
Water Pumping for Aquaculture Emissions	gCO2e/ha ISAS	-	-	-	-	-	-	2,576,237	1,033,132	398,329	2,576,237	1,033,132	398,329
Salicornia irrigation: Pumping Emissions	gCO2e/ha ISAS	36,088	-	-	15,516,259	3,362,262	-	2,620,603	892,590	258,682	2,620,603	892,590	258,682
HRJ Process Energy Emissions	gCO2e/ha ISAS	199,038	268,979	505,549	179,721	280,095	505,549	207,316	301,738	547,195	207,316	301,738	547,195
Total Emissions	gCO2e/ha ISAS	2,634,274	1,832,041	1,721,256	18,095,127	5,626,723	1,721,256	7,731,059	4,153,978	2,712,400	7,803,303	4,211,828	2,742,176
		-	-	-	-	-	-	-	-	-	-	-	-
Salicornia Sequestration	gCO2e/ha ISAS	925,473	1,656,555	3,078,075	925,473	1,656,555	3,078,075	925,473	1,656,555	3,078,075	925,473	1,656,555	3,078,075
Mangrove Sequestration	gCO2e/ha ISAS	3,079,600	3,849,500	4,619,400	1,019,333	1,353,000	1,686,667	1,019,333	1,353,000	1,686,667	1,019,333	1,353,000	1,686,667
Credit from Naphtha	gCO2e/ha ISAS	20,570	49,698	121,347	20,570	49,698	121,347	79,481	190,847	471,089	20,570	49,698	121,347
Credit from electricity	gCO2e/ha ISAS	-	5,108,608	10,653,288	-	-	918,780	-	52,483	157,730	-	-	-
Credit from Jet Fuel	gCO2e/ha ISAS	472,210	815,858	1,546,618	472,210	815,858	1,546,618	1,702,172	2,923,185	5,610,356	472,210	815,858	1,546,618
Credit from MPG (assumed to be gasified into electricity)	gCO2e/ha ISAS	37,911	118,929	187,065	37,911	118,929	187,065	37,911	118,929	187,065	37,911	118,929	187,065
Credit from F-T Diesel	gCO2e/ha ISAS	-	-	-	-	-	-	723,830	1,327,581	2,659,845	-	-	-
Credit from pyrolysis oil (offsets diesel use, adjusted for energy content	gCO2e/ha ISAS	-	-	-	-	-	-	-	-	-	3,762,766	6,921,184	13,358,405
Total Sequestered or Avoided	gCO2e/ha ISAS	8,540,838	17,105,203	27,903,267	4,420,304	7,003,595	12,303,292	6,433,007	10,632,135	18,615,569	8,183,070	13,924,779	24,742,918
		-	-	-	-	-	-	-	-	-	-	-	-
Net Carbon Balance (+/-)	gCO2e/ha ISAS	1,429,281	8,951,249	16,937,918	(16,091,839)	(2,448,542)	4,270,676	(4,945,030)	545,417	5,528,071	(2,037,248)	5,887,538	15,689,382
		1,370,799	3,674,014	5,976,219	(16,150,321)	(2,617,169)	3,043,485	(5,786,253)	(1,144,423)	2,052,342	(5,858,496)	(1,202,273)	2,022,566
Shrimp	MT/ha ISAS	-	-	-	-	-	-	-	-	-	-	-	-
Tilapia	MT/ha ISAS	0.11	0.21	0.26	0.11	0.21	0.26	0.11	0.21	0.26	0.11	0.21	0.26
Salicornia meal	MT/ha ISAS	0.03	0.04	0.05	0.03	0.04	0.05	0.03	0.04	0.05	0.03	0.04	0.05

CHAPTER 8

8 Applicability to RSB Criteria

The results of this Sustainability Assessment are intended to be utilized to meet the criteria and guidelines of the Roundtable on Sustainable Biofuels (RSB) framework as related to the Sustainable Aviation Fuel Users Group's (SAFUG) commitment to follow principles and practices laid out in the RSB framework. The RSB Principles & Criteria for Sustainable Biofuel Production Version 2.0 (RSB-STD-01-001) published on 5 November, 2010 which became effective on 1 January, 2011, "provides guidelines on best practices in the production and processing of biofuel feedstock and raw material, and for the production, use, and transport of liquid biofuel for transport." The standard evaluates the following four types of operators, each subject to different sustainability requirements:

- Feedstock Producers;
- Feedstock Processors;
- Biofuel Producers; and
- Biofuel Blenders [2], [159].

The production of the biofuels (HRJ, FT Jet Fuel, FT Diesel, pyrolysis oil, bio-electricity, etc.) is performed by existing technologies provided to the ISAS and implemented onsite. Therefore, the assumption in this chapter is that the onus of meeting RSB standards for Biofuel Producers and Blenders lies with the technology providers. Each of the twelve RSB standards will be briefly summarized and evaluated from the perspective of the ISAS operator acting only as a Feedstock Producer and Feedstock Processor in Abu Dhabi, and, in some cases, in the UAE in general.

8.1 Principle 1: Legality

Principle 1 states that biofuel operations shall follow all applicable laws and regulations. The ISAS on a commercial scale will likely require a significant amount of preparatory design and permitting work to be undertaken by the firms implementing the system. After a more detailed feasibility study is conducted and pilot scale empirical research is evaluated, applicable laws and regulations of Abu Dhabi and the UAE will need to be met for the commercial scale system to be implemented.

8.2 Principle 2: Planning, Monitoring, & Continuous Improvement

Principle 2 requires all operations to be planned, implemented, and continuously improved upon in an open, transparent, and consultative impact assessment and management process and an economic viability analysis. One of the purposes of this analysis, as well as the Economic and Social Impact study being carried out concurrently at Yale, is to meet the requirements of this principle. Specific social and economic studies identified in this principle will be addressed by our partners at Yale and therefore are not mentioned here. As field experiments continue, further empirical data on the technical feasibility of the ISAS, this analysis, and the LCA tool will be updated to reflect these results. If implemented in a large scale the ISAS will be subject to constant monitoring to ensure that proximate land and water supplies are not negatively impacted by the ISAS operations. The system will be iteratively improved as further research becomes available.

To successfully implement a commercial scale ISAS, it will be essential to include the relevant stakeholders from local, regional, and national governments, including land owners, residents, governing officials, and competing business owners (farmers, aquaculturists). The resulting negotiations should result in consensus-driven agreements that provide Free, Prior, & Informed Consent to the relevant stakeholders. This will be necessary in future stages of ISAS development and research but is not directly addressed herein.

8.3 Principle 3: Greenhouse Gas Emissions

Principle 3 specifies that biofuels shall contribute to climate change mitigation by significantly reducing life cycle greenhouse gas emissions as compared to fossil fuels. As there are no known biofuel policies currently in place in the UAE, the GHG emissions from the ISAS are based on the approach, methodology, and calculations presented herein. The system boundaries, land use change impacts, carbon stock changes, coproduct usage, and waste reduction guidelines elicited in this principle are evaluated and accounted for in this analysis, producing results under several pathway options that not only show reduction in emissions relative to fossil fuels, but show a long-term net carbon benefit for the system's operations as a whole. In accordance with Criterion 3b, the LCA conducted herein includes a full well to wheel (in this case, well to wake) evaluation, and does include land use change, above- and below-ground carbon stock changes, and the beneficial use of coproducts and wastes.

The results detailed in Chapter 7 attempt to use best practices for LCA methodology, though at this time not all practices align with the newly developed GHG calculation methodology being developed by the RSB. As this methodology becomes refined and more data gaps identified in Chapter 6 are filled, the LCA results will be revisited and calibrated with the RSB GHG calculation methodology. Several areas where the methodology used in this LCA and the RSB GHG calculation methodologies diverge are as follows:

- The functional unit is one megajoule of finished biofuel product, or jet fuel under economic allocation, though both the Lower Heating Value (LHV) and Higher Heating Value (HHV) are not provided;
- Capital goods (infrastructure) are not included in this analysis;
- Not all background data was obtained from ecoinvent (for example, fertilizer production data was gathered from various sources identified in Appendix A);
- Land use change was calculated assuming that the existing land that will be used by the ISAS has a negligible quantity of stored carbon and will accumulate carbon over time resulting in a net positive land use change because a specific site has not yet been chosen;
- Land use change was not annualized over 20 years of operations although its long-term potential was evaluated; and
- Without an ISAS design or operating ISAS to use to gather data it is not possible to calculate with any confidence the percent reduction of the ISAS GHG emissions relative to the fossil fuel baseline, however, the range of results presented herein do indicate a high potential for a 50 percent or greater reduction in GHG emissions relative to the fossil fuel baseline.

