EVALUATING RENEWABLE ENERGY OPTIONS FOR SMALL ISLANDS USING EMERGY METHODOLOGY: A CASE STUDY OF COCONUT BIODIESEL IN THE FIJI ISLANDS

BY

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We, the undersigned, certify that Mr. Krishna Raghavan, candidate for the degree of Master of Arts (Island Studies) at the University of Prince Edward Island, Canada, has presented a thesis, in partial fulfillment of the degree requirements, with the following title: "Evaluating Renewable Energy Options for Small Islands Using Emergy Methodology: A Case Study of Coconut Biodiesel in the Fiji Islands", that the thesis is acceptable in form and content, and that a satisfactory knowledge of the field covered by the thesis was demonstrated by the candidate through an oral examination held on April 22, 2014.

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Dedication

In loving memory of my parents
Lakshmi Krishnaswamy and
Nadathoor Raghavachari Krishnaswamy
who gave so much to educate us

ABSTRACT

The Pacific Island Countries including the Fiji Islands are heavily dependent on imported petroleum fuels for their energy needs. This is a major cause of environmental vulnerability as well as economic vulnerability due to high and volatile crude oil prices. A combination of Demand Side Management (DSM) to reduce energy consumption and optimize usage, and Renewable Energy Technologies (RET) to substitute fossil fuels can reduce their vulnerability. DSM consists of Smart Grids, Energy Efficiency and Storage, while RETs substitute fossil fuels by harnessing solar, wind, small hydro, biomass, geothermal and ocean energies. Comparative costs of electricity from RETs show that most of them are cheaper than the typical price of electricity in Pacific island countries.

Nearly half of Fiji's electricity is generated using petroleum fuels that can be substituted by biodiesel produced from locally grown coconuts. To evaluate the sustainability of coconut biodiesel, two different Environmental Accounting methods have been used: i) *Emergy Analysis,* and ii) *Embodied Energy Analysis*. Emergy Analysis is a holistic methodology that integrates all major inputs from the human economy and those coming 'free' from the environment, to evaluate complex systems. Emergy Performance Indicators for coconut biodiesel are: i) Emergy Yield Ratio is 1.32 indicating a low ability to exploit local resources efficiently; ii) Environmental Loading Ratio is 8.57 implying that biodiesel production causes significant environmental or ecosystem stress; and iii) Emergy Index of Sustainability is 0.15 indicating a low contribution to the economy per unit of environmental loading and a very high degree of environmental stress per unit of Emergy yield. Embodied Energy Analysis is a complimentary methodology that accounts for only the commercial energy (in kgs oil equivalent) required directly or indirectly to provide all the inputs (goods and services) for the entire biodiesel production process. Embodied Energy Performance Indicators are: i) Energy Return on Energy Invested is 2.47 which means that it is not worth the effort in energetic terms; and ii) Carbon dioxide Emissions during the production of coconut biodiesel is 1.38 kg CO_2 per kg biodiesel showing that biodiesel is not climate neutral.

This thesis adds to the growing body of knowledge that uses Emergy Analysis to evaluate sustainability of biofuels and other renewable energy options in a holistic manner. This is the first time in reported literature that Emergy Analysis has been used to determine the sustainability of coconut biodiesel. The Emergy and Embodied Energy performance indicators clearly show that coconut biodiesel is not a sustainable alternate source of energy for the Fiji Islands.

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1 INTRODUCTION

1.1 STATEMENT OF THE PROBLEM

The problem is stated according to the following logical progression:

1. Energy is essential for development.
2. Energy demand is growing.
3. Most of the energy used in small island developing states (SIDS) comes from imported petroleum fuels.
4. Most of the SIDS are very vulnerable due to dependency on imported petroleum fuels.
5. What are the alternatives to petroleum fuels?
6. Which is the best alternate energy source?

1.2 OBJECTIVES

The main objective of this study is to identify a methodology for evaluating renewable energy options for small islands in a holistic manner.

The second objective is to apply the methodology to assess the sustainability of biodiesel produced from coconuts in the Fiji Islands.

Social and other parameters, that are essential for the success of renewable energy interventions on small islands, will also be discussed in this thesis.

1.3 JUSTIFICATION OF THE PROBLEM STATEMENT

The focus of this thesis is a case study on the Fiji islands, one of the Pacific island countries. Therefore, the problem statement is now explained using information and data specific for the Pacific island countries and for the Fiji Islands.

1.3.1 Energy is essential for development

Worldwide, around 1.6 billion people do not have access to electricity, including over a billion people in the Asia-Pacific region (UNDP, 2007). Energy services[1] play a crucial role in the development process, particularly for the economic, environmental and social well-being of the poor. They are essential for providing social services such as health and primary education, and an improved quality of life. Energy services have a multiplier effect on safe drinking water, sanitation, health, education, transport and telecommunications; they also create and increase the productivity of income-generating activities in agriculture, industry, and tertiary sectors. Moreover, they have positive impacts on gender inequities and the environment (Modi *et al.,* 2005; UNDP, 2007).

The provision of energy is an essential prerequisite for poverty/hardship reduction. Increased access to energy services is particularly necessary in the Pacific Island Countries (PICs) where poverty/hardship is closely linked to the limited access to basic services, opportunities and adequate resources (UNDP, 2007).

Millennium Development Goals

The Millennium Development Goals (MDGs) are a set of eight time-bound and measurable goals and targets for combating poverty, hunger, illitreacy, gender inequality, disease, and environmental degradation. At the United Nations Millennium Summit in September 2000, world leaders pledged to achieve the Millennium Development Goals by 2015, including the overarching goal of cutting poverty in half.

The eight MDGs are (Modi *et al.,* 2005; UNDP, 2005; United Nations, 2013; UNDP, 2013):

1. Eradicate extreme poverty and hunger
2. Achieve universal primary education

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[1] Energy services refer to services that are provided by fuels, electricity, and mechanical power, including lighting, heating for cooking and space heating, water pumping, grinding, and power for transport.

3. Promote gender equality and empower women
4. Reduce child mortality
5. Improve maternal health
6. Combat HIV/AIDS, malaria, and other diseases
7. Ensure environmental sustainability
8. Develop a global partnership for development

In 2002 the United Nations Secretary-General commissioned the Millennium Project to develop a concrete action plan for the world to achieve the Millennium Development Goals and to reverse the grinding poverty, hunger and disease affecting billions of people. The Project's work was carried out by ten thematic task forces comprised of more than 250 experts from around the world headed by the renowned American economist Professor Jeffrey Sachs, who presented their final recommendations in 2005 (http://www.unmillenniumproject.org/).

Role of Energy in achieving the MDGs

At the World Summit for Sustainable Development in Johannesburg in 2002, it was recognized that affordable and sustainable modern energy services (mainly electricity and clean cooking fuels) are a necessity for countries to meet their Millennium Development Goals, and are essential for the economic, environmental and social well-being of the poor (UNDP, 2007).

Even though there is no MDG specifically on energy, UNDP proposes in '*Energizing the Millennium Development Goals - A Guide to Energy's Role in Reducing Poverty*' (UNDP, 2005) that access to energy services should be treated as an integrated part of MDG strategies since it is an important instrument in helping promote economic growth, social equality, and environmental sustainability. This guide, designed to help development practitioners, gives an overview of the most relevant issues concerning the nexus between development and energy, and provides suggestions and examples on how to address energy as a part of national efforts to reach the MDGs.

Modi *et al.* (2005) specifically address the role of energy services in meeting the MDGs, especially in poor countries that are lagging behind in their efforts to achieve these development goals. By analysing all the linkages between the MDGs and energy, Modi *et al.* argue that much greater quality and quantity of energy services are required to meet the MDGs and that energy services are essential for both social and economic development. To scale up energy services, different approaches are proposed for rural and urban areas, and the importance of associating women with the provision of modern energy services is highlighted. Finally, they provide ten key priority energy interventions for national governments.

The report of the UN Millennium Project underscores the strong links between energy services and achieving the MDG outcomes. All ten task forces of the Millennium Project found that energy services are essential inputs. The report of the Millennium Project highlights the linkages between energy and all the MDGs and recommends that much greater quality and quantity of energy services have to be provided to meet the MDGs (Modi *et al.,* 2005; http://www.unmillenniumproject.org/).

1.3.2 Growth in Energy demand

Energy demand has been growing steadily in the Pacific island countries including Fiji. It is met through procurement of oil (76.0% of the energy mix in 2006) and other energy, mainly biomass (10.6%), gas (8.6%), hydro (4.6%) and coal (0.3%) (Figure 1)(Asian Development Bank [ADB], 2009b).

Pacific Island Countries

During the period 1990 to 2006, the Total Primary Energy Supply (TPES) in the Pacific grew at 3.8% per annum, increasing from 1.7 MTOE[2] in 1990 to 3.0 MTOE in 2006 (Figure 2). Natural gas, which is used only in Papua New Guinea, had an annual growth rate of 8.3%, while oil was second with a growth rate of 4.1% per annum (ADB, 2009b).

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[2] MTOE = million tons of oil equivalent.

Figure 1 Primary Energy Mix in the Pacific, 2006 [2] (ADB, 2009b)

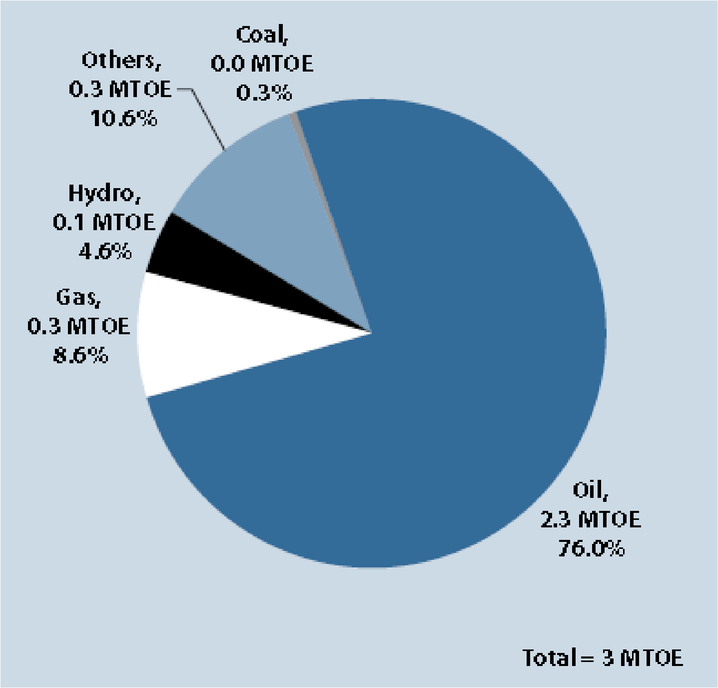
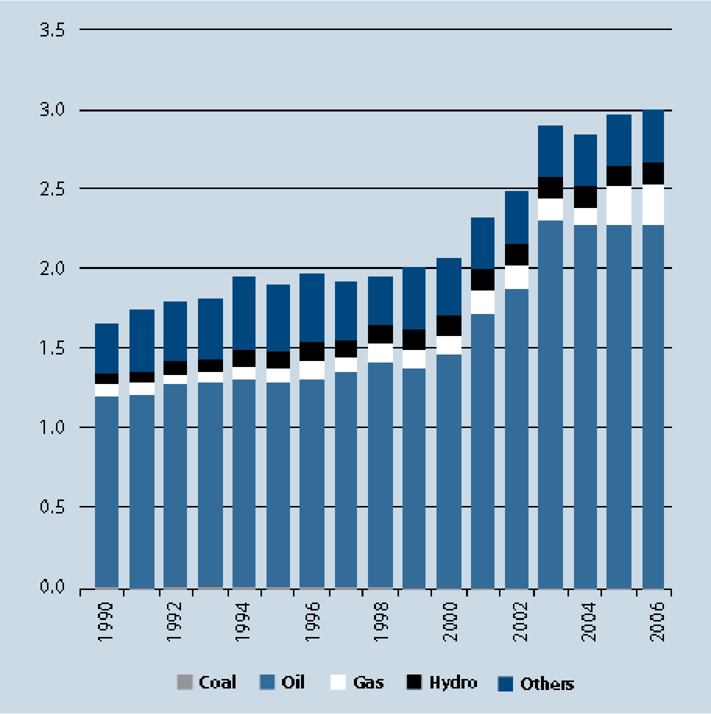


Figure 2 Primary Energy Supply in the Pacific, 1990–2006[3] (ADB, 2009b)



Note: Values in MTOE = million tons of oil equivalent.

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[3] The Pacific comprises Cook Islands, Fiji Islands, Kiribati, Marshall Islands, Federated States of Micronesia, Nauru, Palau, Papua New Guinea, Samoa, Solomon Islands, Timor-Leste, Tonga, Tuvalu, and Vanuatu.

Fiji Islands

Fiji's total final energy consumption (TFEC) grew at an average rate of 6.0% per annum from 238 thousand tons of oil equivalent (KTOE) in 1992 to 537 KTOE in 2006, with a maximum of 650 KTOE in 2004. During the earlier half of this period 1992 to 2000, TFEC grew somewhat slowly at 2.5% per annum, but the average annual growth rate of TFEC increased more than four times to 10.9% during the second half, 2000 to 2006, even though economic growth was only 2.0% per annum during the latter period (Figures 3 and 6) (ADB, 2009b).

The dominant types of energy consumed are oil (85% of the total in 2006) and electricity (12%), followed by coal and biomass (Table 1). From 1992 to 2006, the consumption of oil grew at an average 6.7% per annum, while electricity grew at 4.9% per annum (ADB, 2009b).

Table 1 Fiji's Final Energy Consumption in 2006 [4] (ADB, 2009b)

ITEM	AMOUNT (KTOE)	% OF TOTAL
Industry	186	35%
Transport	247	46%
Other Sectors	104	19%
TOTAL FEC	537	100%
Coal	8	1%
Oil	457	85%
Gas	0	0%
Electricity	63	12%
Others	8	1%

Fiji's total primary energy supply (TPES) in 2006 was dominated by oil (65.0% of the total) and biomass (26.3% of total) (Table 2, Figure 4). During the period 1992 to 2006, Fiji's TPES grew at 2.5% per annum. Oil's share in TPES increased from 40.2% in 1992 to 65.0% in 2006 at an

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[4] KTOE = Thousand Tons of Oil Equivalent; FEC = Final Energy Consumption.

average annual growth rate of 6.1%, and all the oil is imported. During the same period, biomass decreased by 2.3% per annum to 26.3% in 2006, and hydropower increased from 6.1% in 1992 to 7.6% in 2006 (Figures 5 and 6) (ADB, 2009b).

Figure 3 Fiji's Final Energy Consumption by Type, 1992–2006 [4] (ADB, 2009b)

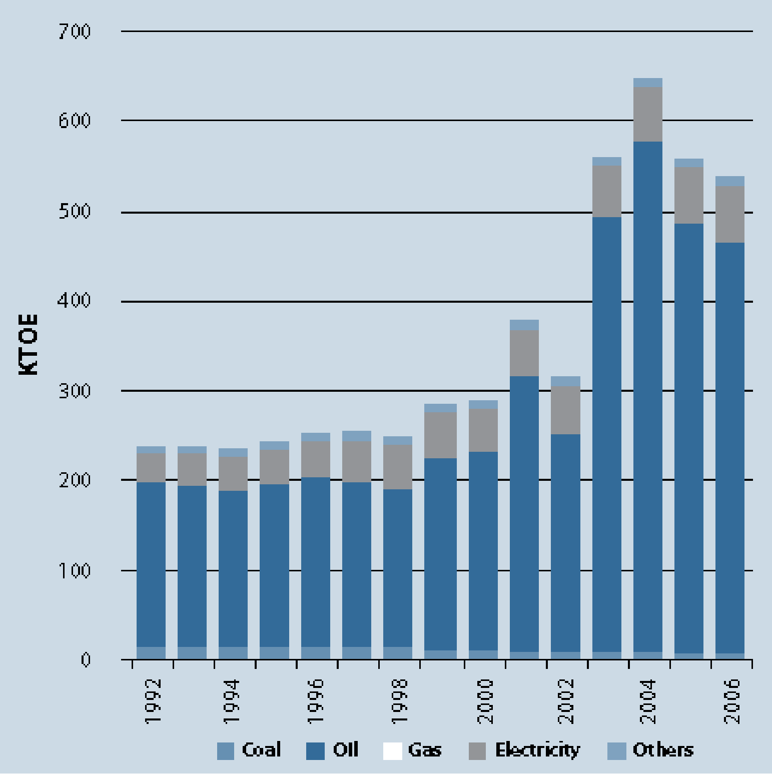

Table 2 Fiji's Primary Energy Supply (KTOE)[5] in 2006 (ADB, 2009b)

SOURCE	AMOUNT (KTOE)	% of Total
Coal	8	1.1%
Oil	503	65.0%
Hydro	0	7.6%
Gas	59	0%
Others	203	26.3%
TOTAL PES	774	100%

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[5] KTOE = thousand tons of oil equivalent; PES = primary energy supply.