The LCA tool and the methodologies presented herein will be updated regularly as new information becomes available and the relevant changes to the GHG balance will be maintained in accordance with Principle 2 guidance.

8.4 Principle 4: Human and Labor Rights

Principle 4 ensures that biofuel operations do not violate human or labor rights and promotes decent work and the well-being of workers. Though this principle will be further addressed by Yale in their study, the working conditions at the ISAS will be in accordance with all applicable labor laws and regulations in Abu Dhabi and the UAE. Specific worker-employer relationships and agreements will need to be specified when a more detailed ISAS design is developed and a system-wide labor force is determined.

8.5 Principle 5: Rural and Social Development

Principle 5 specifies that in regions of poverty, biofuel operations shall contribute to the social and economic development of local, rural, and indigenous people and communities. Due to the unique labor class framework of Abu Dhabi, there is a limited risk that the indigenous people are not at risk of poverty. However, in some of the northern emirates in the UAE, the risk of poverty may be greater, indicating the need for a social development study prior to any large-scale ISAS implementation.

The working class will be protected under the criteria identified in Principle 4. A commercial ISAS may also provide economic diversification for the UAE, a country that currently derives a majority of its wealth from fossil fuel and related industries. Overall, an ISAS in the UAE will promote education for sustainable development in a desert region and provide best practice halo-agricultural methodologies for people in more impoverished nations with similar climates and geography that may contribute to their own social and economic development. The social benefits of a large-scale ISAS was exemplified at Seawater Farms Eritrea nearly ten years ago. A successfully operating commercial ISAS in the UAE could provide investors with the necessary technological proof of concept to incentivize them to invest in similar systems in more impoverished regions, potentially improving the lives of people in those regions.

8.6 Principle 6: Local Food Security

Principle 6 states that biofuel operations shall ensure the human right to adequate food and improve food security in food insecure regions. The arid climate of the UAE prohibits agriculture in many areas and limits the types of local produce and livestock that can survive in the region. The UAE is able to produce some dairy and poultry products, seafood, snack foods, tomatoes, some vegetables, and various other products locally. However, the UAE still imports over 80 percent of its food products [176]. The ISAS addresses the issue of food security by utilizing arid land and converting it into land suitable for food production, including producing fish for human consumption and potentially fodder for livestock consumption (likely depending on whether the energy or livestock feed market is preferential for salicornia straw). One of the key benefits of the ISAS is that it will not compete with existing agricultural land nor will it displace any food production systems. Issues relating to competition between the aquaculture products produced by the ISAS and the existing fishery or aquaculture industries in the UAE will, however, need to be addressed. The ISAS will enhance food security in the region and provide insight for how food insecure regions with similar climates can address their own food supply issues.

However, it is important to note that salicornia oil is edible. This is an issue that will need to be addressed by the ISAS owners, taking into consideration economic and social constraints.

8.7 Principle 7: Conservation

Principle 7 ensures that biofuel operations avoid negative impacts on biodiversity, ecosystems, and other conservation values. The site selection criteria for the ISAS will need to take into account any potentially sensitive ecological areas, especially those along the coast. The ISAS will likely be located in a barren desert with negligible organic matter in the soil and minimal plant and animal life. In fact, the mangrove wetland component of the ISAS will likely provide potential habitat to numerous bird, plant, and marine species, described in more detail in Chapter 2.4.

The risk of the non-native salicornia spreading outside of the ISAS boundaries is limited due to its requirements for establishment as well as the best management pollination and breeding practices that will be employed at the ISAS. However, a Weed Risk Assessment (WRA) may need to be conducted on salicornia before the commercial scale ISAS is approved for development to assert with a higher level of confidence the potential of salicornia to spread outside of the boundaries of the ISAS. The mangrove species used will likely be a native species and the aquaculture species, though not native to the region, will likely not be able to escape their inland ponds, especially in a well managed system.

8.8 Principle 8: Soil

Principle 8 specifies that biofuel operations shall implement practices that reverse soil degradation and/or maintain soil health. Typical desert soils have low soil organic carbon concentrations, often less than 0.5 percent [26], [174]. An ISAS on desert soil could significantly improve the soil quality, contributing organic matter into the soil profile and over time building up soil nutrients that stores a significant quantity of carbon over the long-term. Proper irrigation management on the salicornia fields will be necessary to avoid hypersalinization of the soil. Further research on these practices will evolve out of field experiments. Aquaculture practices typically exclude any chemical requirements [37] and salicornia's biology allows it to be grown with minimal chemical inputs other than aquaculture effluent and some additional fertilizer (see Chapter 2.3). This limits the risk of chemicals entering the soil or surrounding ecosystem.

8.9 Principle 9: Water

Principle 9 states that biofuel operations shall maintain or enhance the quality and quantity of surface and ground water resources and respect prior formal or customary water rights. The ISAS requires some fresh water for hatchery operations. Water used for peripheral tasks such as drinking water for laborers and cleaning equipment is ignored. As with nearly all of the drinking water in the UAE, this water will likely come from a centralized desalination plant operated by the municipality. The energy required to produce this water is accounted for in the LCA and is calculated in the net energy and greenhouse gas calculations in the results of the LCA. The majority of the water used in the ISAS is seawater pumped in from the ocean. Compared to other agriculture and many first generation biofuel systems, the ISAS uses a relatively small quantity of fresh water. In addition, the ISAS does not impact fresh water supplies in the region, only energy capacity as additional energy will be required to desalinate the water used in the hatcheries and potentially for salicornia germination. Ground water supplies should not be impacted by the ISAS because much of the ground water resources in Abu Dhabi are already highly saline (see Chapter 3.1.2) and any ISAS site selection would avoid the areas with lower salinities or fresh groundwater. It will be important that the site that is selected for the commercial scale ISAS is evaluated for the potential impact on groundwater in the area. An additional benefit of the ISAS is that the nutrient rich effluent from the aquaculture processes, which typically requires treatment, will be ‘treated’ by the salicornia and mangrove ecosystems. Ultimately, the final system design should include testing wells throughout the system to ensure the risk of coastal eutrophication or other contamination is minimized.

8.10 Principle 10: Air

Principle 10 ensures that air pollution emission sources from biofuel operations are identified and minimized through an air management plan. The primarily emissions associated with the ISAS have been identified in this analysis and will be further catalogued with ongoing research. If gasification is employed to generate electricity it will likely have to meet the emission control standards of the UAE and employ the necessary Air Pollution Control (APC) and Continuous Emission Monitoring (CEM) technologies that are required. If other technologies are used to process the biomass (salicornia straw and mangrove clippings) such as Fischer-Tropsch or pyrolysis, the emissions from their stacks (if any) will likely need evaluated, monitored, and controlled using appropriate technologies. The emissions from the aquaculture and halo-agriculture processes should be accounted for in the LCA. GHG emissions are discussed in Chapter 8.3. Other emissions from aquaculture, such as the denitrification of a small portion of the NO_3 into N_2 gas should pose no issues from an environmental perspective (see Chapter 2.2.1). Potentially ozone depleting methyl halides may be emitted from the salicornia as a result of natural processes. Due to limited data availability, the scale of these emissions will need to be studied further in field experiments (see Chapter 5.3). When the final design for the ISAS is developed an air management plan, as recommended in this principle, should be developed, refined, adopted, and enforced.

8.11 Principle 11: Use of Technology, Inputs, & Waste Management

Principle 11 states that the use of technologies in biofuel operations shall seek to maximize production efficiency and social and environmental performance, and minimize the risk of damages to the environment and people. Tilapia, shrimp, salicornia, and mangroves are not Genetically Modified Organisms (GMO), though they will be selectively bred as necessary to achieve economical and optimal yields. The technologies used in the aquaculture processes are well-established and commercially available. Most aspects of the halo-agriculture process use slightly modified commercially available farming technologies, though they may require slight modifications to deal with the saline irrigation effluent. The biomass processing technology (gasification, Fischer-Tropsch, pyrolysis) will likely be chosen according to this principle. The chosen technology (unless none is required if the salicornia straw and mangrove trimmings are used as fodder for livestock) will be used because it is able to maximize system production efficiency with the least risk and highest reliability. In addition, the synergies of the integrated system allow the wastes and residues from each of the processes to be interwoven with the rest of the system, minimizing incoming material and energy and nearly eliminating outgoing waste. Any waste or byproducts that are unusable onsite or have no market value will likely be disposed of according to a waste management plan within the scope and guidelines of UAE or Abu Dhabi regulations.