Figure 4 Fiji's Primary Energy Supply by Source in 2006[6] (ADB, 2009b)

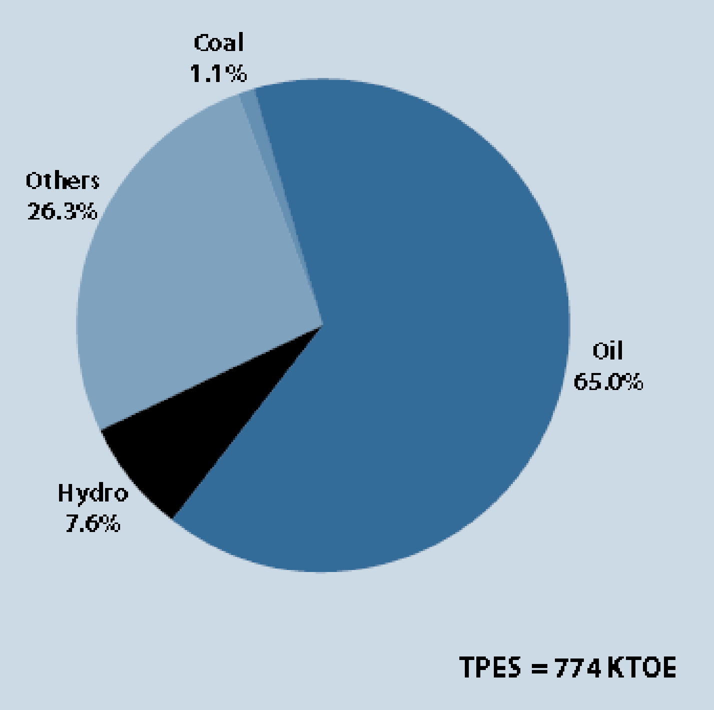
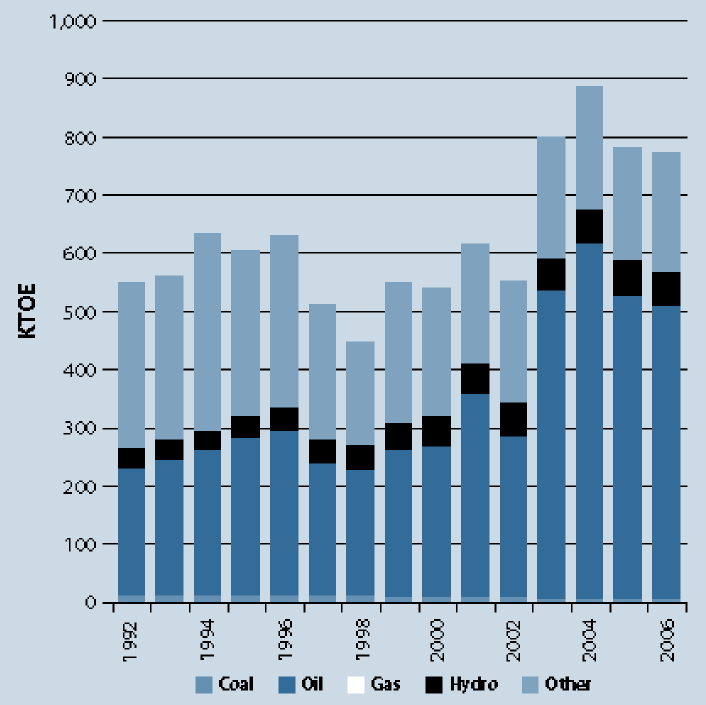


Figure 5 Fiji's Primary Energy Supply by Source, 1992 – 2006 (ADB, 2009b)



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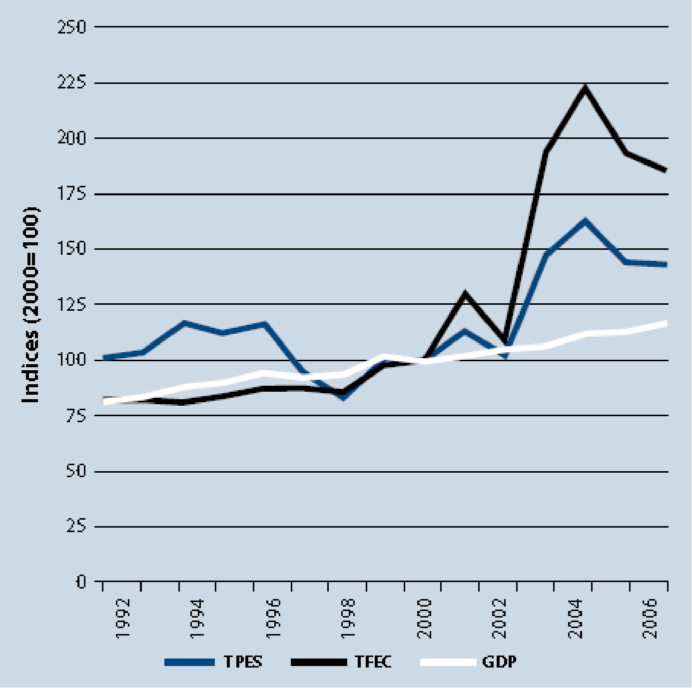
[6] TPES = total primary energy supply.

Indices of growth of TFEC, TPES and GDP from 1992 to 2006 are compared in Figure 6. During this period, the GDP of the Fiji Islands' economy grew steadily at an average annual rate of 2.6% while the population grew at an average annual rate of 0.9%, resulting in a 27% increase in per capita income ($2,296 in 2006 at constant 2000 prices) (ADB, 2009b).

Figure 6 Growth in GDP, TPES, and TFEC, 1992–2006 [7] (ADB, 2009b)



1.3.3 Role of petroleum fuels

At present, most Small Island Developing States (SIDs) are highly dependent on imported petroleum products such as diesel, gasoline, propane and kerosene for their energy needs (United Nations General Assembly, 1994; Alliance of Small Island States, 2005; United Nations Development Program, 2012). The vital role of oil in the economic development and macroeconomic stability of Pacific Island Countries (PICs) is highlighted by the Asian Development Bank in '*Taking Control of Oil - Managing Dependence on Petroleum Fuels in the*

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[7] GDP = gross domestic product; TFEC = total final energy consumption; TPES = total primary energy supply.

Pacific' (ADB, 2009a). This study finds that PICs are extraordinarily dependent on oil, particularly diesel, which makes them highly vulnerable to rising oil prices. The main findings are that the key to energy security and reduced vulnerability is to diversify energy supply, demand-side management, increase the efficiency of existing energy supplies and develop new fuel and electricity sources that are renewable or use cheaper fossil fuels.

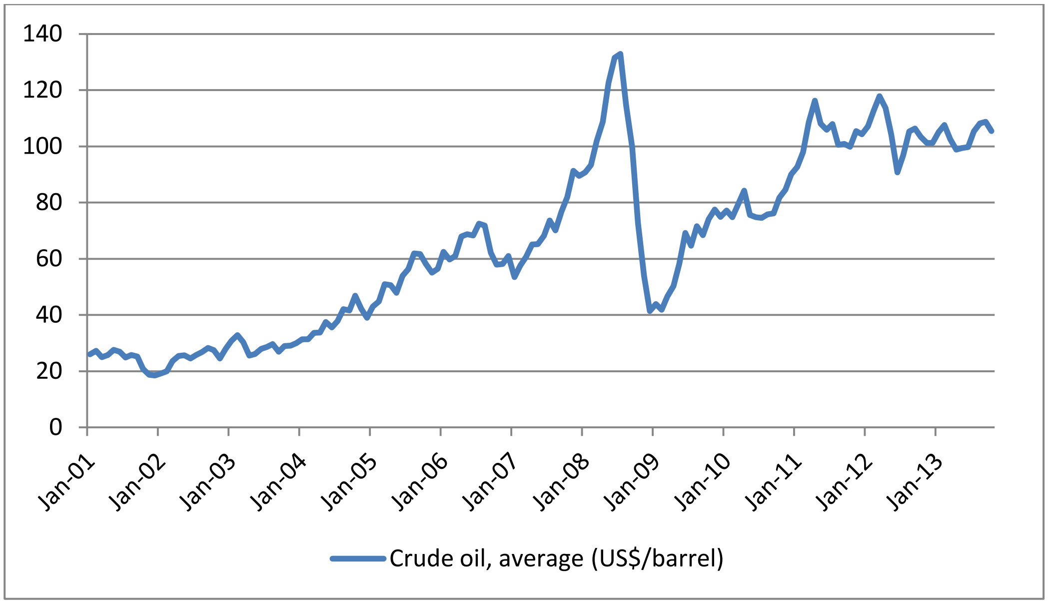
Accurate and up-to-date data on fuel imports and usage by sector for the Pacific islands region are difficult to obtain (ADB, 2009a). Petroleum is responsible for more than 80 per cent of energy generation in the Pacific. Liquid petroleum fuels, particularly diesel, kerosene and gasoline are a source of energy, especially for power generation (25% of oil use) and transportation (75% of oil use) (Pacific Islands Forum Secretariat, 2011).

The wide fluctuations in petroleum fuel prices can be seen in Figure 7. A steady upward movement increased average crude oil prices from below 20 US$/barrel in January 2002 to over 130 US$/barrel in June-July 2008 (World Bank, 2013). Such high oil prices are a supply shock that make sound macroeconomic policy management difficult by increasing inflation, reducing growth and weakening balance of payments. Compared to 39 other developing countries, all seven Pacific island countries including Fiji were among the 10 most vulnerable to international oil price rises (ADB, 2009a).

Pacific Island Countries are separated from each other and from the rest of the world by vast distances, and this makes transport very important for staying connected. The impacts of volatile oil prices include (ADB, 2009a):

- Decrease in the usage of land, sea and air transport;
- Reductions in economic opportunities, output by businesses and income for households due to less and more expensive transport;
- Reduced disposable income due to the increase in the proportion of fuel costs.

Figure 7 Historical Prices for Crude Petroleum Oil, 2001-2013 (World Bank, 2013)



An escalating demand for oil is forecast in the Pacific Island Countries based on the prevailing structure of energy consumption, and this is no longer sustainable as the era of cheap oil has apparently come to an end. The Pacific Island Countries have to move away from the current dependence on oil by harnessing alternate locally available energy sources so as to avoid the adverse effects of volatile world oil prices that inhibit prospects for sustained economic growth and development in the Pacific region (ADB, 2009a).

Value of oil imports of 13 Pacific Island Countries and 7 Low income Asian countries for 5 years (2005-2009) are given as percentages of the GDP, of imports and of exports in Table 3. During this period, annual oil imports of Fiji showed a high of 21.5% of the GDP in 2008, when the value of oil imports equalled 28.9% of the total imports and 39.7% of the total exports of goods and services (International Monetary Fund, 2010).

Table 3 Relative Value of Oil imports: Pacific Islands and Low Income Asia (International Monetary Fund, 2010)

	VALUE of OIL IMPORTS as														
	% of IMPORTS of goods & services					% of GDP					% of EXPORTS of goods & services				
	2005	2006	2007	2008	2009	2005	2006	2007	2008	2009	2005	2006	2007	2008	2009
PACIFIC ISLAND COUNTRIES															
Cook Islands[1]	9.1	21.5	18.4	27.2	31.4	4.0	11.5	9.7	20.0	28.8	140.	591.7	377.5	982.0	2070.1
Fiji Islands	**23.6**	**27.5**	**27.7**	**28.9**	**21.2**	**15.**	**19.0**	**17.5**	**21.5**	**12.6**	**29.0**	**38.1**	**36.2**	**39.7**	**26.6**
Kiribati	13.3	21.6	18.5	-	-	15.	18.8	16.3	-	-	98.6	175.9	156.8	-	-
Marshall Islands ,	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Micronesia, Fed. St.	11.0	13.3	13.2	14.7	9.2	9.4	11.3	11.4	13.8	7.8	58.7	72.6	63.1	67.2	37.7
Nauru[1]	4.5	-	-	-	-	4.5	-	-	-	-	30.8	-	-	-	-
Palau	31.7	38.1	39.0	-	-	18.	23.8	19.5	24.3	0.0	33.2	45.9	36.8	-	-
Papua New Guinea	4.9	4.5	4.4	5.1	3.3	3.4	2.9	3.3	3.1	2.1	4.5	3.4	4.0	4.0	3.3
Samoa	13.8	14.1	15.0	17.2	17.9	7.6	8.6	9.2	9.2	9.4	23.9	25.7	28.1	28.3	30.1
Solomon Islands	24.8	23.2	21.5	22.6	17.7	10.	12.3	12.1	13.1	8.3	30.9	34.6	33.1	35.0	24.7
Tonga	21.6	24.4	25.2	29.6	28.4	11.	12.5	12.7	15.4	15.1	79.1	100.1	99.8	109.5	103.1
Tuvalu[1]	21.7	-	-	-	-	12.	-	-	-	-	4553.	-	-	-	-
Vanuatu	8.2	8.9	14.5	14.0	14.3	4.1	4.2	6.7	7.7	6.9	9.5	10.3	16.9	17.9	15.9
LOW INCOME ASIA															
Bangladesh	11.0	11.3	10.9	10.9	11.3	2.7	2.9	3.0	3.0	2.9	15.1	15.1	15.2	15.1	15.6
Cambodia	18.5	20.4	21.5	27.0	24.2	13.	15.5	15.7	18.4	14.4	20.9	22.5	24.1	34.1	28.9
Lao	12.0	12.6	13.9	14.5	7.2	5.9	5.9	7.4	7.9	3.6	17.4	15.5	19.5	20.9	10.8
Mongolia	19.2	22.5	23.2	25.4	14.8	13.	13.4	14.2	18.8	9.2	20.4	20.8	22.2	32.2	16.7
Nepal	14.9	16.8	13.4	14.7	10.2	4.5	5.1	4.6	4.6	3.6	30.5	39.1	33.2	38.3	28.5
Sri Lanka	16.4	17.8	19.6	21.6	17.2	6.8	7.3	7.7	8.5	4.9	20.9	24.3	26.5	33.2	21.8
Vietnam	12.0	11.9	11.0	13.5	9.4	8.9	9.3	10.2	12.6	7.3	12.9	12.6	13.3	16.2	10.8
AVERAGE – PICs[2]	17.0	19.5	19.9	18.9	16.0	10.6	12.6	12.1	13.5	7.8	40.8	56.3	52.8	43.1	34.5
AVERAGE - Low Income Asia	14.9	16.2	16.2	18.2	13.5	7.9	8.5	9.0	10.5	6.6	19.7	21.4	22.0	27.1	19.0

1. From Asian Development Outlook database-imports and exports of goods only. 2. Excludes Cook Islands, Nauru and Tuvalu as data on services trade is unavailable.

1.3.4 Vulnerability of small island states

International Declarations

The vulnerability of small island states due to dependency on imported petroleum fuels has been a matter of serious concern to the Alliance of Small Island States[8] (Alliance of Small Island States, 2013). This concern has been clearly affirmed in various international declarations adopted by the Small Island Developing States (SIDS) over the last twenty years (United Nations General Assembly, 1994; Alliance of Small Island States, 2005; United Nations Development Program, 2012).

The UN Conference on Environment and Development held in June 1992 in Rio de Janeiro, Brazil, adopted Agenda 21, a comprehensive programme of action for sustainable development (United Nations Environment Program [UNEP], 1992b). Chapter 17 of Agenda 21 brought international attention to the

> special challenges to planning for and implementing sustainable development on small island states, because they are ecologically fragile and vulnerable, and their small size, limited resources, geographic dispersion and isolation from markets, place them at a disadvantage economically and prevent economies of scale. (UNEP, 1992b, chapter 17, para. 17.123)

To promote international and regional cooperation and coordination, Agenda 21 called for the convening of a global conference on the sustainable development of SIDS.

The Global Conference on the Sustainable Development of Small Island Developing States was held in Bridgetown, Barbados during 25 April to 6 May, 1994. Chapter VII of the comprehensive Programme of Action for the Sustainable Development of Small Island Developing States, also called the Barbados Programme of Action (United Nations General Assembly [UNGA], 1994), which deals with Energy Resources states that “Small

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[8] The 39 member Alliance of Small Island States (AOSIS) consists of 15 small island states in the Pacific Ocean, 19 in the Atlantic Ocean and connected seas, and 5 in the Indian Ocean (Alliance of Small Island States, 2013).

Island Developing States are currently heavily dependent on imported petroleum products, largely for transport and electricity generation, energy often accounting for more than 12 per cent of imports" (UNGA, 1994, chapter VII, para. 35). During the period 2005-2009, the average 'oil imports as a percentage of total imports' for the 13 Pacific SIDS varied from 16.0 % to 19.9%, and for the Fiji Islands it varied from 21.2% to 28.9% (Table 3) (International Monetary Fund, 2010).

Ten years after the landmark 1994 Barbados conference, the International Meeting to Review the Implementation of the Program of Action for the Sustainable Development of Small Island Developing States was held at Port Louis, Mauritius in January 2005. The *Mauritius Strategy for the further Implementation of the Program of Action for the Sustainable Development of Small Island Developing States* states in Chapter VII, Energy Resources that "energy dependence is a major source of economic vulnerability for many small island developing States", and many remote and rural small island developing States communities have little or no access to modern and affordable energy services (Alliance of Small Island States, 2005; Chapter VII).

The next major small island states gathering was Achieving Sustainable Energy for All in SIDS – Challenges, Opportunities, Commitments organized by the Alliance of Small Island States in Bridgetown, Barbados on 7-8 May 2012. This Ministerial Conference was focused on sustainable energy and adopted the Barbados Declaration on Achieving Sustainable Energy for All in Small Island Developing States which states that the Ministers

> remain deeply concerned that most SIDS are highly dependent on imported oil and other fossil fuels for transport and electricity generation, and this is a major source of economic vulnerability for SIDS. This leaves SIDS highly exposed to oil-price volatility. The increasing cost of imported fossil fuels represent a major impediment to the achievement of sustainable development and poverty eradication in SIDS, as scarce financial resources are diverted from efforts to promote social and economic development and ensure environmental protection.

> Furthermore, many remote and rural SIDS communities have little or no access to modern and affordable energy services. (UNDP, 2012, p. 1, para. 6)

Vulnerability of SIDS

An analysis of challenges and opportunities faced by SIDS that was carried out by the United Nations Environment Program in 2012 found that dependence on imported petroleum is a major source of vulnerability for many SIDS and one of the main challenges in their pursuit of energy security and poverty reduction (United Nations Environment Program, 2012). This study also found that:

- High and rising oil prices cause severe imbalances in trade, and fuel imports are a heavy drain on limited national financial resources.
- Prices of petroleum products in SIDS are much higher than in other countries and prices of petroleum fuels in the Pacific SIDS are typically 200–300% higher than international values.
- Volatility of the global oil market together with fluctuations in supply and demand magnify the difficulties faced by SIDS economies in obtaining foreign exchange to pay for imported energy resources (*ibid*.).

In *Macroeconomic Impacts of Energy Prices in the Pacific*, the International Monetary Fund (2010) reviews the macroeconomic impacts and policy implications of energy consumption and prices for oil importing PICs. This study finds that energy prices, especially oil, have a huge impact on the small open economies of the PICs, and concludes that energy policy measures that reduce the reliance on imported fossil fuel will contribute to macroeconomic growth, stability and aid poverty reduction. *Overcoming Vulnerability To Rising Oil Prices - Options for Asia and the Pacific* is a study by the United Nations Development Program (UNDP, 2007b) that looks at the effects of rising oil prices especially on the poor, and the macro-economic impact and national vulnerability to oil prices. Several actions that can reduce oil price vulnerability at the national level are proposed including fuel diversification by using renewable energy. Policies to address oil price shocks and peak oil prices have been prioritized in this study.

SIDS are vulnerable not only to the economic impacts but also to the environmental impacts of imported petroleum fuels. Petroleum products are transported long distances to islands and stocks need to be stored before usage, both of which can be causes of environmental problems. Numerous oil spills from broken or damaged tankers near coastal regions have caused immense damage to marine ecosystems, and to aquatic and bird life (NOAA, 1992). Unloading, storage and re-loading of oil at island terminals can also lead to oil spills on land or sea for various reasons (Crowfoot, 2012). Moreover, greenhouse gas emissions from the use of fossil fuels is one of the primary causes of global warming and climate change (Intergovernmental Panel on Climate Change [IPCC], 2007a), the harmful effects of which include sea level rise and an increasing frequency of extreme climate events (IPCC, 2007b).

Limitations imposed by environmental concerns are also important in the production of intermediate energy carriers such as electricity and heat from oil and gas, and these limitations are easy to understand and accept qualitatively. However, environmental impacts can be very difficult to analyze quantitatively in a manner that allows us to evaluate, compare and rank several energy production options in order to select the best one.

Oil Price Vulnerability Index

In general vulnerability is defined as the degree to which a system (human or natural) is susceptible to, or unable to cope with, adverse effects of an event. The three commonly accepted aspects of vulnerability are hazards, resistance and damage. The hazards are basically environmental (or external) variables, which are not under the control of a given country and they are the resultant outcomes of international events. The resistance is derived out of economic variables basically representing the fundamental strength of the economy. The damage is the acquired vulnerability over a period of time represented by social variables captured through level of human development. A vulnerability index for a country capturing the influences of all these variables would be a useful

> tool for many purposes like identifying specific problems, devising defense mechanisms, evolving strategic alternatives and planning for the future eventualities. (Balachandra & Mongia, 2007, p. 2)

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The UNDP Regional Energy Program for Poverty Reduction based in Bangkok developed a composite oil-price vulnerability index (OPVI) for 24 countries of the Asia-Pacific region including 6 SIDS (Fiji, Maldives, Papua New Guinea, Samoa, Solomon Islands and Vanuatu) using the following method. A set of 15 variables that influence the oil price vulnerability level of a country were identified by the UNDP team who then grouped these variables under two categories (Balachandra & Mongia, 2007):

1. Economy-related variables - Real GDP growth rate, GDP per capita, Balance of payments - current account, Budget balance, Import cover, Share of net oil fuel subsidy/tax revenue in GDP, Contribution of food and beverages to inflation, Trade as % of GDP, Gini Index and Human Development Index.
2. Energy-related variables - Oil intensity of GDP, Oil import dependence, Share of oil in primary energy consumption, Oil reserves to production ratio and Share of transport in oil consumption (*ibid*.).

However, after using logical reasoning and statistical analysis to eliminate dependent variables and double counting, Balachandra & Mongia selected the following 8 variables for detailed study:

1. Real GDP growth rate
2. GDP per capita
3. Balance of payments-current account
4. Budget balance
5. Import cover
6. Oil intensity of GDP
7. Oil import dependence
8. Share of oil in primary energy consumption.

The OVPI of the 24 countries was calculated by Balachandra & Mongia using Principal Component Analysis with weighted factor scores. They then ranked and categorized the countries under low, medium and high vulnerability to oil prices (Table 4).

Table 4 Categorization of Countries based on Oil-Price Vulnerability Index (Balachandra & Mongia, 2007)

Low OPVI	Iran, China, Malaysia
Medium OPVI	SIDS: Papua New Guinea. OTHER COUNTRIES: Bhutan, India Indonesia, Thailand, Mongolia, Vietnam, Myanmar
High OPVI	**SIDS: Fiji, Samoa, Solomon Islands, Vanuatu, Maldives.** OTHER COUNTRIES: Philippines, Afghanistan, Nepal, Bangladesh, Pakistan, Lao PDR, Sri Lanka, Cambodia

Five out of the six SIDS (Fiji, Samoa, Solomon Islands, Vanuatu and Maldives) are highly vulnerable to oil prices. Papua New Guinea is the only SIDS that has a medium OVPI due to its petroleum reserves and very low per capita energy consumption[9]. Four SIDS in the Pacific are among the seven most vulnerable countries out of the 24 Asia-Pacific countries ranked in order of vulnerability (Balachandra & Mongia, 2007).

The Pacific island countries are among countries that are most vulnerable to increases in oil prices in the Asia-Pacific region (UNDP, 2007b). Even though Fiji is blessed with hydropower resources (unlike some other Pacific island countries), only 50 percent of Fiji's electricity generation mix in 2010 came from hydropower; the remaining 50 percent was produced from diesel and heavy fuel oil (Fiji Electricity Authority, 2011). Fiji spent 684 million US$ on oil imports in 2008 and the value of this equalled 39.7% of exports and 21.5% of the GDP (International Monetary Fund, 2010; Fiji Bureau of Statistics, 2014).

1.3.5 What are the alternatives to petroleum fuels?

Alternative energy sources that can reduce or eliminate the usage of fossil fuels are:

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[9] Less than 10% of the population of Papua New Guinea have access to electricity (UNDP, 2007a)

- Solar energy
- Wind power
- Hydro power
- Biomass and Biofuels
- Geothermal power
- Ocean energy (tidal power, wave energy, ocean thermal energy).

For best effect, using alternate energy sources has to go together with demand side management practises that reduce energy consumption and optimise energy usage.

1.3.6 Which alternate energy source is the best?

Issues in Sustainability

Sustainability of energy production (electricity, heat, etc.) from fossil fuels (coal, natural gas, diesel, gasoline, etc.) or from renewable energy sources (solar, wind, hydro, biomass, etc.) is difficult to measure. It is often assumed in a qualitative manner that if electricity is generated from a renewable energy source then it must be more sustainable than electricity generated from fossil fuels. However, this is not always true because we have to account for net energy as well as renewability in order to measure sustainability (Brown & Ulgiati, 1997).

Another common assumption is that renewable energy sources that release less greenhouse gases such as carbon dioxide are more sustainable than fossil fuels that release more greenhouse gases. Greenhouse gases are related to environmental concerns about global warming. However, we should not rely only on carbon dioxide emissions to measure sustainability since net energy and use of environmental services may be far more destructive and threatening to human well being in the long run than the effects of carbon dioxide released (Brown & Ulgiati, 2002).

Net energy, also known as Energy Return on Energy Invested (EROEI), is the ratio of energy *out* to energy *in* which tells us how much more energy is produced than is required to develop and operate the system. EROEI evaluations of biofuels show that, in many cases, it is not sustainable because of the fossil fuels used for growing biomass and converting it to a fuel. Often, biomass would give higher net energy if used directly (Ulgiati, 2001; Heinberg, 2009).

Table 5 Life cycle EROEI for Fossil Fuels and Renewable Energy (Heinberg, 2009)

FOSSIL FUELS	
Coal	50
Oil – Crude	19
Natural gas	10
Oil - Tar sands	5.2 to 5.8
Oil - Oil shale	1.5 to 4
RENEWABLE ENERGY	
Hydropower	11 to 267
Wind	18
Wave	15
Nuclear	1.1 to 15
Geothermal	2 to 13
Solar PV	3.8 to 10
Biodiesel	1.9 to 9
Ethanol	0.5 to 8
Tidal	6
Solar thermal	1.6

In *Searching for a Miracle: Net Energy Limits & the Fate of Industrial Society*, Heinberg (2009) uses nine key criteria to compare energy systems and their limits. He then introduces a tenth criterion that limits energy options: *Net Energy* or *Energy Return on Energy Invested* (EROEI). Eighteen energy sources, both renewable and fossil based, have been assessed and compared using EROEI. Heinberg then uses a process of elimination to propose a future energy mix. Life-cycle EROEI for fossil fuels and renewable energy sources calculated by Heinberg are given in Table 5.

Fossil fuels in general have EROEI of more than 10 except in the case of oil from tar sands and shale. The EROEI of coal at 50 explains why it is still widely used for electricity production in the USA, China and India. Crude oil has an EROEI of 19 — much lower than the EROEI of 100 that prevailed in the early days of petroleum exploration (around a century ago) when oil wells were easy to access. Amongst the renewable energies, hydropower has the highest EROEI ranging from 11 to 267, and wind power is rated 18. Other renewable energies listed by Heinberg tend to have lower EROEI, except some geothermal power plants that can reach 13. Wave power has a high EROEI of 15 but this technology is just crossing the stage from research to commercial development, with no significant practical capacity so far.

Biofuels have some of the lowest energy returns and some ethanol production processes can have an EROEI very close to 1. This means that the energy required to produce one litre of ethanol is nearly equal to the energy in one litre of fuel ethanol produced. Therefore, ethanol production does not make any net global contribution to the economic process, though it may still be produced for geopolitical reasons and supported by substantial financial subsidies, as in the USA for corn ethanol (Taylor, 2009). It is important to remember that an energy source with a high EROEI may have negative environmental impacts that cost society more than its net economic yield. These costs are not factored into Heinberg’s calculations.

Therefore, a holistic evaluation and comparison of various energy supply options has to take into account net energy yield as well as environmental impacts. Emergy Analysis, that gives us Emergy based Performance Indicators, provides a tool that takes into account all these factors. The Emergy Index of Sustainability considers both the resource's economic contribution and its environmental impact and is therefore able to evaluate and compare energy supply options in a holistic manner (Brown & Ulgiati, 1997). A second approach, the Embodied Energy Analysis, gives us the EROEI together with life cycle carbon dioxide emissions (Brown & Herendeen, 1996). These indices will be discussed in detail in Sections 2.2 and 2.3.

1.4 ENERGY SUSTAINABILITY FRAMEWORK

The key elements of an Energy Sustainability Framework for small islands can be grouped under:

1. Renewable Energy Technologies
2. Demand Side Management.

The focus of this thesis is on evaluating Renewable Energy (RE) options. RE technologies that can be used on small islands will be described under the following categories:

1. Solar energy
2. Wind power
3. Hydro power
4. Bio-energy
5. Ocean energy
6. RE for transport
7. RE for water.

However, the substitution of fossil fuels by RE technologies has to be supported by Demand Side Management (DSM) practises to reduce energy consumption and optimise energy usage.