8.12 Principle 12: Land Rights

Principle 12 ensures that biofuel operations respect land right and land use rights. For this principle to be met, a site must first be chosen and then evaluated for prior ownership and rights.

8.13 Overall Applicability of ISAS to RSB Principles & Criteria

A properly managed ISAS has the potential to meet the twelve principles of the RSB Principles & Criteria for Sustainable Biofuel Production, Version Two [2]. It is not yet possible to ascertain whether all of the principles can or will be met in practice until further data is gathered from field experiments and a pilot scale integrated system is tested. Many of the above criteria will only be met under certain fuel production pathways and design criteria. In addition, many of the criteria depend largely on finding an appropriate site. Using information available in the literature and expert interviews, an ISAS may be able to produce biofuels and food on a commercial scale in Abu Dhabi with minimal social impacts, a limited impact on drinking water supplies, and a net GHG emission benefit meeting the principles of the RSB.

CHAPTER 9

9 Conclusions and Recommendations

9.1 Conclusions

Stratton et al. [61] states that a salicornia-based biofuel could have a 100 percent reduction in life cycle GHG emissions if soil carbon sequestration could be validated. The results of this analysis support this conclusion, along with its uncertainty. Overall, the ISAS has the potential to provide drop-in aviation and other biofuels with life cycle greenhouse gas emissions less than those of conventional fossil aviation fuels. The ISAS offers the additional benefits of using a limited supply of freshwater and, in many pathways, providing for beneficial land use change. If sited appropriately, the ISAS should also have a limited impact on wildlife, freshwater supplies, and biodiversity. In fact, the mangroves will likely increase richness in biodiversity, provide a habitat for new wildlife, and act as barrier to coastal erosion and storms. The ISAS may also provide a source of relatively sustainably produced fish and shrimp.

The Gasification Pathway had reduced fossil process energy requirements and overall emissions due primarily to the use of the electricity produced onsite for pumping. The Pyrolysis Pathway resulted in the largest amount of fuel produced due to its high process efficiency but due to the lower energy density of the pyrolysis oil it did not result in the largest GHG reduction. The Fischer-Tropsch pathway, however, yielded the largest quantity of jet fuel because it produces both HRJ and FT Jet. Depending upon the needs of the region and the goals of the ISAS, each of these pathways has advantages and disadvantages from a GHG emission and energy perspective. Overall, using the economic allocation methodology recommended by the RSB, the net GHG emissions from HRJ produced in the ISAS, ignoring biogenic carbon sequestration in the salicornia and mangrove biomass, still revealed substantially reduced net GHG emissions per megajoule of jet fuel when compared to fossil jet fuel.

Due to limited data availability, unproven regional best practices, an incomplete system design, and the lack of a chosen site, the ISAS presents a range of uncertainty and risk that must be addressed prior to commercialization. Much of the data used in this analysis is from dated sources. Additionally, a disproportional amount of the data is from the same several authors who have performed extensive research in this subject area. Though salicornia has been effectively cultivated in this region, it has yet to be proven on a large enough scale to make a commercial scale ISAS viable at this time. Without a site selected it is difficult to make accurate assumptions for several key variables that play a considerable role in the net GHG and energy results of the system, namely site elevation and soil type (which relate to energy consumption and irrigation requirements). Other design characteristics of the ISAS need to be further developed for more refined analysis of the system. The range of data available results in noticeably wide uncertainty bars in the figures provided in Chapter 7. However, the general trend in the baseline results reveals the high potential for net carbon sequestration in many of the pathways as well as the large surplus of fuels produced within the system. As additional research and experimentation moves forward, it is likely that the wide range of uncertainty presented in the results will be narrowed, allowing for more refined analysis and accurate results that can be applied to the RSB principles examined in Chapter 8.

9.2 Recommendations for Next Steps

The information presented herein lays a strong foundation for further research on both the ISAS processes and the agronomics of growing salicornia. The most immediate need for this research is to verify the potential economics of the ISAS by conducting greenhouse and field experiments growing salicornia under different irrigation water salinities and fertilizer regimes in the Abu Dhabi climate. Once the yields can be validated, both in terms of biomass and oil content, the uncertainty in the production process can be greatly narrowed. However, it is important to note that the seedstock for these experiments may come from wild strains of salicornia and may require several generations of selective breeding before commercially viable yields are bred into the varieties used. Once a robust strain has been shown to be cultivated successfully in Abu Dhabi it will be necessary to determine best management practices to maximize yields as well as optimizing the three systems (aquaculture, halo-agriculture, mangrove silviculture) to provide the greatest overall system benefits and yields. Using these best management practices on a 100-200 hectare pilot scale facility will be among the final steps in the development stage, verifying the potential of the ISAS and providing empirical data to use to calculate commercial scale economic viability.

Concurrently with any agronomic research is the necessity to find an appropriate site in the region for developing a pilot scale facility and conducting any larger scale field experiments. Site characteristics play a substantial role in the system design and overall energy balance of the system, mainly due to the large volume of water pumping that is required. Of equal importance are the soil characteristics of the site, which significantly impacts the growth of salicornia as well as the best management practices necessary to achieve maximum yields for a given soil quality and permeability.

To expedite the development of the pilot scale facilities the agronomic research, selective breeding, and site determination can be conducted in parallel, provided appropriate resources are allocated to the systems. The results of these preliminary analyses can be input into the LCA model used to determine the results presented in Chapter 7 to provide updated, more region specific results with narrower uncertainty bars.

CHAPTER 10

10 References

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APPENDIX A

Appendix A – Input Assumptions & Additional References

It is important to note that not all data provided in this Appendix A are used in calculations for the results provided in this analysis.