1.4.1 Demand Side Management

Demand Side Management (DSM) for the isolated electric grids found on islands essentially consists of three components (Eurelectric, 2012):

a) <u>Smart Grids</u>

Smart grids are intelligent electrical networks that can balance supply and demand. They enable demand side participation by allowing customers to manage and adjust their electricity consumption in response to real-time price signals that change according to network peak loads. The main intention is to shift customer loads from peak load hours to off-peak hours when the power generation system is underutilized. This is done by using ‘time of day’ tariffs with high prices during the network peak, so that educated customers can reduce the cost of their energy by reducing their peak energy consumption. Moreover, a central control system can turn off heating and cooling loads during the network peak hours. Smart grids lower power generation costs by improving asset utilization and generation efficiency, and by reducing capital investment required only for peak generation (*ibid*.).

b) Energy Efficiency

There are several ways of improving energy efficiency and managing the growth of system demand (Eurelectric, 2012):

- *Electrical Appliances* - Energy efficiency information on products can assist customers to choose efficient electrical appliances that can achieve significant energy savings.
- *Heat Pumps* - Heat pump technology, which uses low-grade heat of the earth or water bodies, can give considerable savings in energy used for heating and cooling.
- *Building Regulations* - New building materials and climate friendly designs are fairly low cost methods of making buildings more energy efficient and reducing their energy needs.

c) Storage

Energy storage is a key enabling technology that can fulfil several functions in isolated power systems found on islands such as peak shaving, stabilising intermittent production, quality of electricity, continuity of service, voltage control and frequency control (*ibid*.).

1.4.2 Renewable Energy Technologies for Islands

To produce electricity and heat, the main renewable energy (RE) resources on islands that can be used to substitute fossil fuels are solar, wind, hydro, biomass, geothermal and ocean energies. In addition, two applications that need unique considerations will be described: a) RE for transport, and b) RE for water.

Solar Energy

Solar thermal devices produce heat whereas photovoltaic cells produce electricity; concentrators can be used for both. The main applications of solar thermal and solar PV are given in Table 6. Solar photovoltaic (SPV) was one of the most expensive renewable energy options for electrification but significant cost reductions have lowered SPV panel prices dramatically over the last three decades. Moreover, off-grid SPV systems require a battery bank for storage; this is around one-third of the system cost and has to be replaced every 5 to 8 years. SPV is very reliable for small amounts of power for niche applications like off-grid lighting, telecommunications, etc., but its high cost rules it out for powering small and medium scale industries or for grid-tie applications without substantial subsidies. These subsidies are given in the form of feed-in tariff programs in Germany and the province of Ontario in Canada, or as equipment grants as in USA (Mabee *et al.*, 2012).

Table 6 Applications of Solar Thermal and Photovoltaics

SOLAR THERMAL	SOLAR PHOTOVOLTAIC
Water Heaters	Lanterns
Cookers	Home Lighting Systems
Driers	Power Plants
Space heating	Pumps
Desalination (MSF, VC)	Desalination (ED, RO)
Solar ponds	
Furnaces, Crematoriums	

Concentrating Solar Power (CSP)

CSP uses mirrors or lenses to concentrate the sun's rays to heat a fluid and produce steam. The steam drives a turbine and generates power in the same way as conventional power plants. In order to generate electricity after sunset or on cloudy days, CSP systems can have heat storage. This improves the economic viability by producing dispatchable electricity and facilitating grid integration. There are two types of CSP plants (IRENA, 2012e):

- *Line-focusing systems* have single-axis tracking systems. They include Parabolic Trough and Linear Fresnel plants.
- *Point-focusing systems* have two-axis tracking systems and much higher concentration factors. They include Solar Dish systems and Solar Tower plants.

Wind power

The types of wind generators, their applications and capacities are classified in Table 7.

Table 7 Classification of Wind Turbine Generators (Raghavan, 2003)

SIZE	CAPACITY	APPLICATION	GENERATOR
Small	< 50 kW	Stand Alone, Off-grid	Permanent Magnet alternator
Medium	50 - 500 kW	Wind-Diesel	Induction (asynchronous), Multi-pole
Large	0.5 – 5 MW	Grid Connected	Induction, Multi-pole

Small and medium sized wind turbines have good application possibilities on islands with sufficient wind speeds for pumping water and generating electricity. Small wind turbine generators for off-grid, stand-alone applications can easily be combined with solar photovoltaic arrays to give wind-solar hybrid systems that normally incorporate a voltage control system, battery bank and inverter. Medium sized wind turbines (50 - 250 kW) can be used in wind-diesel hybrid systems to reduce diesel fuel consumption on islands with diesel power plants. Tilt-up towers make it easy to install and maintain these wind turbines without a crane, and this is ideal on islands with limited infrastructure. Large grid connected wind turbines require very good roads, large cranes and a strong electricity grid; these conditions are not often found on small islands (Raghavan, 2003).

Hydro power

Hydro power plants can be classified according to their sizes as shown in Table 8. Hydro power is cheap and is available for 24 hours a day without battery storage. Power in the daytime can be used for small industries and in the night for lights, etc. This is an important consideration for islands where employment opportunities and income generation from the productive uses of the energy in the daytime forms an essential part of the development process.

Table 8 Classification of Hydropower schemes (Harvey *et al.*, 2009)

NAME	SIZE RANGE	UNITS
Pico hydro	< 5	kW
Micro hydro	5 – 100	kW
Mini hydro	0.1 – 3	MW
Small hydro	3 – 15	MW
Large hydro	> 15	MW

There are three types of hydro electric schemes (Harvey *et al.*, 2009):

1. *Run-of-the-river* hydro is the most environment friendly type. It takes water from a stream or river and puts it back into the river after the power plant; therefore it does not need a dam.
2. *Hydro schemes with storage* can store enough water to cover fluctuations in the stream flow over a day (diurnal), over a season (seasonal) or over a year (annual). Big dams or reservoirs are best avoided since the lakes of large dams submerge huge areas of land causing large-scale displacement of population in addition to environmental impacts.
3. *Pumped Hydro* in which an elevated storage is used to store water pumped using an intermittent source like wind power, so that it can be used during peak loads. An existing power plant powered by water from a high level storage like a lake can make this option financially attractive (*ibid.*).

Bio-energy

Biomass resources, bioenergy conversion technologies and usage are summarized in Table 9.

Table 9 Bioenergy Conversion Technologies and Uses

TECHNOLOGY	BIOMASS RESOURCE	USAGE
Biofuels	Sugarcane, Grains, Sugar beet for Ethanol Oil Seeds for Pure Plant Oils Plant Oils for Biodiesel	Automobile engines Power generation
Combustion	Wood Agricultural residues	Heat Steam (electricity)
Biomass Gasifier (Producer gas)	Wood chips, sawdust Agricultural residues- straw, rice husk, groundnut shells, etc.	Thermal Shaft Power Electricity
Anaerobic Digester (Biogas)	Animal wastes from farms Human wastes Sewage wastes Municipal Solid Waste – landfills	Cooking & Heating Lights Shaft Power Electricity

In a biomass gasifier, combustion takes place under a controlled supply of air resulting in a fuel gas called *producer gas* (carbon monoxide and hydrogen). Bio-degradable biomass such as animal and human wastes can be processed in an anaerobic digester in the presence of methanogenic bacteria to produce biogas which is a mixture of methane and carbon dioxide. Both gases can be used for heating and cooking. They can also substitute diesel, gasoline or natural gas for power generation.

Geothermal

Geothermal energy uses the immense heat stored within the earth. It is commonly found in regions with volcanic activity and harnesses the earth's heat energy stored in rock and in trapped vapour or liquids, such as water or brines. Geothermal energy can be used for heating and for generating electricity; it can also be used for cooling. Temperatures over 100°C are required for electricity generation, but a wider range of temperatures can be used for heating applications that include space and water heating for buildings, swimming pools, greenhouses, aquaculture and industrial processes. Adsorption chillers can use the heat to provide space cooling (International Energy Agency [IEA], 2011).

In order to use geothermal energy in a sustainable way, the rate of heat removal has to be lower than the rate at which heat is replenished from within the earth. If the rate of heat extraction is maintained below the maximum sustainable production level, constant energy production from the system is possible for 100 to 300 years (IEA, 2011).

The potential for geothermal power in the Caribbean islands has been estimated to be 10,000 MW (Brophy & Poux, 2013). In the Pacific islands, the geothermal potential of Papua New Guinea has been estimated to be 3,000 to 4,000 MW (McCoy-West *et al.*, 2011), while the potentials of Fiji, Solomon Islands and Tonga have been estimated to be 50 MW each (Asmundsson, 2008).

Low grade heat from shallow depths under the earth or from large water bodies can also be harnessed by Ground Source Heat Pumps to heat and cool buildings. Such heat pumps are also referred to as Geothermal in some parts of the world.

Ocean energy

Three main types of energy can be harnessed for power from the ocean waters:
a) Tidal Power; b) Wave Power; and c) OTEC - Ocean Thermal Energy Conversion. The different techniques used to convert these types of ocean energy are listed in Table 10.

Table 10 Ocean Energy Conversion – Types and Techniques

TIDAL	WAVE	OTEC
• Tidal Stream Generator • Tidal Barrage (can increase silting)	• Oscillating Water Column • Over topping • Floats, Pitching, Rolling	• Open cycle (working fluid) • Closed cycle (sea water) • Hybrid

Tidal power uses a dam with reversible hydro turbines that are turned by tidal waters flowing both ways. Wave power devices capture the energy of waves in open water. OTEC uses the temperature difference between the top of the ocean and the layer 30 to 40 metres below the surface to evaporate sea water or a working fluid that drives a turbine-generator. Tidal power is a proven technology, but both wave power and OTEC technologies are still in the research and pilot demonstration stage, with some projects in the early stages of commercialization (http://www.oceanenergycouncil.com/).

RE for Transport

The transport sector is more difficult to convert to renewable fuels than production of heat and electricity. Renewable energy fuels commonly used in the transportation sector are given in Table 11 together with their sources and how they are used.

Table 11 Renewable Fuels used in Transport sector (Raghavan, 2003)

FUEL	SOURCE	USAGE	REMARKS
Ethanol	• Fermentation and distillation of juices of sugarcane, sugarbeet. • Feedstock preparation is necessary for starchy (corn, potato) and cellulosic materials (wood, grass).	• Substitute gasoline in spark ignition engines. • Substitute diesel in compression ignition engines (additive is necessary).	• Used in Brazil for over 30 years. • Used in Sweden for buses for over 20 years.
Pure plant oil	• Pressing Oil Seeds such as rape seed, cotton seed, coconuts, jathropa, pongamia, etc.	• Substitute diesel in compression ignition engines (no additive is necessary).	• Local production and usage increases self-sufficiency. • Diesel engine has to be adapted.
Biodiesel	• Esterification of Plant oils.	• Substitute diesel in engines for transport & power generation.	• No adaptation required in diesel engines. • Present distribution infrastructure can be used.
Hydrogen	• Electrolysis of water using electricity produced by wind, solar or other RE sources.	• Fuel cells + electric car • Direct combustion in gas engines.	• Not yet commercialized • No Supply & Distribution infrastructure.

FUEL	SOURCE	USAGE	REMARKS
Producer gas	• Gasification of biomass such as wood, coconut shells, grass, etc.	Substitutes upto • 85% diesel in a compression ignition engine, or • 100% gasoline in spark ignition engine	• 15-20% diesel fuel required for ignition. • Gas has to be purified and compressed for storage on vehicles.
Biogas	• Anaerobic digestion of biodegradables wastes (sewage, animal & human wastes),	(same as above)	(same as above)
Electric cars	• Electricity to charge batteries must come from RE sources.	• Electric motors drive wheels.	• Limited distances. • Expensive & batteries last only 3-4 years.

Liquid fuels from biomass fall broadly under two categories: alcohols and plant oils. Biodiesel is made from plant oil by an esterification process. Pure plant oil and biodiesel can be used only in compression ignition (diesel) engines, whereas ethanol can be used in both spark ignition (gasoline) engines as well as compression ignition (diesel) engines. Biogas and producer gas can be used in compression ignition engines in a dual-fuel mode to substitute upto 85% of diesel fuel, whereas 100% gas can be used in a spark ignition (gasoline or natural gas) engine. The gases can be purified and compressed for use in automobiles.

RE for Water

Table 12 shows the main seawater desalination techniques that are based on distillation or membrane processes. In most cases, the equipment used for desalination is the same equipment used on big ships or on conventional sources of power supply on the mainland. Low-cost, appropriate technologies like solar stills can distil water directly using solar radiation. While solar stills are good for small-scale, local production of water, they are rarely used for large desalination plants because they require large areas of land.

Table 12 Seawater Desalination Processes (Raghavan, 2003)

PROCESS	EXAMPLES
Thermal Processes salt water is heated and the vapour is condensed as fresh water (distillation).	MSF - Multi-Stage Flash MED - Multi-Effect Distillation VC - Vapour Compression
Membrane Processes use the ability of membranes to separate salts from water.	ED - Electrodialysis (voltage-driven process) RO - Reverse Osmosis (pressure-driven process)

1.5 INTRODUCTION TO EMERGY AND EMBODIED ENERGY

Emergy Analysis (also known as *Emergy Accounting* or *Emergy Synthesis*) is an Environmental Accounting method that integrates all major inputs from the human economy and those coming '*free*' from the environment, to evaluate complex systems. Emergy is defined as the sum of all inputs of energy directly or indirectly required by a process to provide a given product when the inputs are expressed in the same form (or type) of energy, usually solar energy.

The amount of input Emergy (expressed as solar Emergy) per unit output energy is termed Solar Transformity. The Solar Transformity gives a measure of the concentration of solar Emergy through a hierarchy of processes or levels. Solar Emergy is usually measured in solar Emergy Joules also called solar Emjoules (sej). Solar Transformity is expressed as solar Emjoules per joule of product (sej/J) or solar Emergy joules per unit of product (e.g. sej/gram).

The first step in Emergy Analysis is to draw an Emergy System Diagram (Section 2.2.1). Secondly, an Emergy Evaluation Table (Section 2.2.2) is prepared from which the following Emergy Performance Indicators (Sec 2.2.3) are calculated to evaluate the sustainability of the given product:

- Percent Renewable Emergy (%REN) - is the ratio of renewable energy to total energy used by the production process, and indicates the sustainability of the process. An energy supply option must have a high %REN to be sustainable in the long term.

- Emergy Yield Ratio (EYR) - is the ratio of the Emergy of the process output to the Emergy of the inputs purchased from outside the system boundary. EYR is a measure of how well the process is able to exploit local resources to provide net benefits to society.
- Environmental Loading Ratio (ELR) - is the ratio of non-renewable and purchased Emergy to free renewable Emergy. ELR expresses the use of environmental services by a system and is a measure of ecosystem stress due to the entire production process for the energy supply option (i.e. coconut biodiesel in this case study).
- Emergy Index of Sustainability (EIS) - is the ratio of Emergy Yield Ratio to Environmental Loading Ratio, i.e. EYR/ELR. The EIS is a measure of the contribution of the energy supply option to the economy per unit of environmental loading.

Embodied Energy Analysis (EEA) considers only the commercial energy required directly or indirectly to provide all the inputs (goods and services) for the entire biodiesel production process (Section 2.3). The Energy Return on Energy Invested (EROEI) calculated by the EEA is a number that gives the Joules of biodiesel produced (Energy Return) from using one Joule of input energy (Energy Invested). The carbon dioxide (CO_2) emissions during the production of biodiesel are then estimated by multiplying the total Embodied Energy of biodiesel in 'kg oil equivalent' by the CO_2 emissions per kg of petroleum oil.

In comparisons of energy systems, the most sustainable on the long term will have highest %REN, EYR, EIS and EROEI, and the lowest ELR and CO_2 emissions.

1.6 LITREATURE REVIEW

The newly created International Renewable Energy Agency (IRENA) based in the United Arab Emirates has carried out a series of excellent studies on renewable energy resources and technologies as well as regional assessments and country profiles:

1. *Renewable Power Generation Costs in 2012: An Overview (*IRENA, 2013*)*
2. *Renewable Power Generation Costs - Summary for Policy Makers (*IRENA, 2012a*)*
3. *Policy Challenges for Renewable Energy Deployment in Pacific Island Countries and Territories (*IRENA, 2012b*)*
4. *Renewable Energy Country Profiles: Pacific (*IRENA, 2012c*)*
5. *Electricity Storage and Renewables for Island Power - A Guide for Decision Makers (*IRENA, 2012d*)*
6. *Concentrating solar power (*IRENA, 2012e*)*
7. *Biomass for Power Generation (*IRENA, 2012f*)*
8. *Hydropower (*IRENA, 2012g*)*
9. *Solar Photovoltaics (*IRENA, 2012h*)*
10. *Wind Power (*IRENA, 2012i*)*

These reports are based on a comprehensive analysis of around 8,000 medium to large-scale commissioned or proposed renewable power generation projects from a range of data sources. IRENA highlights that for off-grid power supply, renewables are already the default economic solution. For new grid supply and grid extension, renewables are increasingly becoming the most competitive option.

100% Renewable Energy Islands in Tuvalu, Fiji and Tonga (Raghavan, 2003) is a case study of eleven islands in three Pacific island countries that proposes a plan for making them totally free of fossil fuels. All the renewable energy resources have been evaluated and appropriate technologies are then proposed so that the heat and electricity requirements of these eleven islands can come solely from renewables. *Action Plan for Providing 100% of the Energy Requirements of Lakshadweep Islands from RES* (Raghavan & Kishore, 2001) is a similar study for seven inhabited islands of the Lakshadweep archipelago in the Arabian Sea.

A comprehensive coverage of all aspects of the planning and implementation of micro-hydro power generation and distribution for developing countries is found in *Micro-Hydro Design Manual* (Harvey *et al.*, 2009). This manual covers the design of the overall micro-hydro power scheme including site assessment, as well as design and data for all components of the scheme. Case studies from many developing countries highlight potential problems during implementation at remote sites and how to overcome them.

Key findings in the International Energy Agency's *Technology Roadmap - Geothermal Heat and Power* (International Energy Agency, 2011) include the status and prospects for geothermal heat and electricity, required policy framework and research & development priorities. The roadmap then proposes seven key actions required over the next ten years to tap the full potential of geothermal resources. McCoy-West *et al.* (2011) studied 20 Pacific Island nations and territories and short-listed eight having high and moderate potential for future pre-feasibility geoscientific exploration, risk evaluation (for resource capacity, hazard and financial modeling), and assessment for small (including off-grid) plant development.

Beginning in the 1950s, Prof. H.T. Odum recognized the principles of energy quality as an outgrowth of his investigations and simulation modelling of ecosystems of humans and nature. This led to the first formal recognition of energy quality in 1971 in his book *Environment, Power and Society* (Odum, 1971). In this book, Odum introduced the Energy Systems Language — a visual mathematics tool that provides an overview of the energy system studied — and developed the concept of ecological engineering. Moreover, he explored the interrelationships of energy and environment, and their importance to the well-being of humanity and the planet. Odum was working on the final revision of the manuscript of the second edition *of Environment, Power and Society* when he passed away in 2002. The manuscript was finalised and published by his wife Elizabeth Odum and his colleagues Mark Brown and Dan Campbell as *Environment Power and Society for the 21st Century – The Hierarchy of Energy* (Odum, 2007). In this edition, Odum included the concepts of Emergy and Transformity.

From 1971, Odum's thinking evolved for twenty five years, and in 1996 he published his comprehensive treatise on Emergy as a measure of real wealth in *Environmental Accounting: Emergy and Environmental Policy Making* (Odum, 1996). Odum describes in detail the basic principles of Emergy Analysis and all its major applications, and provides a rational approach to evaluating commodities, services and environmental goods. Chapter 1 introduces the lens of systems overview, and its use to evaluate Emergy. Chapter 2 contains the scientific basis of the Emergy concept in the natural energy hierarchy of the universe. Chapter 3 estimates the Emergy budget of the earth. Chapter 4 relates Emergy and money. Chapter 5 summarizes the procedure for making an Emergy evaluation table. Then several chapters show how to use Emergy to evaluate environments, minerals, waters, primary energy sources, economic developments, nations and international trade. Chapter 13, concerning the time dimension, considers how Emergy oscillates according to scales of size and time. Chapter 14 contains comparisons with other approaches and responses to criticisms, and Chapter 15 suggests areas for fruitful applications to policy.

Data required for Emergy computations have been published in a series of five folios:

- *Folio #1: Introduction and Global Budget* (Odum *et al*., 2000)
- *Folio #2: Emergy of Global Processes* (Odum, 2000)
- *Folio #3 - Emergy of Ecosystems* (Brown & Bardi, 2001)
- *Folio #4 - Emergy of Florida Agriculture* (Brandt-Williams, 2002)
- *Folio #5 - Emergy of Landforms* (Kangas, 2002).

A complementary methodology is Embodied Energy Analysis which measures Energy Return on Energy Invested (EROEI) and carbon dioxide (CO_2) emissions. Brown & Ulgiati (2004) compare the two approaches. They present a brief synopsis of the Emergy Analysis methodology in *Emergy Analysis and Environmental Accounting* and use several case studies of energy conversion systems (oil plant, wind, geothermal, OTEC[10], hydropower) to illustrate the critical difference between Emergy Analysis and Embodied

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[10] Ocean Thermal Energy Conversion

Energy Analysis. In *Embodied Energy Analysis and EMERGY analysis: a comparative view*, Brown & Herendeen (1996) give details of the Emergy accounting procedures and discuss differences and similarities between Embodied Energy Analysis and Emergy Analysis by using the two approaches to analyze the same systems. In *Energy analysis and EMERGY analysis—a comparison*, Herendeen (2004) gives a detailed comparison of the two accounting procedures.

In *Sustainable Biomass Production: A Comparison between Gross Energy Requirement and Emergy Synthesis Methods*, Franzese *et al.* (2009) compare two cropping systems (corn production in Italy and willow production in Sweden) by means of the parallel application of both methods. Because corn production is more energy intensive than growing willow trees, they found that the EROEI (Energy Return on Energy Invested) of corn (3.82) is only one-fifth the EROEI of willow (19.50). The energy intensive nature of corn production is also reflected in the transformity of corn (7.34E+04 seJ/J) being more than four times that of willow (1.62E+04 seJ/J).

Brown & Ulgiati (2002) use Emergy and Embodied Energy Accounting techniques to compare six power generating systems in *Emergy Evaluations and Environmental Loading of Electricity Production Systems*: three renewable (geothermal, hydroelectric, wind) and three fossil fired (natural gas, oil, coal thermal). They found that:

1. The renewable power plants had the highest %REN (percent renewable energy) — wind (86.61), geothermal (69.67), and hydro (68.84) — but the fossil fuel plants all had %REN of less than 10%. Brown & Ulgiati note that fossil thermal power plants have a non-negligible fraction of renewable inputs (6.56% to 8.79%) because of vital renewable inputs to power plant activity such as the oxygen supply to the combustion process, which is renewed by solar radiation driving the photosynthesis of green plants. Other renewable inputs to power plant activity include cooling water from the river or sea, and wind needed for dispersal of smoke and other airborne contaminants.
2. Emergy Yield Ratio (EYR) varied from a high of 7.6 for hydroelectric generation to the lowest rating of 4.2 for the oil fired thermal plant. The low EYR of the

geothermal system (4.81) indicates a high emergy content of the resources invested from outside.

3. Environmental Loading Ratio (ELR) of the oil fired plant (14.24) and the coal plant (11.37) were found to be very high whereas the renewable energy systems had lower and therefore more desirable ELRs, all less than 1.0.
4. Emergy Index of Sustainability (EIS) of the wind power plant (48.30) is the highest followed by the hydroelectric plant (16.90) and the geothermal plant (11.05). All the fossil fuel plants had EIS less than 1.0.
5. The renewable power plants — hydroelectric (23.81)and geothermal (20.83) — have the highest and therefore most desirable EROEI, whereas the fossil fired plants have the lowest — methane plant (0.36) and coal plant (0.25).
6. As expected, they found high CO_2 emissions from the fossil fired power plants — coal (1109 g CO_2 /kWh), oil (923 g CO_2/kWh) and methane (759 g CO_2/kWh) — compared to renewable energy power plants hydropower (12 g CO_2/kWh) and wind (36 g CO_2/kWh). However, the geothermal power plant (655 g CO_2/kWh) has high CO_2 emissions due to the carbon dioxide in deep aquifer waters that are used as the steam source and then vented to the atmosphere through cooling towers.

To evaluate the environmental impact of biodiesel production from soybean in Brazil, Cavalett & Ortega (2010) have used environmental impact indicators from Emergy Analysis (EA), and Embodied Energy Analysis (EEA) in *Integrated environmental assessment of biodiesel production from soybean in Brazil*. The EEA gave an energy return of 2.48 J of biodiesel per Joule of fossil fuel invested, and carbon dioxide emissions of 0.86 kg of CO_2 per litre of biodiesel. The EA found that the Transformity of biodiesel (solar emergy in solar emjoules (seJ) per joule of product) is 3.90E+05 seJ/J [11], EYR is 1.62 and %REN is 31%. Taking into consideration all the performance indicators, Cavalett & Ortega conclude that in spite of a possible contribution to reducing CO_2 emissions, soybean biodiesel is not a viable alternative to petroleum diesel.

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[11] Numbers in this study are given in the scientific notation. 3.90E+05 seJ/J = 3.90 x 10^5 = 390,000 seJ/J

In *Critical Analysis of the Swedish Biofuel Policy using Emergy Synthesis,* Cavalett & Rydberg (2010) use Emergy Analysis to analyse biofuels promoted by Swedish energy policies. They evaluated three different biofuels in Sweden: Ethanol from wheat (Transformity = 9.19E+04 seJ/J, %REN = 12%, EYR = 1.15); Methanol from willow (Transformity = 6.06E+04 seJ/J, %REN = 10%, EYR = 1.11) and Biodiesel from rapeseed (Transformity = 13.6E+04 seJ/J, %REN = 11%, EYR = 1.27). They also evaluated ethanol production in Brazil from sugarcane (Transformity = 7.07E+04 seJ/J, %REN = 19%, EYR = 1.38) because it is promoted by the Swedish Government. Their main findings are: a) Ethanol from sugarcane in Brazil has a lower Transformity and a higher %REN than biofuels produced in Sweden; and b) All three biofuels are heavily dependent on non-renewable resources and have higher Transformities than fossil fuels. Cavalett & Rydberg conclude that none of the analyzed biofuels can be considered a sustainable substitute for fossil fuels due to their very low Emergy Yield Ratio and low %REN.

Jarméus (2013) uses Emergy Analysis to compare the production of biodiesel with biogas from algae, in his Master's thesis on *Emergy Analysis of Biodiesel and Biogas Production from Baltic Sea Macro Algae*. His evaluation included all processes from harvesting of the algae, transport of the algae to the processing plants, and processing of the algae to biodiesel or biogas. He found the Transformity for biogas (9.12E+04 seJ/J) to be an order of magnitude lower than the transformity for biodiesel (5.04E+05 seJ/J). However, Jarméus found that the emergy performance indicators for biodiesel were better than for biogas. The Emergy Yield Ratio for biodiesel (6.44) was found to be higher than biogas (3.66), the Environmental Loading Ratio for biodiesel (0.184) was lower than biogas (494); and the Percent Renewable Energy for biodiesel (84%) is higher than biogas (67%).

Paoli *et al.* (2008) used Emergy Analysis to compare two different solar technologies in *Solar power: An approach to transformity evaluation*. Solar thermal collectors for heat were found to be a much more sustainable way of using solar energy when compared to solar photovoltaics for electricity because they have a lower Transformity, a higher

Percent Renewable Energy, a higher Emergy Yield Ratio and a lower Environmental Loading Ratio.

Brown & Ulgiati (1997) provide a reference set of indices based on Emergy for the evaluation of eco-technological processes and whole economies in *Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation*. They stress indices such as Emergy yield ratio, environmental loading ratio and Emergy investment ratio, and then define a new index: the Emergy sustainability index. The Emergy indices are shown to be functions of renewable, non-renewable and purchased Emergy inflows. The usefulness of the indices is demonstrated for several ecological engineering activities (including oil spill restoration, land reclamation and wastewater recycle through wetlands), several production systems and several national economies.

Raghavan (2005) evaluates the major biomass resources in small island countries in *Biofuels in Small Island Developing States*, and describes the technologies that can be used to harness this renewable resource. The percentage of power generation that can be substituted by power from biofuels is also given. *Biofuels from Coconuts* (Raghavan, 2010) evaluates the potential for power generation from all parts of the coconut palm in the major coconut growing countries, and provides technical details of the biofuels technologies. *Developing a Biofuels Industry in Fiji* is a Cabinet Strategy Paper prepared for the Government of the Fiji Islands by Binger *et al*. (2005) that studies the two major biomass resources of Fiji (coconuts and sugarcane) and proposes a phased action plan to develop a biofuels industry in the Fiji Islands.

In *Biofuel from Coconut Resources in Rotuma - A Feasibility Study on the Establishment of an Electrification Scheme using local Energy Resources*, Zieroth *et al*. (2007) use GIS[12] to assess the coconut resource on the island of Rotuma in the Fiji Islands and provide a detailed description of the techno-economic feasibility of substituting biofuel for diesel power generation all over the island. Of the total coconut production of 7.5 million nuts

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[12] Geographical Information System

per annum on the island of Rotuma, they found that 5 million nuts could be harvested. After allowing for traditional local consumption (1.5 million nuts) they estimated 3.5 million nuts to be available for coconut oil (CNO) production. Zieroth *et al*. calculated that the potential CNO production (690,000 litres) represents a diesel equivalent of approximately 635,000 litres, which is more than three times Rotuma's estimated annual diesel fuel consumption of 184,000 litres. Moreover, they expect that the production of CNO on the island could be significantly increased through a coconut palm rehabilitation program that would include replanting and refurbishment of old plantations.

ERIA (2010) carried out a sustainability assessment of four biomass resources being developed on a large scale in East Asia, in *Sustainability Assessment of Biomass Energy Utilisation in Selected East Asian Countries.* The four biomass resources assessed in this study are: a) Biodiesel from Jatropha in India; b) Biodiesel from Jatropha in Indonesia; c) Bioethanol from Cassava in Thailand; and d) Biodiesel from Coconut in the Philippines. To assess the sustainability of biofuel production, ERIA used Greenhouse Gas Emissions (GHGs) as an indicator of environmental impacts, total value added (TVA) as an indicator of economic impacts, and Human Development Index (HDI) as an indicator of social impacts. ERIA's main findings in this study are:

1. For production of biodiesel from coconuts in the Philippines, copra production has the highest net profit, whereas biodiesel production has the lowest net profit. The use of coconut biodiesel to replace petroleum diesel in the Philippines results in emissions reduction of 2.8 tons CO_2 per ha per year. The majority (66%) of coconut farmers in the Philippines as well as a majority of employees in the biodiesel plant noticed an improvement in their living conditions due to the production of coconut biodiesel.
2. Jatropha production in India is not economically viable because the cost incurred during the cultivation stage is much higher than the revenue generated. Both TVA and net profit are quite attractive for the biodiesel production stage, as long as the Jatropha oil seeds are available at a reasonable price.

3. Indonesian farmers cultivating Jatropha for biodiesel benefit only a little from the cultivation stage, but utilization of Jatropha waste for producing biogas increased their earnings significantly.
4. Economic assessment of the bioethanol production process in Thailand indicates that it is economically viable. In spite of a lower social development than employees at the biorefinery complex, sugarcane farmers benefit from contract farming for the sugar-ethanol plant because it provides an assured source of annual income.