		Assumption/Input/Variable	Units	Worst	Base	Best	Reference/Notes
1	GENERAL ISAS PARAMETERS	ISAS Aquaculture allocation, land area	%	10%	10%	10%	Assumptions
2		Shrimp allocation within Aquaculture	%	50%	50%	50%	Assumptions
3		Tilapia allocation within Aquaculture	%	50%	50%	50%	Assumptions
4		ISAS Salicornia allocation, land area	%	70%	70%	70%	Assumptions
5		ISAS Mangrove allocation, land area	%	20%	20%	20%	Difference between total and aquaculture and salicornia land area
6		Total ISAS size	ha	100,000	100,000	100,000	Includes workable area (Roads, buildings, etc. assumed to be negligible or extra land outside of ISAS land area)
7							
8	AQUACULTURE INPUTS	Gross Shrimp Feed, per ha of shrimp	MT/ha shrimp	7	7	7	Feed input is held constant and yields are varied based upon the Feed Conversion Ratio. With 2 yields/yr this is doubled.
9		Shrimp Feed Conversion Ratio (FCR)	dimensionless	3.5	2	1.78	Boyd 2007, Table 2, from Boyd & Polioudakis 2006, Table 2, for Tiger Prawn, Penaeus monodon, http://uaeagricent.moew.gov.ae/FISHERIES/shrimp_e.stm for worst, 1.78 from Casillas-Hernandez 2007 table 4 (Larsson 1994 from Ricardo).
10		Feed Components	%	100.0%	100.0%	100.0%	
11		Soybean Meal	%	24.5%	24.5%	24.5%	Boyd 2007, Table 2. Filler added because Boyd's table only adds up to 94%
12		Wheat middlings	%	27.5%	27.5%	27.5%	Assume no environmental impact
13		Fish meal	%	19.0%	19.0%	19.0%	
14		Shrimp head meal	%	13.5%	13.5%	13.5%	Assume environmental impact equivalent to that of fishmeal
15		Squid meal	%	5.0%	5.0%	5.0%	Assume environmental impact equivalent to that of fishmeal
16		Oil	%	4.5%	4.5%	4.5%	Assume no environmental impact, as per allocation procedures in SimaPro
17		Filler	%	6.0%	6.0%	6.0%	Assume no environmental impact
18							
19		Aquaculture operational period/yr	%	66.7%	66.7%	66.7%	8 months of operations per year
20				CO2	CH4	N2O	
21		Fishmeal emissions	g emission/MT fishmeal	1,110,000	1,410	(1,530)	SimaPro (note that N2O emissions are negative due to allocation procedures built into SimaPro), from LCA Food DK library
22		Fishmeal energy consumption (thermal)	MJ/MT fishmeal	6,207			SimaPro, from LCA Food DK library
23		Fishmeal energy consumption (electrical)	MJ/MT fishmeal	676.8			SimaPro, from LCA Food DK library
24		Emissions for fishmeal, CO2	gCO2e %	100.01%			
25		Emissions for fishmeal, CH4	gCO2e %	0.13%			
26		Emissions for fishmeal, N2O	gCO2e %	-0.14%			
27				CO2	CH4	N2O	
28		Soymeal production emissions	g emission/MT soymeal	15,000	(302)	399	SimaPro (note that CH4 emissions are negative due to allocation procedures built into SimaPro), from LCA Food DK library
29		Soymeal energy consumption (thermal)	MJ/MT soymeal	487.0			SimaPro, from LCA Food DK library
30		Soymeal energy consumption (electrical)	MJ/MT soymeal	50.6			SimaPro, from LCA Food DK library
31		Emissions for soybean, CO2	gCO2e %	99.35%			
32		Emissions for soybean, CH4	gCO2e %	-2.00%			
33		Emissions for soybean, N2O	gCO2e %	2.64%			
34							
35		Feed Production Energy	MJ/MT feed consumed	2,799	2,799	2,698	Papatryphon et al 2004, Table 3, for Feed production for rainbow trout, with various amounts of fish, plant, etc. Doesn't specify energy source, through Sun 2009 implies it's electricity
36							
37		Freshwater requirement for aquaculture	m3/ha/yr	0	0	0	Assumption
38							
39		Percent of feed replaceable by salicornia meal	%	14.4%	14.4%	14.4%	14.4% of total feed can be replaced by salicornia meal, as in Acosta-Ruiz et al (2004). Here, it is assumed that sobyean meal is what is replaced
40		Percent of shrimp offals from processing	%	0%	0%	0%	None can be used (Timmons 2010)
41							
42		Percent of shrimp leftover after processing	%	54%	60%	66%	+/- 10% of 66% yield proposed by Timmons 2010, whole, shell on tail yield
43							
44		Desired salinity of aquaculture water	ppt	42	42	42	This is an assumption for the maximum salinity tolerance that the aquaculture water can be maintained at that will not negatively impact the yields.
45							
46		Soybean land area necessary for feed	ha soy/MT shrimp	0.22	0.22	0.22	Boyd & Polioudakis 2006, Table 3. Might be more effective to use energy/emissions for soybean meal from GREET.
47							
48		Gross Tilapia Feed, per ha tilapia	MT/ha tilapia	3.9	3.9	3.9	Timmons 2010 expects 3 MT/ha of tilapia. Using FCR of 1.3, 3.9 MT feed/ha produces 3 MT fish/ha
49		Tilapia Feed Conversion Ratio (FCR)	dimensionless	1.8	1.5	1.2	Boyd 2007, Table 2, from Boyd & Polioudakis 2006, Table 2, for worst, Timmons 2010 for average and best for tilapia over 100 grams
50		Feed Components	%	100.0%	100.0%	100.0%	Boyd 2007, Table 2. Filler added because Boyd's table does not add up to 100%
51		Soybean Meal	%	38.3%	38.3%	38.3%	
52		Cottonseed Meal	%	50.8%	50.8%	50.8%	Assume no environmental impact
53		Wheat middlings	%	4.0%	4.0%	4.0%	Assume no environmental impact
54		Fish meal	%	4.0%	4.0%	4.0%	
55		Oil	%	1.5%	1.5%	1.5%	Assume no environmental impact
56		Filler	%	1.4%	1.4%	1.4%	Assume no environmental impact
57							
58		Nitrogen composition of feed	%	6%	7.0%	8.0%	Timmons 2010
59		Phosphorous composition of feed	%	1.0%	1.2%	1.3%	Timmons 2010 for base, +/- 10% for Best and Worst
60							
61		Percent shrimp feed that may pass through to tilapia	%	0.0%	0.0%	0.0%	None expected b/c ponds operated in parallel, not cage system.
62		Percent of feed replaceable by salicornia meal	%	50%	75.0%	100.0%	Belal and Dosari (1999) up to 40% of fishmeal replaced with Salicornia. This accounted for 40% of the total mass of feed. Because in Boyd's (2007) feed table, soybean meal is nearly 40% of the feed, best case assumes that all soybean can be replaced with Salicornia meal. Worst and base case assume lower percentage
63		Percent of tilapia offals from processing	%	0%	0%	0%	
64							
65		Percent of tilapia processed to be sold	%	27%	30%	33%	+/- 10% of 30% yield proposed by Timmons 2010
66							
67	AQUACULTURE HATCHERIES	Tilapia freshwater req't	m3/day	1219	1219	1219	Design parameters provided by Timmons (2010)
68		Shrimp seawater req't	m3/day	3686	3686	3686	Design parameters provided by Timmons (2010)
69		Hatchery operations	days	120	120	120	Spawing lasts about 4 months (Timmons 2010)
70							
71		Additional Protein for hatchery feed	%	19%	27%	34%	Typical feed ~32% protein, hatcheries need 38-43% protein (Timmons 2010), so the additional protein in feed required is scaled up by this percentage.
72							
73		Feed Components for Tilapia Feed for Hatchery	%	100%	100%	100%	Assume that soybean meal and fishmeal can evenly be increased to account for the additional protein required in feed for hatchery, reducing other components comparatively
74		Soybean Meal	%	42%	43%	45%	
75		Cottonseed Meal	%	47%	46%	44%	Assume no environmental impact
76		Wheat middlings	%	4%	4%	4%	Assume no environmental impact
77		Fish meal	%	4.4%	5%	5%	
78		Oil	%	1%	1%	1%	Assume no environmental impact
79		Filler	%	1%	1%	1%	Assume no environmental impact
80							
81		Feed Components for Shrimp Feed for Hatchery	%	100%	100%	100%	
82		Soybean Meal	%	26%	26%	27%	
83		Wheat middlings	%	25%	25%	24%	Assume no environmental impact
84		Fish meal	%	20%	20%	21%	
85		Shrimp head meal	%	14%	14%	15%	Assume environmental impact equivalent to that of fishmeal
86		Squid meal	%	5%	5%	5%	Assume environmental impact equivalent to that of fishmeal