The ERIA study provides an excellent economic assessment of the biofuels studied. However, it does not evaluate all the environmental impacts of the biofuels production process. Even while calculating life cycle greenhouse gas emissions, the ERIA study does not consider emissions associated with manufacturing of machines and vehicles, constructing irrigation structures, buildings, infrastructures, etc. as well as manual labour for new planting, pruning, harvesting, machine operating, driving, etc. On the other hand, the Emergy analysis carried out in this study evaluates all the environmental impacts in a comprehensive manner by taking into account all direct and indirect inputs to the entire biofuel production process.

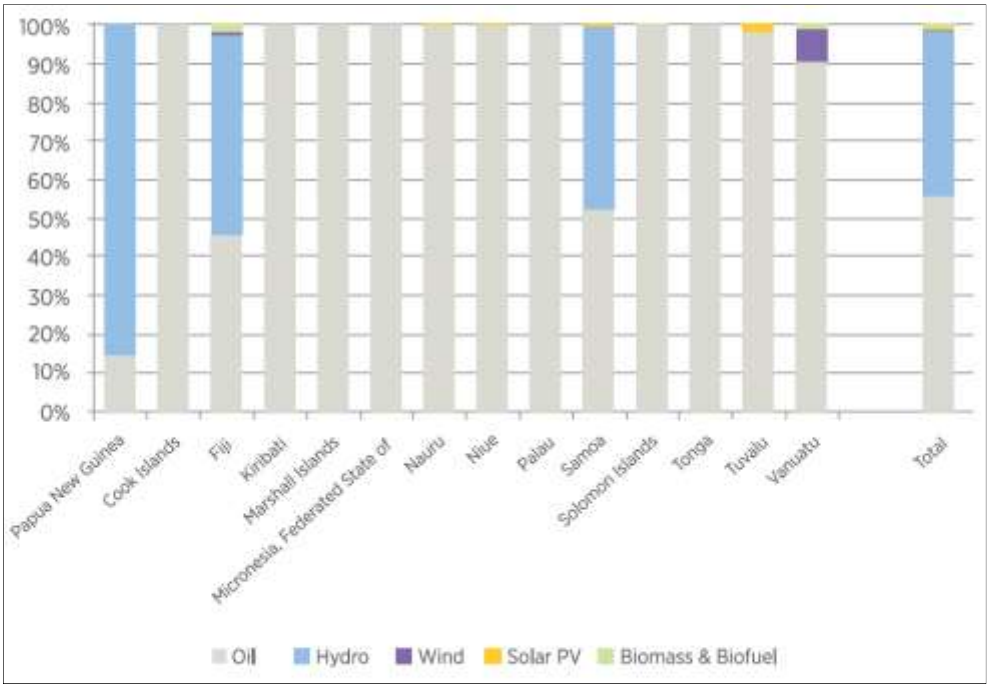
2 EMERGY ANALYSIS METHODOLOGY

2.1 COCONUT BIODIESEL AS AN ALTERNATIVE FUEL FOR POWER GENERATION IN FIJI

2.1.1 Rationale

Diesel and heavy fuel oil are widely used in the Pacific Island Countries (PICs) for power generation. In 2010, about 80% of the primary energy consumption in PICs came from oil. About 75% of the oil consumed is used for transportation and more than 20% is used for electricity generation (Figure 8) (IRENA, 2012b).

Figure 8 Gross Electricity Generation by Source for Main Grids in Pacific Islands in 2010 (IRENA, 2012b)



On the other hand, most Pacific islands have abundant resources of coconuts from which coconut oil can be produced (Table 13). The coconut oil can be transformed by a process called esterification into biodiesel that can be used as a direct substitute for diesel fuel (Krishna *et al.*, 2009; Raghavan, 2005).[13]

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[13] Most of the properties of coconut oil and diesel fuel are similar but coconut oil is more viscous than diesel and its combustion characteristics are different from those of diesel. Unless the diesel engine is modified properly for use with pure coconut oil, long term testing on the direct use of coconut oil as a

Table 13 Coconut Production in Pacific Island Countries in 2007 (Krishna *et al.*, 2009)

COUNTRY	COCONUT PRODUCTION (tons)	AREA HARVESTED (ha)	COCONUT YIELD (tons/ha)	COCONUT OIL PRODUCTION (tons)
American	4,700	2,200	2.14	65
Cook	2,000	730	2.74	0
Fiji	140,000	50,000	2.8	9,500
French	87,000	20,000	4.35	4,300
Guam	53,200	9,600	5.54	1,200
Kiribati	110,000	29,000	3.79	1,900
F.S.M	41,000	16,600	2.47	2,950
New	16,500	2,800	5.89	90
Papua New	677,000	203,000	3.33	57,000
Samoa	146,000	21,700	6.73	4,550
Tokelau	3,000	600	5	30
Tonga	58,500	8,300	7.05	1,100
Tuvalu	1,700	1,700	1	20
Vanuatu	322,000	76,000	4.24	12,500

For this case study, two Environmental Accounting methods (Emergy Analysis and Embodied Energy Analysis) will be applied to the production of biodiesel from coconuts — also called Coconut Biodiesel — to determine if it is a sustainable energy option.

2.1.2 Site Description: Fiji Islands

Fiji Islands has been chosen for this case study because:

- Fiji uses large amounts of diesel and heavy fuel oil for power generation. In 2010, 50% of power generated by the Fiji Electricity Authority (FEA), equal to 415,130 MWh of electricity, came from diesel power plants that used 86,610 tons of diesel and heavy fuel oil (Fiji Electricity Authority, 2011).

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diesel fuel substitute has shown that it damages the diesel engine due to deposits formed by incomplete combustion and polymerisation (Vaitilingom 2008, Krishna *et al.*. 2009, Uriarte 2010).

- Fiji has abundant coconut resources. Biodiesel made from locally produced coconut oil could potentially replace about 20% of Fiji's entire diesel consumption (Cloin, 2006).
- Reliable data for diesel fuel used for power generation and for coconut production is available.
- Fiji Islands has a Biofuels Development Program for substituting imported petroleum fuels with locally produced biofuels, including biodiesel from coconut oil (Binger *et al.,* 2005). The National Energy Policy of the Fiji Islands aims at 90% renewables for the electricity sector by 2015 (59% from hydropower, 30% from biomass and 1% from windpower) (Nakavulevu, 2011).

The Fiji archipelago, lying between 16 and 20 degrees south of the equator, consists of 332 islands, mostly volcanic in origin, of which only 105 islands are inhabited. The land area of the Fiji Islands is 18,333 km^2 and its Exclusive Economic Zone is 1.26 million km^2. The two largest islands comprise 87% of the total land area: Viti Levu (10, 390 km^2) and Vanua Levu (5,538 km^2). The maximum height above sea level is 1,324 metres (South Pacific Applied Geoscience Commission [SOPAC], 2002). The population in 2010 was 861,000, 94% of whom live on the two main islands of Viti Levu and Vanua Levu (IRENA, 2012c).

The climate is tropical oceanic with tempering influences from the prevalent southeast trade winds. Average rainfall in the wet, windward sides of the islands is 2,625 mm/annum (World Bank, 2014b) but the rainfall in the drier, leeward sides can be as low as 440 mm/annum. The mean annual temperature is 28°C. The main natural hazards are cyclones, storm surges, coastal flooding, river flooding, drought, earthquakes, landslides, tsunami and volcanic eruptions (SOPAC, 2002).

The GDP in 2012 was 3.9 billion US$ with a per capita GDP of 4,459 US$ per annum (World Bank, 2014a). The economic base is diverse with a strong tourism sector plus sugar, agriculture, garment and mining industries. Exports include sugar, garments, gold, coconut products, tropical fruits, root crops, vegetables, tobacco, fish, and timber products (SOPAC, 2002).

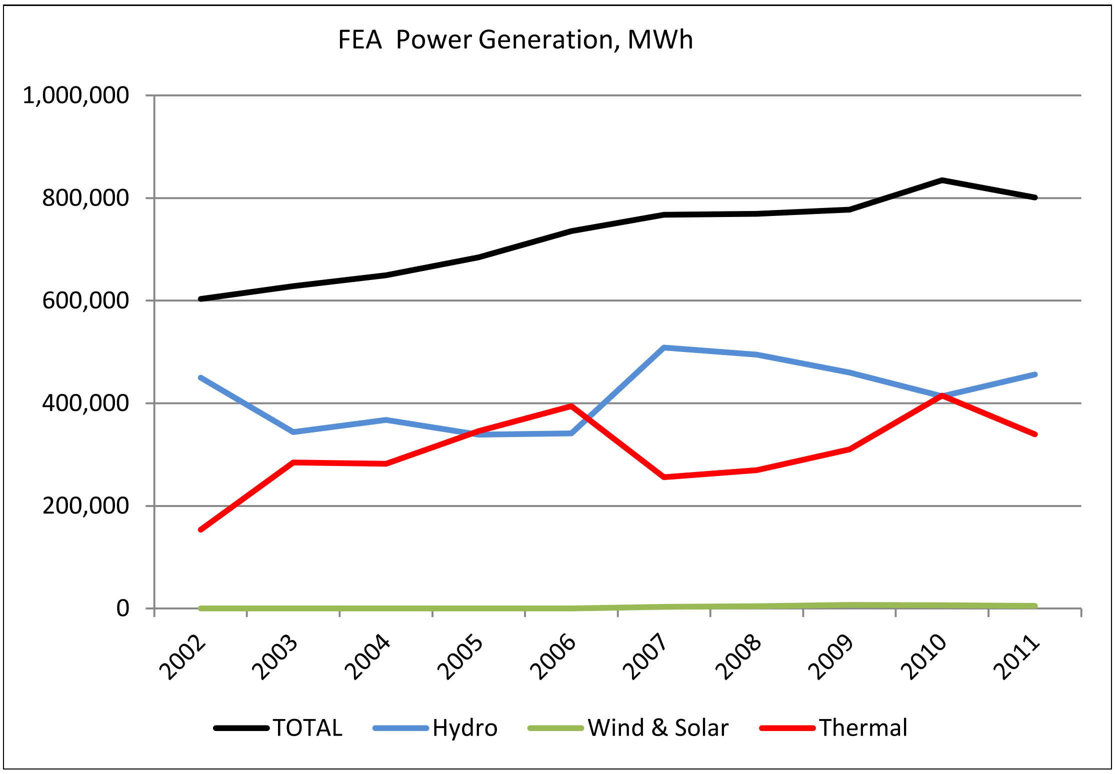
2.1.3 Power Generation in Fiji

During the ten year period 2002 to 2011, the share of thermal power (generated using diesel and heavy fuel oil) in the Fiji Electricity Authority's total generation mix varied from a low of 25% in 2002 to a high of 54% in 2006 (Table 14). The total power generation showed an average annual growth rate of 4.2% with a maximum growth rate of 7.4% in 2010 (Fiji Electricity Authority, 2011).

Table 14 Power Generation in the Fiji Islands (Fiji Electricity Authority [FEA], 2011)

Years	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
TOTAL, MWh	603,709	628,359	649,558	684,773	735,622	767,827	769,439	777,327	835,169	801,206
Hydro, MWh	450,198	343,729	367,357	338,739	341,255	508,486	495,090	460,192	413,619	456,469
Wind & Solar, MWh	10	9	6	2	4	3351	4604	7211	6420	4,977
Thermal[14], MWh	153,501	284,621	282,195	346,033	394,364	255,989	269,745	309,924	415,130	339,760
Thermal, % of Total	25%	45%	43%	51%	54%	33%	35%	40%	50%	42%

Figure 9 Power Generation by the Fiji Electricity Authority, 2002 – 2011 (FEA, 2011)



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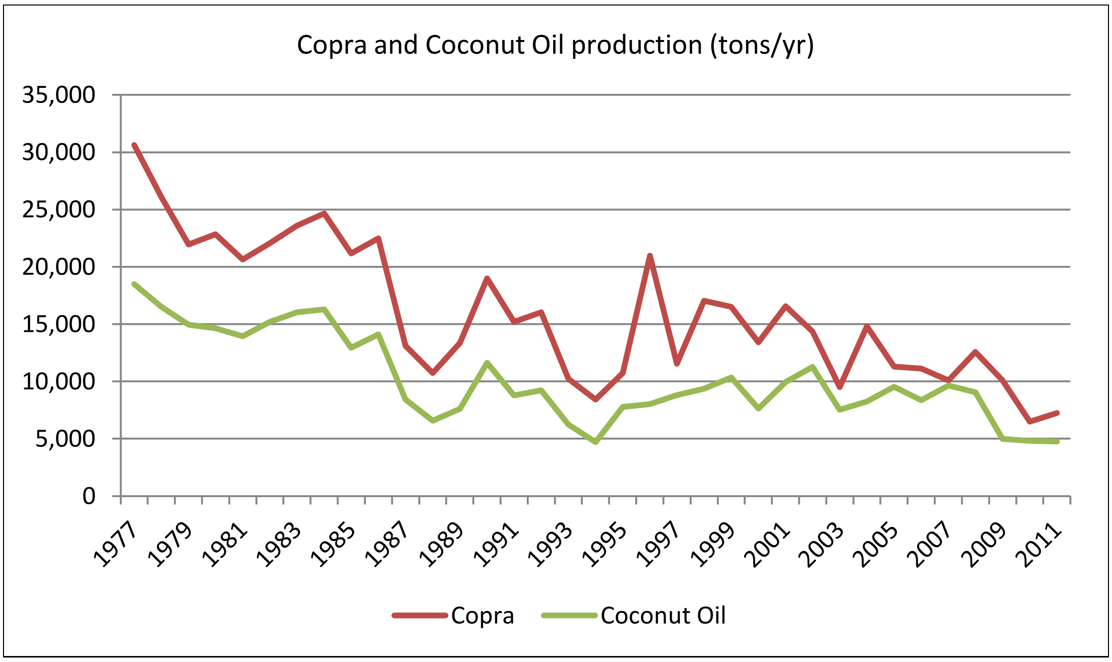
[14] Thermal power in the Fiji Islands is generated from diesel and heavy fuel oils.

Over 90% of FEA's hydropower generation comes from the 80 MW Monasavu hydel project. The annual rainfall that fills the Monasavu reservoir determines the maximum quantity of hydropower that can be generated during that year. After using all the available hydropower, FEA then generates enough thermal power to meet the loads. The quantity of thermal power generated is therefore inversely proportional to the hydropower generated (Figure 9) (Binger *et al.,* 2005).

2.1.4 Coconut production in Fiji

Over the last 35 years, there has been a decline in production of copra and coconut oil as shown in Figure 10. During the period 1977 to 2011, copra production in the Fiji Islands fell from a maximum of 30,600 tons/yr in 1977 to less than 6,500 tons/yr in 2010, while the production of coconut oil fell from 18,500 tons/yr in 1977 to 4,765 tons/yr in 2011 (Fiji Bureau of Statistics, 2012). However, the potential for coconut oil production is higher since significant quantities of coconuts are not harvested on many of the islands in Fiji (Zieroth *et al.,* 2007).

Figure 10 Copra and Coconut oil production in the Fiji Islands (Fiji Bureau of Statistics, 2012)



The Fiji National Agricultural Census (2009) gives the plantation area under coconuts as 15,009 ha[15]. Taking a conservative yield of 3 tons copra per ha, and an oil extraction of 600 litres of coconut oil per ton of copra, the potential coconut oil production is 27 million litres per annum (Singh, 2012). This quantity of coconut oil is equivalent to 23.5 million litres of diesel fuel[16].

2.2 EMERGY ANALYSIS

While comparing the sustainability of energy sources in order to select the best option, it is necessary to take into account quantitatively all the energy inputs as well as the environmental services that are used. *Emergy Analysis* (also known as *Emergy Accounting* or *Emergy Synthesis*) is an Environmental Accounting method that integrates all major inputs from the human economy and those coming '*free*' from the environment, to evaluate complex systems. Emergy theory was developed over a period of nearly 30 years by Professor H.T. Odum and his colleagues in the University of Florida at Gainesville to evaluate complex systems holistically. The principles of Emergy theory and its applications are described clearly in Odum's landmark book *Environmental Accounting: Emergy and Environmental Policy Making* (Odum, 1996).