		Assumption/Input/Variable	Units	Worst	Base	Best	Reference/Notes
87		Oil	%	4%	4%	4%	Assume no environmental impact
88		Filler	%	6%	5%	5%	Assume no environmental impact
89							
90		Tilapia fry req'd per year	fry/ha tilapia aqua	6,000	6,000	6,000	Timmons 2010 (based on expected yield of 3 MT/ha harvesting at 1 kg target, with 50% mortality from fry to market.
91		FCR for tilapia fry under 100 g	dimensionless	0.90	0.80	0.70	Timmons 2010, assume this FCR for all hatchery phases
92		Fry goal weight	MT/fry	0.0001			Timmons 2010
93		Approx feed req'd for tilapia hatchery	MT/ha tilapia aqua	0.54	0.48	0.42	Based on FCR's and expected yields
94							
95		Shrimp larvae req'd per harvest	larvae/ha shrimp aqua	400,000	400,000	400,000	Timmons 2010 (assumes 50% mortality from larvae to market, harvesting at 15 grams, expecting 3 MT/ha)
96		FCR for shrimp larvae		3.5	2	1.78	Assumes same as for full grown shrimp
97		Larvae goal weight	MT/larvae	0.000001			Timmons 2010
98		Approx feed req'd for shrimp hatchery	MT/ha shrimp aqua	1.40	0.80	0.71	Based on FCR's and expected yields
99							
100		Portion feed that can be replaced by salicornia meal	%	14.4%	14.4%	14.4%	From Acosta-Ruiz et al (2004), 14.4% of total feed, used to replace a portion of the soybean meal.
101							
102	FISH & SHRIMP PROCESSING	Electricity required for freezing	kWh/MT	54.0	30.4	6.75	Sun 2009, section 3.1.3, extrapolated linearly from Sun's functional unit. Best is if it's a local market, ~10 days frozen data used for worst case is if it's for a commercial market, ~40 days storage. Base is average of Best and Worst Cases
103		Plastic material for packaging	MT PET/MT shrimp	0.009	0.009	0.009	Sun 2009 Section 3.1.3 from Mungkung 2005
104							
105	SALICORNIA	Seed Requirement	MT/ha	0.03	0.0275	0.025	Glenn et al 1991 used 25 kg seed/ha, Abdal 2009 used 30 kg/ha
106		Gross Seed Yield	MT/ha	1.39	1.99	3.06	Glenn 1991 Table 1. Worst case from lowest Glenn data. Base case ave. of Glenn data. Best case is if 1 MT/ha of oil can be achieved, as in Best Case assumption for oil yield.
107		Seed Oil Content	%	26.00%	28.95%	33.00%	Anwar 2002, Table 1, 27.2; 29.7; 32.0 Glenn 1991, Table 2, 26; 28.2; 33
108		Net Seed Oil Content	%	22.10%	26.06%	31.35%	Based on assumption that usable oil from soybean is between 17 and 19 percent by mass despite an assumption that the seeds contain 20 percent oil by mass.
109		Oil Yield	MT/ha	0.354	0.568	1.000	Worst and Base Cases calculated using seed yield and oil contents. Best Case assumes 1 MT/ha of oil can be achieved with best management growing and breeding practices.
110		Protein Content (of seed)	%	30.00%	32.14%	35.51%	Anwar 2002, Table 1, 31; 33.07; 35.51 Glenn 1991, Table 2, 30; 31.2; 33
111		Fiber Content (of seed)	%	4.80%	5.40%	7.99%	Anwar 2002, Table 1, 4.8; 5.79; 7.99 Glenn 1991, Table 2, 5; 5.3; 7
112		Ash Content (of seed)	%	5.00%	5.78%	8.10%	Anwar 2002, Table 1, 5.6; 6.06; 8.1 Glenn 1991, Table 2, 5; 5.5; 7
113		Total Biomass Yield (Mexico variety)	MT/ha	12.7	16.75	24.6	Glenn 1991 Table 1 total Biomass yields from 1.27 - 2.46 kg/m2, with average for Base. Used for all Pathways except Pathway 4.
114		Total Biomass Yield (Eritrea variety)	MT/ha	10.2	13.4	19.7	Zerai et al 2010, Table 6, Eritrean lines significantly less dry biomass than other lines. Used that percentage relative to Mexico variety. Seed yields did not vary significantly between the lines, so the seed variety only impacts straw production. Used in place of Mexico variety in Pathway 4, Eritrean Strain.
115		Total Biomass Yield (Houerou data)	MT/ha	0.5	2.8	5.0	Le Houerou 1996 page 123
116							
117	GROWTH PERIOD	Period of time for salicornia growth	months/yr	8.0	8.0	8.0	8 months per year to avoid hot summers (Glenn 2010)
118		Germination period for salicornia seeds	months/yr	1.0	1.0	1.0	1 month of germination
119		Period of time for salicornia growth	% of year	67%	67%	67%	
120		Germination period for salicornia seeds	% of total salicornia growth cycle	12.5%	12.5%	12.5%	Only necessary if freshwater is required for germination, assume 1 month
121							
122	ENERGY CONTENT	Oil	MJ/MT	37,011	37,011	37,011	Anwar 2002 indicates Salicornia and Safflower oil are similar. USDA website has safflower oil at http://199.133.10.140/codesearchwebapp/(zgdll245s3kry5rfjrhwtp2s)/codesearch.aspx
123		Salicornia Meal	MJ/MT	19,400	19,400	19,400	Attia 1997, Abstract,
124		Straw	MJ/MT	15,100	16,300	17,400	Stratton et al 2010, Table 90
125							
126		Ash content of Straw	%	52.0%	41.0%	30.0%	Grattan 2008 for Worst. Zerai et al. 2010 and Ayala & O'Leary 1995 and Glenn et al. from Biosaline Halophyte book (pg. 232) for Best. Average of two for Base
127		Ash content of straw after pressing (for use w/pyrolysis)	%	8.0%	5.0%	2.0%	Using graph from Venderbosch and Prins 2010 and comments from Glenn (2010) that salicornia straw can be rinsed and pressed to remove most of the salt.
128							
129	FERTILIZER REQUIREMENTS	Nitrogen	MT/ha	0.200	0.175	0.150	Worst Case from Glenn et al. 1991 Best Case from Vandevivere 2010, with Base Case as average.
130		Phosphate (P2O5)	MT/ha	0.100	0.100	0.100	Abdal 2009
131							
132	FERTILIZER PRODUCTION ENERGY AND EMISSIONS	Nitrogen	MJ/MT product	57,460	48,408	48,408	GREET v1.8c, Ag_Inputs Table 3 Row 67, for base and best cases, West & Marland 2002, Table 3 & 4 for worst
133		Nitrogen	gCO2e/MT req'd	2,986,849	2,986,849	2,986,849	GREET v1.8c, Ag_Inputs Table 3 Row 81
134		Phosphate (P2O5)	MJ/MT product	13,983	13,983	7,030	GREET v1.8c, Ag_Inputs Table 3 Row 67, for worst and base cases, West & Marland 2002, Table 3 & 4 for best
135		Phosphate (P2O5)	gCO2e/MT req'd	1,028,824	1,028,824	1,028,824	GREET v1.8c, Ag_Inputs Table 3 Row 81
136							
137	CARBON CONTENT	Carbon content of salicornia	% Carbon in plant	24.3%	24.7%	25.0%	Glenn 1992, pg. 6 and Glenn 1993 pg. 6, calculated from Table 3.
138		Carbon in straw	% plant carbon in straw	90%	90%	90%	Glenn 1993 pg. 8, straw contains 90% of total carbon
139		Percentage straw plowed in for long-term storage	%	10%	10%	10%	Base assumption is 10%. This assumption is varied in the High Carbon Sequestration Scenario.
140		Minimum biomass stored	%	30%	30%	30%	If plants grow up to 50 cm tall, and produce X tons biomass/ha, and 15 cm roots are belowground (Glenn 1997), then 15/50, or 30% of aboveground biomass could be below ground and stored each harvest @ X% carbon
141		Percentage of plowed straw C that goes into long-term storage	%	30%	40%	50%	Glenn 1993, pg. 6
142		S. bigelovii fossil C ratio for production	MT fossil C/C in biomass	0.3	0.2625	0.225	Glenn 1992, pg. 7
143							
144	MANGROVES	Wood	MT/ha	8.6	9.6	10.6	Poynter 2005, Table 5, estimated yields of "paper pulp, firewood, and animal feed" used for Base Case. Best and Worst Cases assumed to be +/- 10% of Base Case values
145		Wood Energy Content	MJ/MT	15,400	18,600	20,600	Worst: Stratton et al 2010, Appendix A, Base: Average wood from McKnedry 2001, Table 1 Best: Energy content of poplar, from Gray 2007, Table 9
146		Ash Content of Mangrove biomass	%	4%	2%	1%	McKendry 2001 , Table 1, has average wood ash content of 1%. Best Case is assumed to be 1%, with Base Case at 2% and Worst Case at 4%.
147		Carbon Credit for mangrove biomass storage, baseline	MT CO2e/ha/yr	5.10	6.77	8.43	From Duarte, Middelburg, & Caraco (2004) and Chmura et al. (2003), Table 1 & Fig. 1, ~139 - 165 grams of organic carbon buried per m^2 per year, with Chmura et al. (2003) mentioning 210 +/-. 20 g per m^2 per year. Range used is therefore 139 - 230 g per m^2 per year, with average for base. Used for all Pathways except Pathway 7.
148		High Carbon Credit sequestration assumption for mangrove biomass storage	MT CO2e/ha/yr	15.40	19.25	23.10	Poynter 2005, Table D.1 for Base Case, with Best and Worst +/- 20%. Used in Pathway 7, High Carbon Sequestration.
149							

		Assumption/Input/Variable	Units	Worst	Base	Best	Reference/Notes
150	WATER PUMPING AND DESAL						
151	AQUACULTURE PUMPING	Elevation	meter > sea level	25	17.5	10	Vandevivere (2010) mentioned that typical seawater aquaculture facilites are 10-20 meters above sea level, we assume a worst case of 25 m, best case of 10 m, with the Base case as the average.
152		Pumping Efficiency	%	70%	80%	90%	Assumed efficiencies of electrical pumps.
153		Percent of Aquaculture Ponds in drying stage	%	0%	0%	0%	Assuming that all ponds are active during the 8 months of the growing cycle. Only downtime will be in summer.
154		Water exchange rate in shrimp ponds	%	8%	6%	5%	Philippe mentions 0% first six weeks, up to 10% exchange/day depending on age of shrimp. Use here a rough range to account for the variability.
155		Pond volumes	m3/ha aquaculture	17,500	17,500	17,500	Assume square 10 ha ponds (316 x 316 m) with bottoms sloping from 1.5 to 2 m in depth (Timmons 2010)
156		Evaporation Rate	m/yr	3.0	2.5	2.0	Evaporation rate 2-3 m/yr, coincides with 3000mm/yr from Physical geography Abu Dhabi document and Jubail Wildlife Sanctuary paper from Saudi Arabia, also see -->
157	SALICORNIA PUMPING						
158		Average water req't	m/day	0.020	0.015	0.010	Salicornia water requirement, ~double evapotranspiration req't, from Philippe
159		Elevation from aquaculture to salicornia fields	meters>aqua	20	15	10	Philippe mentions salicornia fields to be slightly higher than aquaculture and that for a large track (up to 70,000 ha) it may be 20-30 m higher than the aquaculture facilities.
160		Conversion to slugs	1 slug/ft^3	515.379	kg/m^3		http://www.engineeringtoolbox.com/unit-converter-d_185.html#Density
161							
162	DESALINATION	Estimated Brackish water salinity	ppt	18			This is an input based on Water Desalting Planning Guide for Water Utilities, Table 5 4, pg. 52. It is used to set a baseline salinity for brackish and seawater based on this publication (which doesn't specificy salinity, but does provide the energy for RO for brackish and seawater)
163		Assumed global average seawater salinity	ppt	36			
164		Incoming water into aquaculture to account for evaporative losses	ppt	40			
165		Effluent Salinity	ppt	42	42	42	
166		Enter salinity of worst, base, and best case for groundwater getting desalinated	ppt	46	46	46	These values will determine the energy required per unit volume of groundwater/seawater that will need to be desalinated. Must be positive numbers less than 46 (the salinity of seawater in Persian Gulf). Default are 46, 35, and 25 for Worst, Base, and Best case, respectively.
167		Desired Salinity for salicornia	ppt	42	42	42	
168		Salinity of desalinated water	ppt	0	0	0	
169		Elevation to pump water for desalination	meters>sea level	50	25	5	
170							
171		MSF and MED	gCO2/MG	80,000,000			Internal calculations, not used in current scenarios.
172		MSF and MED	gCO2/m3	21,134			Internal calculations, not used in current scenarios.
173							
174		1 m3 is	MG	0.003785412			Internal calculations, not used in current scenarios.
175		1 MG is	m3	3785.412			Internal calculations, not used in current scenarios.
176							
177		Multi-stage flash desal, thermal energy req't	MJ/m3	57.6	57.6	57.6	Raluy et al. 2004
178		Multi-stage flash desal, electrical energy req't	MJ/m3	18.0	15.3	12.6	Raluy et al. 2004
179		Multi-effect distillation, thermal energy req't	MJ/m3	50.4	50.4	50.4	Raluy et al. 2004
180		Multi-effect distillation, electrical energy req't	MJ/m3	9.0	7.2	5.4	Raluy et al. 2004
181		Reverse Osmosis	MJ/m3	17.4	17.4	17.4	Based on salinity of water being desalinated. Data extrapolated from Table 5-4 of the Water Desalting Planning Guide for Water Utilities. The calculations are performed in a separate sheet.
182							
183	DILUTION WITH GROUNDWATER	Pumping elevation for brackish groundwater	meters>water table	50	25	5	Assumptions. Not used in current calculations
184		Enter salinity for worst, base, and best case for groundwater being used to dilute the seawater below 46 ppt (as defined above)	ppt	25	22	18	Assumptions. Not used in current calculations
185							
186	TRANSPORTATION	Distance to 'market'	km, roundtrip	200	100	50	Truck is assumed to be a 28t truck, same as used in simaPro from LCA Food DK library
187							
188	ENERGY USE AND EMISSIONS FROM TRANSPORT						
189		Diesel consumed for transport	MJ/tkm	4.60	3.50	1.10	Calcs and references in transport tab. This from Lenzen, 2008, Table 3.17
190		Emissions from ISAS transport 1, from Lenzen	gCO2e/tkm	370.00	260.00	110.00	Lenzen, 2008, Table 3.17
191		Emissions by species, CO2	% of gCO2e/tkm	93.22%			SimaPro, 28t Truck from www.lcafood.dk library
192		Emissions by species, CH4	% of gCO2e/tkm	3.96%			SimaPro, 28t Truck from www.lcafood.dk library
193		Emissions by species, N2O	% of gCO2e/tkm	2.82%			SimaPro, 28t Truck from www.lcafood.dk library
194							
195	FUEL CHARACTERISTICS	Fossil Diesel Carbon	% Carbon	85%	85%	85%	Glenn 1992, pg. 7
196		Fossil Diesel Density	g/L	835	835	835	Hileman et al. 2010, via Stratton et al. 2010, Appendix A
197		Fossil Diesel Energy Content	MJ/L	35.5	35.5	35.5	Hileman et al. 2010, via Stratton et al. 2010, Appendix A
198		Fossil Diesel Emissions (Direct)	gCO2e/MJ	74.3	74.3	74.3	Hileman et al. 2010, via Stratton et al. 2010, Appendix A
199		Fossil Diesel Emissions (Lifecycle)	kgCO2e/MMBTU	95	95	95	NETL, 2008, Table 7-2, 95 kgCO2e/MMBTU
200		Fossil Diesel Emissions (Lifecycle)	gCO2e/MJ	90.04	90.04	90.04	
201		Emissions by species, CO2	% gCO2e/MJ	97.26%			NETL, 2008, Table 7-2
202		Emissions by species, CH4	% gCO2e/MJ	2.59%			NETL, 2008, Table 7-2
203		Emissions by species, N2O	% gCO2e/MJ	0.15%			NETL, 2008, Table 7-2
204		Gasoline	kgCO2e/MMBTU	96.30	96.30	96.30	NETL, 2008, Table 7-2, 96.3 kgCO2e/MMBTU
205		Gasoline	gCO2e/MJ	91.27	91.27	91.27	
206		Gasoline	MJ/kg	43.50			Schafer et al. 2009 and Hileman et al. 2009
207		Gasoline	MJ/L	32.20			Schafer et al. 2009 and Hileman et al. 2009
208		Emissions by species, CO2	% gCO2e/MJ	95.43%			NETL, 2008, Table 7-2
209		Emissions by species, CH4	% gCO2e/MJ	2.95%			NETL, 2008, Table 7-2
210		Emissions by species, N2O	% gCO2e/MJ	1.65%			NETL, 2008, Table 7-2
211		Gasoline density	kg/L	0.74			Schafer et al. 2009 and Hileman et al. 2009
212		Conventional Jet Fuel Emissions (Lifecycle)	kgCO2e/MMBTU	92.90			NETL, 2008, Table 7-2, 96.3 kgCO2e/MMBTU
213		Conventional Jet Fuel Emissions (Lifecycle)	gCO2e/MJ	88.05			
214		Emissions by species, CO2	% gCO2e/MJ	96.66%			NETL, 2008, Table 7-2
215		Emissions by species, CH4	% gCO2e/MJ	2.58%			NETL, 2008, Table 7-2
216		Emissions by species, N2O	% gCO2e/MJ	0.76%			NETL, 2008, Table 7-2
217		Conventional Jet Fuel non-combustion emissions	kgCO2e/MMBTU	15.20			
218		Conventional Jet Fuel non-combustion emissions	gCO2e/MJ	14.41			
219		Conventional Diesel non-combustion emissions	kgCO2e/MMBTU	18.30			
220		Conventional Diesel non-combustion emissions	gCO2e/MJ	17.35			
221		Conventional Gasoline non-combustion emissions	kgCO2e/MMBTU	19.70			
222		Conventional Gasoline non-combustion emissions	gCO2e/MJ	18.67			
223							
224		Density of conventional diesel	kg/L	0.835			Schafer and Hileman et al. 2009
225		Energy content of conventional diesel	MJ/kg	42.5			Schafer and Hileman et al. 2009
226		Energy Density of HRJ/FT Jet	MJ/kg	44.10			Stratton et al 2010 Appendix A
227		Energy Density of HRJ/FT Jet	MJ/MT	44,100			
228		Energy Density of HRJ/FT Jet	MJ/L	33.52			
229		Density of HRJ/FT Jet	kg/L	0.76			Stratton et al 2010 Appendix A
230		Carbon Content HRJ	%	84.70%			Stratton et al 2010 Appendix A
231		Energy Density of FT Diesel	MJ/kg	44.00			
232		Energy Density of FT Diesel	MJ/MT	44,000			
233		Density of FT Diesel	kg/L	0.78			
234		Carbon Content FT Diesel	%	87.10%			
235		Energy Density of Propane MG	MJ/MT	43,189			US Fuel Trends 2009, Table B.4
236		Energy Density of HR/FT Naphtha	MJ/kg	44.40			Stratton et al 2010 Appendix A