> Emergy is defined as the sum of all inputs of energy directly or indirectly required by a process to provide a given product when the inputs are expressed in the same form (or type) of energy, usually solar energy. Most often, inputs to a process are the result of another process (or a chain of processes), in which energy has been concentrated and upgraded. Thus Emergy is derived by summing all inputs (expressed in equivalent energy of a single form; such as solar energy) used in the chain of processes that yielded the output in question. On a unit basis, one joule or gram of a given output is produced by dissipating a given amount of solar equivalent energy. The amount of input Emergy (expressed as solar Emergy) per unit output energy is termed, 'solar transformity'. The solar

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[15] hectares

[16] The energy content of one litre of coconut oil is equal to 0.87 litres of diesel fuel (Binger *et al*., 2005).

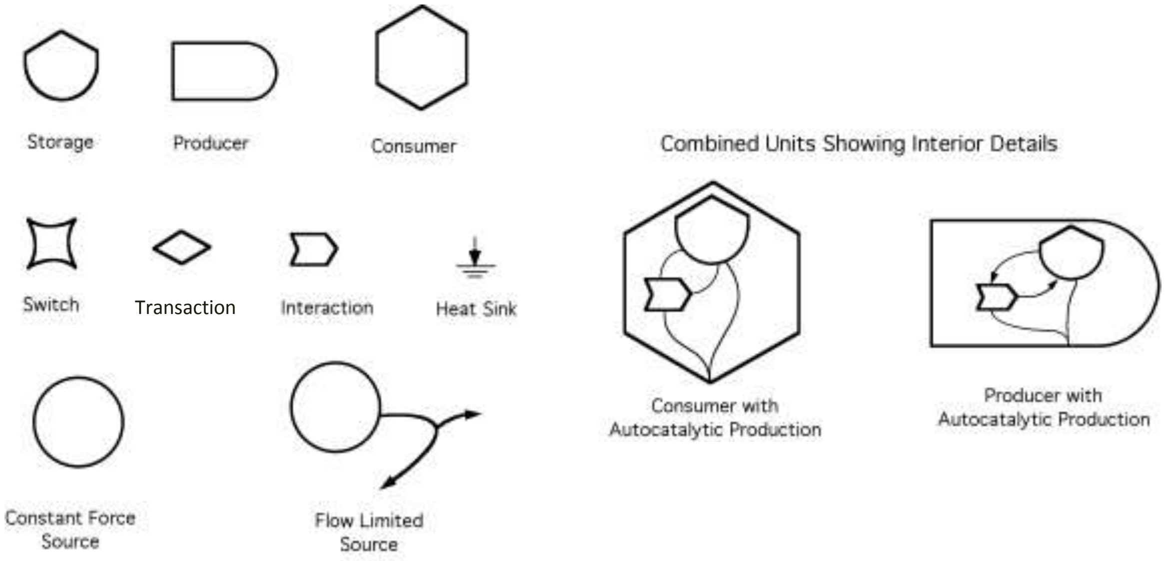
> transformity gives a measure of the concentration of solar Emergy through a hierarchy of processes or levels; it can therefore be considered a quality factor, a measure of the global process supporting the item under study. Once transformities are known for classes of items, the total Emergy of an item can be expressed as:
>
> Emergy = Available Energy of item x Transformity.
>
> Solar Emergy is usually measured in solar Emergy joules (sej), while solar transformity is expressed as solar Emergy joules per joule of product (sej/J). When an item is expressed in other units than joules, e.g. grams, the quality factor is energy/mass (sej/g). (Brown & Ulgiati, 1997, p. 54)

There are 3 main steps to evaluate a system:

1. Emergy System Diagram is drawn.
2. Emergy Evaluation Table is constructed from the diagram, incorporating all the resources, labour and energy used in the process.
3. Emergy Performance Indicators are calculated and used to interpret the quantitative results.

2.2.1 Emergy System Diagram

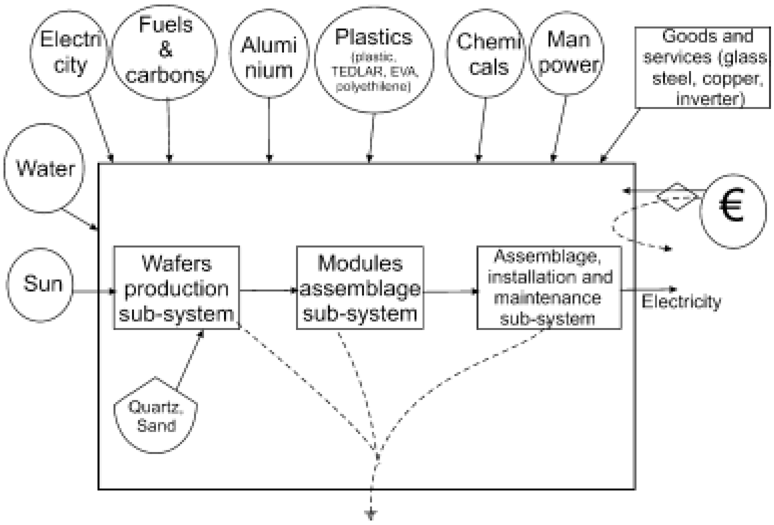
Figure 11 Emergy Systems Symbols (www.Emergy.org)



Basic symbols used in an Emergy systems diagram (Source, Storage, Interaction, etc.) are shown in Figure 11. These symbols are used to form increasingly complex symbols like Producer and Consumer. In this way, highly complex ecological systems can be represented by around 20 symbols, making it easy to understand interactions between major components of the ecosystem (www.Emergy.org).

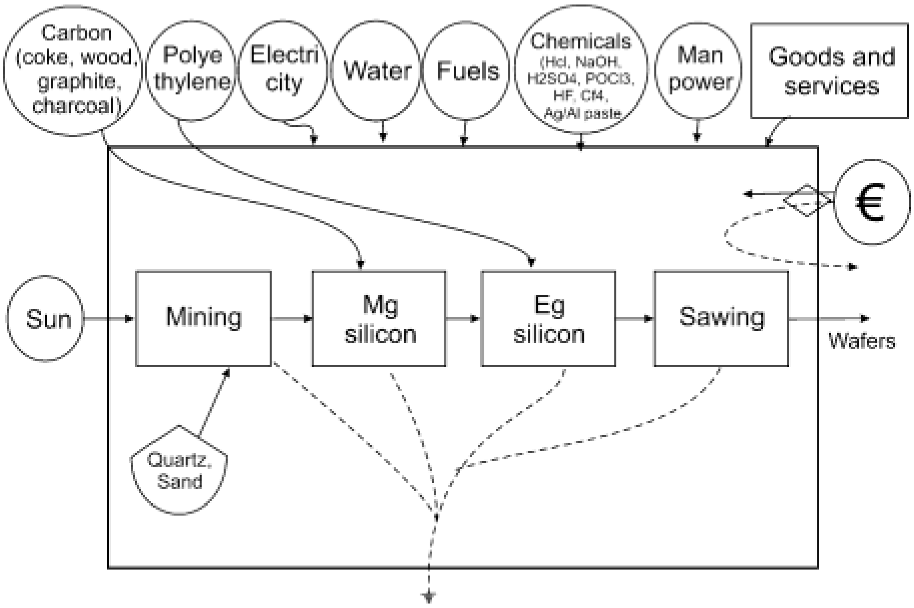
Figure 12 shows a system diagram for the production of solar photovoltaic (PV) panels. There are three sub-systems in the production of PV panels: a) Wafer Production, b) Module Assemblage, and c) Assemblage, Installation and Maintenance. The final product of the rectangular system boundary is electricity shown on the right. Outside the rectangular system boundary are the circles that are sources for inputs used by the solar PV panels. On the left are the free inputs from the environment such as sunlight and water. On the top are the labour and material inputs such as fuels, electricity, manpower, for which transactions (diamond shape) are required, mostly financial.

Figure 12 System Diagram for Electricity Production from SPV modules (Paoli *et al.*, 2008)



In order to keep a system diagram from getting too complex, sub-systems are shown as boxes. Another system diagram is drawn for each sub-system where the details are shown. The system diagram of the Wafer Production sub-system is shown in Figure 13. Quartz /sand is shown as a non-renewable storage which is mined to provide the silicon raw material for the wafers. The final product of this system is shown on the right as silicon wafers which is also the product of Wafer Production sub-system of Figure 12.

Figure 13 System Diagram for Production of PV silicon wafers (Paoli *et al.*, 2008)



2.2.2 Emergy Evaluation Table

Table 15 shows the Emergy evaluation table for production of silicon wafers according to the system diagram shown in Figure 13 (Paoli *et al.*, 2008).

- Column-C lists all the inputs that go into the process, and Column-B gives the source of the inputs:
  - Sun light is a free renewable input, so it is 100%R;
  - Quartz /silica sand is a free non-renewable input, so it is 100%N;
  - Coke, charcoal, etc. are purchased outright from the main economy, so 100%F;
- Column-D gives the ‘Quantity per panel’ of each input used in the production of one panel.
- Column-E gives the ‘Transformity’ of each input. Transformity values may be available from past work in the literature; otherwise they have to be estimated or calculated.
- Column-F is the ‘Emergy per panel’ calculated as the product of D x E.

- Column-G is the ‘Empower per panel’. This is the Emergy per panel per year. The lifetime of the panels is 20 years, so this is F / 20.
- Column-H is the ‘Empower per plant”. The plant consists of 215 panels, so this is G x 215.

Table 15 Emergy Evaluation Table for SPV Wafer Production Sub-system (Paoli *et al.*, 2008)

A	B	C	D	E	F	G	H
ITEM			**QUANTITY PER PANEL**	**TRANSFORMITY (sej / unit of quantity)**	**EMERGY PER PANEL (sej / panel)**	**EMPOWER PER PANEL (sej / panel /year)**	**EMPOWER PER PLANT (sej / plant /year)**
T0	100%R	Sun	6.58E+10	1	6.58E+10	3.29E+09	7.08E+11
1	100%N	Quartz/ silica sand	2.84E+03	1.00E+09	2.84E+12	1.42E+11	3.06E+13
2	100%F	Coke	1.11E+07	4.00E+04	4.43E+11	2.22E+10	4.76E+12
3	100%F	Charcoal	2.41E+07	1.06E+05	2.56E+12	1.28E+11	2.75E+13
4	100%F	Graphite	1.30E+02	3.15E+09	4.09E+11	2.04E+10	4.39E+12
6	100%F	Poly-ethylene	6.36E−01	5.87E+09	3.73E+09	1.87E+08	4.01E+10
7	100%F	HCl	5.99E+02	3.64E+09	2.18E+12	1.09E+11	2.34E+13
8	100%F	NaOH	5.80E+00	1.90E+09	1.10E+10	5.51E+08	1.18E+11
9	100%F	H_2SO_4	4.30E+00	3.64E+09	1.57E+10	7.83E+08	1.68E+11
10	100%F	$POCl_3$	6.00E−02	1.01E+09	6.06E+07	3.03E+06	6.51E+08
11	100%F	HF	1.10E+00	9.89E+08	1.09E+09	5.44E+07	1.17E+10
12	100%F	CF4	7.00E−02	1.01E+09	7.07E+07	3.54E+06	7.60E+08
13	100%F	Ag/Al paste	6.00E−01	1.69E+10	1.01E+10	5.07E+08	1.09E+11
14	100%F	Natural gas	1.22E+08	4.80E+04	5.84E+12	2.92E+11	6.28E+13
15	100%F	Electricity	7.49E+08	1.74E+05	1.30E+14	6.51E+12	1.40E+15
T1	TOTAL						1.57E+15

Note: Numbers in this study are given in the scientific notation. 6.58E+05 = 6.58 x 10^5 = 658,000

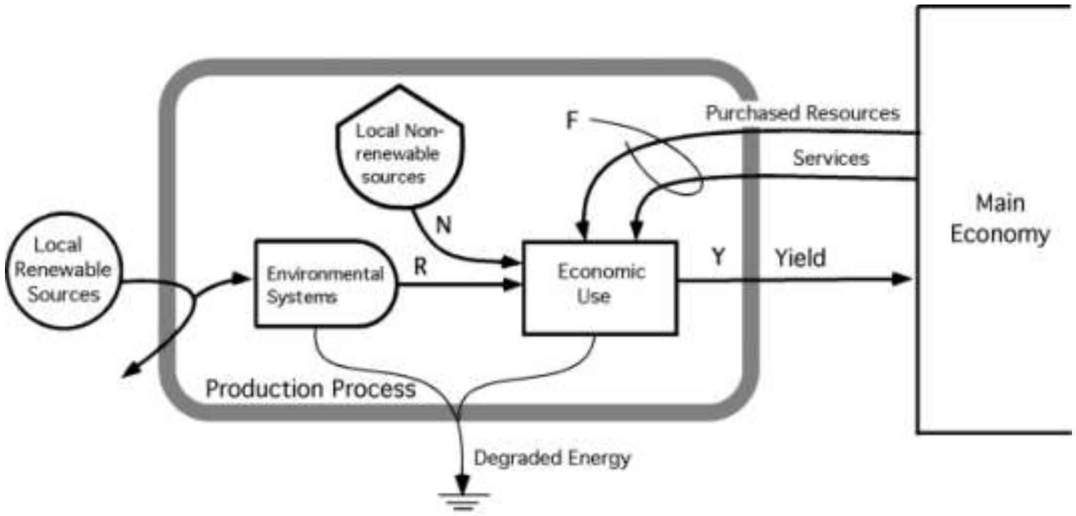
2.2.3 Performance Indicators

Performance indicators are calculated from the Emergy flows of the systems diagram shown in Figure 14. Emergy flows are grouped under:

- N free *non-renewable* resource EMERGY from local environment; e.g. coal, natural gas.

- R free *renewable* EMERGY of environmental inputs, e.g. sun, wind, rain.
- F is the purchased goods and services, e.g. human services, machinery, fertilizers.
- Y is the yield from the production process, e.g. electricity, heat.

Figure 14 Systems Diagram with Flows used in Performance Indicator Ratios
(Brown & Ulgiati, 2004)



The key performance indicators are derived from the flows according to the following equations:

- Yield: Y = R + N + F
- % Renewable Energy: %REN = R / Y
- Emergy Yield Ratio: EYR = Y / F
- Environmental Loading Ratio: ELR = (F + N) / R
- Emergy Index of Sustainability: EIS = EYR / ELR

The performance indicators allow us to evaluate and compare the overall sustainability of the various energy supply options (Brown & Ulgiati, 1997).

Percent Renewable Emergy: %REN

%REN is the ratio of renewable energy to total energy used by the production process, and indicates the sustainability of the process. %REN is an indicator that relates renewable inputs (R) to total inputs (Y) for a process. An energy supply option must have a high %REN to be sustainable in the long term.

Emergy Yield Ratio: EYR

EYR is the ratio of the Emergy of the process output to the Emergy of the inputs purchased from outside the system boundary. EYR is a measure of how well the process is able to exploit local resources (R+N) by means of the investment from outside (F), to provide net benefits to society (Y). EYR does not differentiate between renewable and non-renewable flows, but only between local and imported (purchased or 'invested') Emergy flows. EYR can therefore be high due to a high value of local renewable resources or due to a high value of local non-renewable resources (Brown & Ulgiati, 2002).

Environmental Loading Ratio: ELR

ELR is the ratio of non-renewable and purchased Emergy (F+N) to free renewable Emergy (R). ELR is a measure of the use of environmental services by a system. ELR indicates the pressure of an energy production process on the environment and can be considered to be a measure of ecosystem stress due to the energy supply option (Brown & Ulgiati, 2002).