		Assumption/Input/Variable	Units	Worst	Base	Best	Reference/Notes
237		Density of HR/FT Naphtha	kg/L	0.70			Stratton et al 2010 Appendix A
238		Energy Density of naphtha	MJ/L	31.08			
239		Carbon Content Naphtha	%	84.20%			Stratton et al 2010 Appendix A
240		n-hexane	g/mL	0.6660	ASTM D1298		http://www.chemicalland21.com/petrochemical/n-HEXANE.htm
241							
242	GHG EQUIVALENTS	Natural Gas for electricity, life cycle GHG intensity	gCO2e/kWh	751.00	577.00	469.00	Meier 2002 - 469 tonneCO2e/GWh elec for Best Spath & Mann 2000, pg. 5 for Best, IGCC Page 139 and 140 for open vs closed cycle Base: Table 6.29 in Lenzen 2008 for combined cycle Worst: Table 6.27 for open cycle gqas turbine. For comparison, GREET v1.8d is 188,300.4 gCO2e/MMBTU, or 178.5 g/MJ (electric tab sum of N153 + O153)
243		Natural Gas for electricity, life cycle GHG intensity	gCO2e/MJ	208.61	160.28	130.28	
244		Emissions by species, CO2	% gCO2e/MJ	92.93%			GREET v1.8d, electric tab, N149:O153 for Fuel and Feedstock emissions
245		Emissions by species, CH4	% gCO2e/MJ	6.43%			GREET v1.8d, electric tab, N149:O153 for Fuel and Feedstock emissions
246		Emissions by species, N2O	% gCO2e/MJ	0.64%			GREET v1.8d, electric tab, N149:O153 for Fuel and Feedstock emissions
247		Natural Gas for steam	gCO2e/MJ	80.17	80.17	80.17	GREET v1.8d, taken from NG electricity generation emissions, includes T&D, @ 80% efficiency, so 1,250,000 btu NG/mmbtu steam produced, NG tab sum of AS126-AS128, w/emissions factors for CH4 and N2O
248		Emissions by species, CO2	% gCO2e/MJ	95.00%			GREET v1.8d, electric tab, AS126:AS128 for Production of Displaced Steam using Natural Gas
249		Emissions by species, CH4	% gCO2e/MJ	4.48%			GREET v1.8d, electric tab, AS126:AS128 for Production of Displaced Steam using Natural Gas
250		Emissions by species, N2O	% gCO2e/MJ	0.52%			GREET v1.8d, electric tab, AS126:AS128 for Production of Displaced Steam using Natural Gas
251		Liquid Petroleum Gas (LPG)	gCO2e/MJ	13.75	13.75	13.75	GREET v1.8d, sum of AT160 + AU160 in NG tab
252		Emissions by species, CO2	% gCO2e/MJ	79.19%			GREET v1.8d, NG tab, AT156:AU160
253		Emissions by species, CH4	% gCO2e/MJ	20.44%			GREET v1.8d, NG tab, AT156:AU160
254		Emissions by species, N2O	% gCO2e/MJ	0.38%			GREET v1.8d, NG tab, AT156:AU160
255							
256		Stored carbon in biomass conversion to gCO2e	gCO2/g stored carbon	3.67			Based on molecular weights of carbon (12) and oxygen (16), so (12+16+16)/12 = 3.67 times the mass of stored carbon is the amnt CO2.
257							
258	HYDROGEN PRODUCTION	Emissions	gCO2e/MT H2	11,888,000	11,888,000	11,888,000	Spath NREL 2001, page 5
259		Emissions by species, CO2	% gCO2e/MT H2	89.3%			Spath NREL 2001, page 19
260		Emissions by species, CH4	% gCO2e/MT H2	10.6%			Spath NREL 2001, page 19
261		Emissions by species, N2O	% gCO2e/MT H2	0.1%			Spath NREL 2001, page 19
262		Energy Consumption	MJ/kg H2	183	183	183	Spath NREL 2001, Table 6
263							
264	OIL EXTRACTION FROM SEEDS	Electricity	MJ/MT oil	629	377	236	Stratton et al 2010, Table 88, modeled from soybean oil extraction from GREET
265		Natural Gas	MJ/MT oil	6,740	4,044	2,527	ibid, as steam w/80% efficiency
266		N-hexane (LPG surrogate)	MJ/MT oil	657	394	246	ibid
267							
268	MATERIALS FOR HYDROPROCESSING	Hydrogen	MT/MT oil	0.0215	0.0338	0.0448	Agenda Item 2: Review of aviation emissions-related activities within ICAO and internationally U.S. FUEL TRENDS ANALYSIS AND COMPARISON TO GIACC/4-IP/1, Table B.4
269		HRJ Production	MT fuel/MT oil	0.578	0.587	0.599	Agenda Item 2: Review of aviation emissions-related activities within ICAO and internationally U.S. FUEL TRENDS ANALYSIS AND COMPARISON TO GIACC/4-IP/1, Table B.4
270		Propane MG Production	MT fuel/MT oil	0.020	0.048	0.050	ibid
271		Naphtha Production	MT fuel/MT oil	0.258	0.262	0.268	ibid
272		Hydroprocessing Process Energy from Electricity	MJ/MT oil	148.02	193.75	244.90	Agenda Item 2: Review of aviation emissions-related activities within ICAO and internationally U.S. FUEL TRENDS ANALYSIS AND COMPARISON TO GIACC/4-IP/1, Table B.4
273		Hydroprocessing Process Energy from Natural Gas	MJ/MT oil	228.99	249.81	270.63	ibid
274							
275	FISCHER-TROPSCH	Process Efficiency	%	42%	45%	52%	Stratton et al 2010
276		Product Slates					
277		F-T Jet	%	25%	25%	25%	
278		F-T Diesel	%	55%	55%	55%	Stratton et al 2010 and US Fuel Trends 2009 both use 25% max jet fuel
279		F-T Naphtha	%	20%	20%	20%	
280							
281		F-T Jet	%	43%	43%	43%	Average of Gray and Stratton. Used in all Pathways.
282		F-T Diesel	%	28%	28%	28%	
283		F-T Naphtha	%	30%	30%	30%	
284							
285		F-T Jet	%	60%	60%	60%	Gray 2007 mentions that 60% FT jet is possible
286		F-T Diesel	%	0%	0%	0%	
287		F-T Naphtha	%	40%	40%	40%	
288							
289		F-T Process Energy	MJ PE to convert 1 MJ feedstock into 1 MJ fuel	1.38	1.22	0.92	Based on Process Efficiency = 1 MJ fuel/(1 MJ feedstock + Process Energy). Process energy assumed to be from feedstock itself, no fossil inputs.
290		Co-produced electricity	MJ elec/MJ feedstock input	0	0.00366	0.00732	Worst: Stratton et al 2010 & NETL 2009 Table D-1 show no coproduced electricity for export Base: Average of best and worst Best: Gray 2007, Table 15 for 15% BTL facility
291							
292	GASIFICATION TO ELECTRICITY	Power Plant Efficiency	%	32.1%	37.6%	43.0%	Stratton et al 2010, Table 75, biomass boiler ranges. Low and high given, Base is average of these.
293		Electricity allocated to Aquaculture	%	50.0%	50.0%	50.0%	Assumption.
294		Electricity allocated to Salicornia	%	50.0%	50.0%	50.0%	Assumption.
295							
296	PYROLYSIS	Pyrolysis oil energy content	MJ/MT	16,000	17,500	19,000	Venderbosch and Prins 2010, Table 1 though Holmgren 2008 Table 2 shows pyrolysis oil to be 15,200/41,800 (36%) heating value of crude oil, HHV
297		Bio-char energy content	MJ/MT	26,500			Bridgewater & Peacocke, 2000, Table 8, HHV
298		Bio-gas energy content	MJ/MT	4,000			Bridgewater & Peacocke, 2000, Table 8, HHV
299		Pyrolysis oil yield (assumes ash free biomass)	Percent	50%	63%	75%	Holmgren et al, 2008
300	*unused in calculations*	Naphtha yield from pyrolysis oil	Percent	21%			Holmgren et al, 2008
301	*unused in calculations*	Diesel yield from pyrolysis oil	Percent	21%			Holmgren et al, 2008
302	*unused in calculations*	Water/CO2 yield from pyrolysis oil	Percent	60%			Holmgren et al, 2008
303	*unused in calculations*	Bio-oil yield	Percent	75%			Bridgewater & Peacocke, 2000, Table 8
304	*unused in calculations*	Bio-char yield	Percent	15%			Bridgewater & Peacocke, 2000, Table 8
305	*unused in calculations*	Bio-gas yield	Percent	15%			Bridgewater & Peacocke, 2000, Table 8
306		Pyrolysis oil density	kg/m3	1,200	MT/m3	1.20	Venderbosch and Prins 2010
307	*unused in calculations*	Energy required for heating biomass	MJ thermal/MT	1,500			Venderbosch and Prins 2010
308	*unused in calculations*	For 2000 kg/hr fuid bed pyrolysis	Chemical heat input MW	10.4			Venderbosch and Prins 2010, Table 3
309	*unused in calculations*	For 2000 kg/hr fuid bed pyrolysis	Heat, MW	7.8			Venderbosch and Prins 2010, Table 3
310	*unused in calculations*	Pyrolysis efficiency	Percent	45.0%			Venderbosch and Prins 2010, Table 5
311	*All thermal energy*	Converting bulky wood into briquettes	kwh/MT	20.6			Zhong et al. 2010, page 2
312	*unused in calculations*	Flash pyrolysis/char combustion	Net J/g biomass	2850.5			Zhong et al. 2010, Table 1
313		Quenching	kwh	40.0			Zhong et al. 2010, Table 1
314		Pumping/filtration	kwh	6.0			Zhong et al. 2010, Table 1
315		Excess gas combustion	kwh	57.0			Zhong et al. 2010, Table 1
316		Gas combustion	kwh	57.0			Zhong et al. 2010, Table 1
317							
318	OTHER FACTORS	Natural gas power plant efficiency, IGCC (LHV)	%	56%	58%	60%	Electric Generation Efficiency, 2007, pg.7 http://www.epa.gov/cleanrgy/energy-and-you/affect/natural-gas.html

		Assumption/Input/Variable	Units	Worst	Base	Best	Reference/Notes
319		Seawater density	kg/m3	1035	1029	1025	Wikipedia for base and best, and http://hypertextbook.com/facts/2002/EdwardLaValley.shtml for worst case
320		Seawater density	slugs/ft^3	2.01	2.00	1.99	
321		Gravity	m/s2	9.807	9.807	9.807	
322		Credit for producing naphtha	gCO2e/liter naphtha	265	371	477	Worst: Gray 2007, Section 4.5, pg. 55. Lifecycle CO2/bbl comparison of FT naphtha to Petroleum naphtha, 881 lbsCO2/bbl compared to 788 lbsCO2/bbl Base: Average best and worst Best: NETL 2009 page 93, Table B-5, 75.8 kgCO2/bbl petroleum naphtha well-to-gate displaced Eventually could add in the energy necessary to turn naphtha into gasoline.
323							
324	IPCC EMISSIONS FACTORS			IPCC 2007, 100 year horizon			
325		CH4	25	Changes in Atmospheric Constituents and in Radiative Forcing in Climate Change 2007, Table 2.14			
326		N2O	298	Changes in Atmospheric Constituents and in Radiative Forcing in Climate Change 2007, Table 2.14			
327		CO2	1	Changes in Atmospheric Constituents and in Radiative Forcing in Climate Change 2007, Table 2.14			
328							
329	ECONOMIC VALUES	Natural Gas	$/MJ	$0.0057			Marker et al. 2005 Table 27
330		Pyrolysis oil value	$/MJ	$0.0045	11.9%	more than heavy fuel oil	Marker et al. 2005 Table 27
331		Heavy Fuel Oil	$/MJ	$0.0040			Marker et al. 2005 Table 27
332		Naphtha	$/MT	$293.93	-12.0%	less than diesel	Marker et al. 2005 Table 33
333		Naphtha	$/MJ	$0.0068			
334		Diesel	$/MT	$333.84			Marker et al. 2005 Table 33
335		Diesel	$/MJ	$0.0076	90.6%	more than heavy fuel oil	
336		Electricity	$/kwh	$0.054			UAE electricity price (http://gulfnews.com/news/gulf/uae/general/dubai-introduces-new-rates-to-curb-use-of-electricity-and-water-1.85172)
337		Electricity	$/MJ	$0.015			
338							
339		Below used in calculations, from EIA for 2007 (http://www.eia.doe.gov/aer/txt/ptb0303.html)					
340		Natural Gas	$/million BTU	$9.30			
341			$/MJ	$0.00881			
342		Jet Fuel	$/million BTU	$16.01	$3.06	3.78623546	
343			$/MJ	$0.01517	$0.81	$0.0241	
344		LPG (use for MPG)	$/million BTU	$18.84			
345			$/MJ	$0.01786			
346		Residual Fuel Oil	$/million BTU	$8.56			
347			$/MJ	$0.00811			
348		Pyrolysis Oil (based on residual fuel oil price)	$/million BTU	$9.58			
349			$/MJ	$0.00908			
350		Diesel (based on residual fuel oil price)	$/million BTU	16.32	$3.01	3.78623546	
351			$/MJ	$0.01546	$0.79	$0.0179	
352		Naphtha (relative to diesel)	$/million BTU	14.36			
353			$/MJ	$0.01361			
354		Retail Electricity	$/million BTU	$26.84			
355			$/MJ	$0.02544			
356			$/kwh	$0.09158			
357							
358		Shrimp pricing	$/MT	$20,450.59			5 year average, from http://www.indexmundi.com/commodities/?commodity=shrimp&months=60
359		Shrimp calorific value, average of raw and crustaceans, shrimp, mixed species, cooked, moist heat	kJ/g	3.97			http://www.nal.usda.gov/fnic/foodcomp/cgi-bin/list_nut_edit.pl
360		Shrimp calorific value	MJ/g	0.00397			
361		Shrimp calorific value	MJ/MT	3,970			
362		Shrimp value per MJ of shrimp	$/MJ	$5.15			
363		Tilapia pricing	$/MT	$4,343.64			Using average pricing from imports and exports of all Tilapia in USA for 2011, http://www.st.nmfs.noaa.gov/st1/trade/cumulative_data/TradeDataProduct.html
364		Tilapia calorific value, average of raw and fresh, cooked, dry heat	kJ/g	4.69			http://www.nal.usda.gov/fnic/foodcomp/cgi-bin/list_nut_edit.pl
365		Tilapia calorific value	MJ/g	0.00469			
366		Tilapia calorific value	MJ/MT	4,690			
367		Tilapia value per MJ of tilapia	$/MJ	$0.93			
368		Soybean meal pricing (for salicornia meal)	$/MT	$308.43			5 year average, from http://www.indexmundi.com/commodities/?commodity=soybean-meal&months=60
369		Soy meal, defatted, raw, crude protein basis (N x 6.25)	kJ/g	14.10			http://www.nal.usda.gov/fnic/foodcomp/cgi-bin/list_nut_edit.pl
370		Soy meal calorific value	MJ/g	0.01410			
371		Soy meal calorific value	MJ/MT	14,100			
372		Soy meal value per MJ of soy meal	$/MJ	$0.02			
373							
374		1 million BTU	1,055.06	MJ			
375		1 million BTU	293.07	kwh			

APPENDIX B

Appendix B – Abbreviations and Acronyms

Bio-SPK – Biomass derived Synthetic Paraffinic Kerosene (aka HRJ)

CDM – Clean Development Mechanism

CO_2 – Carbon dioxide

CH_4 – Methane

FT – Fischer-Tropsch

GHG – Greenhouse Gas

GREET – Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation

GWP – Global Warming Potential

HRD – Hydroprocessed Renewable Diesel

HRJ – Hydroprocessed Renewable Jet Fuel (aka Bio-SPK)

IGCC – Integrated Gasification Combined Cycle

IPCC – Intergovernmental Panel on Climate Change

ISAS – Integrated Seawater Agriculture System

ISO – International Organization for Standardization

LCA – Life Cycle Assessment

LPG – Liquefied Petroleum Gas

LUC – Land Use Change

N_2O – Nitrous oxide or Dinitrogen monoxide

PPT – Parts per thousand (for measuring salinity)

QBTU – Quadrillion British Thermal Units, or 1.055 x 10^{18} joules

RSB – Roundtable on Sustainable Biofuels

SPK – Synthetic Paraffinic Kerosene

UAE – United Arab Emirates

UNFCC – United Nations Framework Convention on Climate Change

WRA – Weed Risk Assessment