Emergy Index of Sustainability: EIS

EIS is the ratio of Emergy Yield Ratio to Environmental Loading Ratio (EYR/ELR). Since we are interested in getting the highest yield ratio combined with the lowest environmental loading, this will be measured by the ratio EYR/ELR. The EIS is a measure of the contribution of the energy supply option to the economy per unit of environmental loading. A low EIS indicates a high degree of environmental loading due to the process, whereas a high EIS indicates a low environmental loading. Products or processes that are not sustainable in the long run will have an EIS of less than 1, and products and processes that make sustainable contributions to the economy will have an EIS greater than one. Processes and products that are sustainable in the medium run will have an

EIS between 1.0 and 5.0, and an EIS greater than 5.0 indicates long range sustainability (Brown & Ulgiati, 2002).

Solar Energy for Heat and Electricity

This example illustrates the use of emergy performance indicators by Paoli *et al.* (2008) for comparing solar thermal collectors for heating water with solar photovoltaics panels for producing electricity. They have also compared the transformities of solar energy with fossil fuels for producing heat and electricity.

Paoli *et al.* found that the Emergy Yield Ratio (EYR) for Solar Thermal (1.19) is only a little more than the EYR for Solar Photovoltaic (1.03) (Table 16). However, the Environmental Loading Ratio (ELR) for Solar Photovoltaic (48.93) is nearly nine times the ELR for Solar Thermal (5.54). Consequently, the Emergy Index of Sustainability (EIS) for Solar Thermal (0.21) is ten times the EIS for Solar Photovoltaic (0.02). It should be noted that the quality of energy is different for heat and electricity and this is shown by the Transformity of electricity produced by Solar Photovoltaic panels (8.92E+04) which is more than four times the transformity of heat produced by Solar Thermal collectors (1.58E+04) (Table 15)(Paoli *et al.,* 2008).

Table 16 Emergy Performance Indicators for Solar Thermal and Photo Voltaic Technologies (Paoli *et al.*, 2008)

INDICATOR	SOLAR THERMAL (for heat)	SOLAR PHOTOVOLTAIC (for electricity)
%REN	0.15	0.02
EYR	1.19	1.03
ELR	5.54	48.93
EIS	0.21	0.02
Transformity (sej/J)	15,800 (Heat)	89,200 (Electricity)

Paoli *et al.* have also compared the transformities of solar energy with fossil fuels for both heat and electricity (Table 17). Both solar technologies are more efficient than their fossil fuel alternatives. Solar heating is three times more efficient than methane, while solar electricity is nearly twice as efficient as coal thermal.

Table 17 Transformity (sej/J) of Solar and Fossil Fuel technologies for Heat and Electricity (Paoli *et al.*, 2008)

	SOLAR technologies	FOSSIL FUEL technologies
HEAT	15,800	48,000 (methane)
ELECTRICITY	89,200	170,000 (coal thermal)

2.3 EMBODIED ENERGY ANALYSIS

Emergy Analysis does not calculate the Net Energy, also called Energy Return on Energy Invested (EROEI), which is one of the important indicators for evaluating the sustainability of biodiesel or any other energy supply option. EROEI is derived from the quantity of commercial energy inputs that are required, directly or indirectly, during the entire biodiesel production process, including the agricultural and industrial phases. The environmental accounting method used to determine the EROEI is called the Embodied Energy Analysis (EEA) which looks at the gross energy requirement of the analysed system.

While applying the EEA method, the IFIAS[17] convention is followed in which only non-renewable (fossil) fuels are counted directly, whereas renewable inputs and free environmental inputs such as rain, topsoil, etc. are not counted. Since Emergy Analysis counts all inputs including direct renewables and free environmental services, the EEA complements the Emergy Analysis by providing additional performance indicators that give further insights into the sustainability of the analyzed process.

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[17] International Federation of Institutes for Advanced Study

Embodied Energy Calculation

EEA accounts for the commercial energy required directly or indirectly to provide all the inputs (goods and services) for the entire biodiesel production process (Brown & Herendeen, 1996; Cavalett & Ortega, 2010).

In the EEA method, all materials and energy inputs used in the biodiesel production process are multiplied by their own individual oil equivalent factors (in kg oil equivalent per unit) to give the oil equivalent of each input (in kgs oil equivalent). The oil equivalents of all the inputs are summed up to give the Total Embodied Energy that is required to produce biodiesel (in kgs oil equivalent). The Total Embodied Energy is then multiplied by the standard calorific value of oil fuel (4.186E+07 Joules per kg) to give the Gross Energy Requirement (GER) to produce one kg of biodiesel (in Joules per kg biodiesel). The energy content of one kg of biodiesel produced (in Joules per kg biodiesel) is divided by the GER to give the Energy Return on Energy Invested (EROEI). The EROEI is therefore a number that gives the Joules of biodiesel produced for every one Joule of gross energy required by the production process.

Carbon Dioxide Emissions

The carbon dioxide (CO_2) emissions during the production of biodiesel are estimated by multiplying the Total Embodied Energy of biodiesel (in kg oil equivalent) by the stoichiometric CO_2 emissions of petroleum oil (3.2 kg CO_2 per kg oil).

3 RESULTS

3.1 EMERGY ANALYSIS

Emergy Analysis has been carried out for the production of Coconut Biodiesel. The biodiesel can be used as a fuel in standard diesel generating sets instead of the petroleum diesel that is normally used on the islands. Performance Indicators of biodiesel, based on the Emergy analysis, are then used to determine its sustainability in a holistic manner.

3.1.1 Data for Emergy Analysis

The production chain for biodiesel production from coconuts is shown in Figure 15. The main steps are:

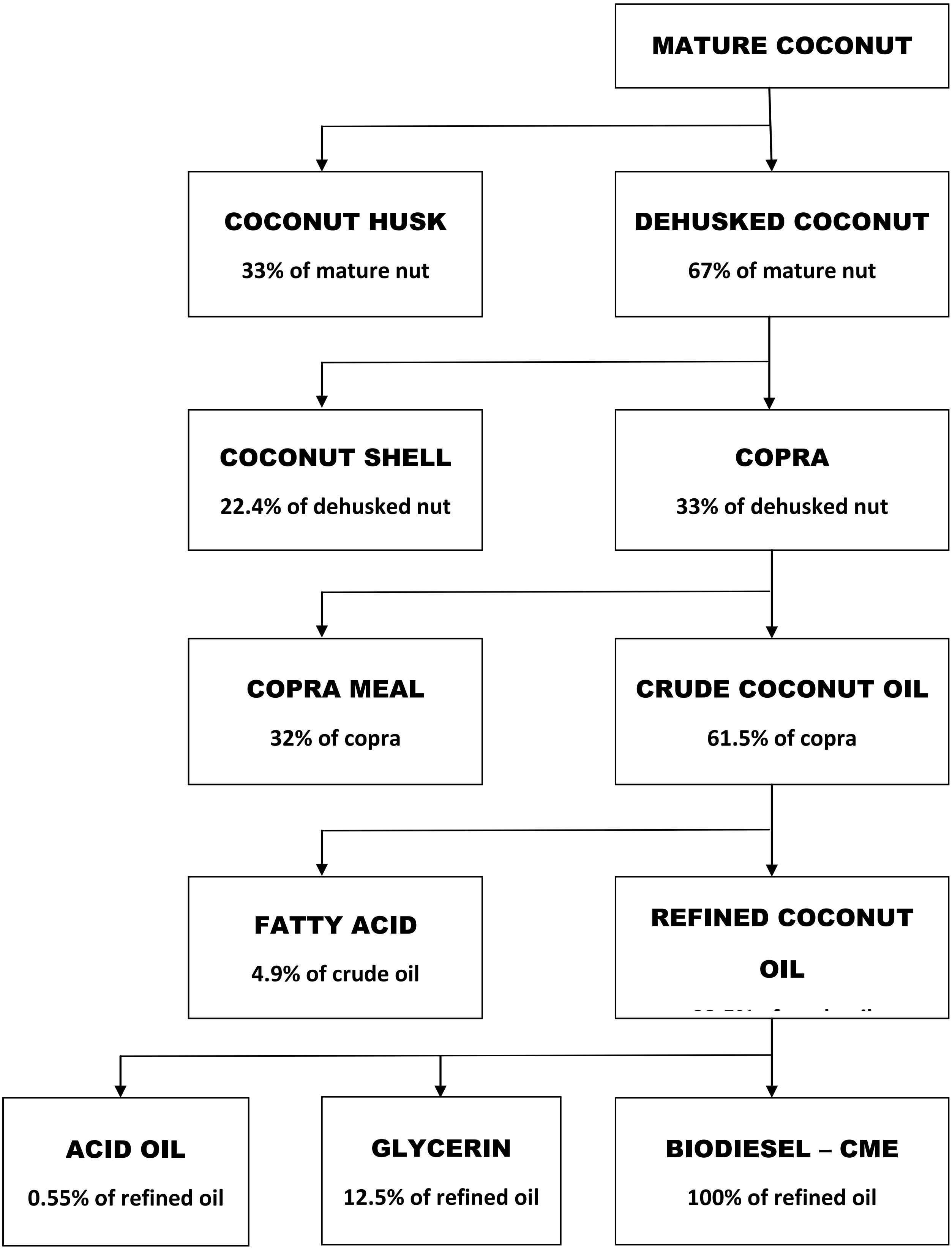
1. Production of Mature Coconuts
2. Production of Copra from Mature Coconuts (by drying the kernel)
3. Production of Coconut Oil from Copra (by expelling oil and refining crude oil)
4. Production of Biodiesel from Coconut Oil (by esterification process).

Step #1 is the agricultural phase, and Steps #2, #3 and #4 are the industrial phase.

Financial data for these four steps in the production of coconut biodiesel is given in the Appendix:

- Break-down of costs and returns are given in Tables 28 to 31, and Figures 20 to 23.
- Net profits are given in Table 32, and Figures 24 and 25.
- Value added by intermediate products are given in Table 33, and Figures 26 and 27.

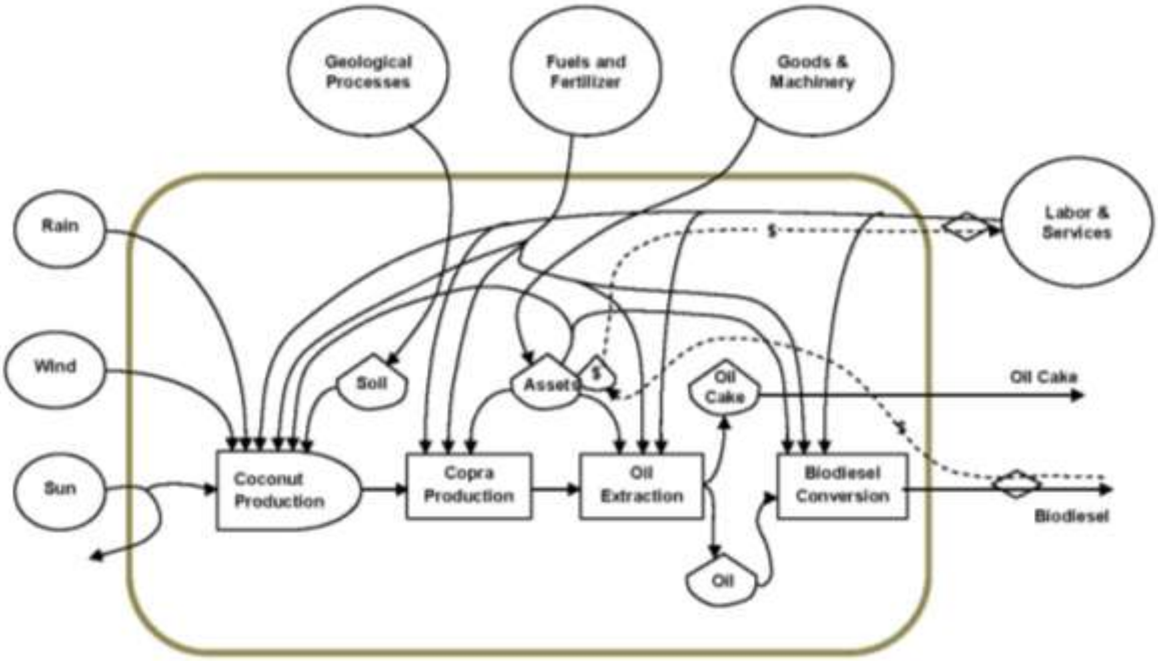
Figure 15 Production Chain for Coconut Biodiesel



3.1.2 Emergy System Diagram

The system diagram for production of coconut biodiesel is shown in Figure 16.

Figure 16 Emergy System Diagram for Production of Coconut Biodiesel



The symbols in the system diagram are:

1. *Big Rectangular Box* (thick line) defines the system boundary.
2. *Small Rectangular Boxes* show Conversion processes within the system such as Copra Production, Oil Extraction and Biodiesel Conversion.
3. *Circles* show all external inputs coming into the system from outside the system boundary (both renewable and non-renewable).
4. *Tanks* show storages within the system such as Soil, Material Assets, Financial Assets ($).
5. *Bullet* shows a production process, in this case production of coconuts.
6. *Solid Lines with Arrowheads* show the flow of materials.
7. *Dashed Lines with Arrowheads* show the flow of money ($).
8. *Solid Lines with Arrowheads emerging on the right side show* of the system boundary are the outputs of the system.
9. *Diamonds* show financial transactions for purchase of materials, labour and services.

Goods & Machinery goes into the storage *Assets* from where it is used for the various operations. *Assets* also has the money storage marked *$* which is used to store revenues from sales and to pay for Labour and Services.

There are four main processes in the production of biodiesel:

1. *Coconut Production* - including harvesting of mature coconuts.
2. *Copra Production* – to dry the coconut kernel.
3. *Oil Extraction* – to produce refined coconut oil from copra.
4. *Biodiesel Conversion* – to produce biodiesel from coconut oil by the esterification process.

For coconut production, the main renewable inputs are shown on the left of the diagram:

1. *Sun* - provides solar radiation for photosynthesis.
2. *Wind* - helps in evapo-transpiration.
3. *Rain* - provides water for the coconut palms. Some rain is evapo-transpired by the plants while the remainder goes as surface runoff.
4. *Geological Processes* - provide the soil for the plants to grow.

In addition, the coconut plantation needs the following non-renewable inputs:

1. *Fuels and Fertilizer* - for plant nutrition and for harvesting the coconuts.
2. *Goods and Machinery* - for cultivation and for harvesting.
3. *Labour and Services* - to carry out the required tasks.

The *Copra Production, Oil Extraction* and *Biodiesel Conversion* processes require only non-renewable inputs:

1. *Fuels.*
2. *Goods and Machinery*.
3. *Labour and Services*.

3.1.3 Emergy Evaluation Table

The Emergy Evaluation Table given below (Table 18) has been prepared according to the methodology given in Section 2.2.2.

Table 18 Emergy Analysis for Biodiesel Production from Coconuts

#	ITEM	UNITS	AMOUNT (ha-1 yr-1)[18]	SPECIFIC EMERGY (seJ unit-1)	REF. FOR SPECIFIC EMERGY	EMERGY (seJ ha-1 yr-1)
COCONUT PRODUCTION						
Renewable inputs						
1	Sunlight	J	7.19E+13	1.00E+00	[1]	7.19E+13
2	Rain water (chemical potential)	J	6.48E+10	3.06E+04	[2]	1.98E+15
3	Earth cycle	J	3.00E+10	1.02E+04	[2]	3.06E+14
Non-renewable inputs						
4	Organic matter in topsoil used up	J	2.53E+10	1.24E+05	[2]	3.14E+15
5	Fertilizer	g	2.15E+05	6.38E+09	[2]	1.37E+15
6	Pesticides	g	3.58E+04	2.49E+10	[3]	8.92E+14
7	Diesel	J	6.67E+09	1.11E+05	[4]	7.40E+14
8	Steel for Agricultural machinery	g	1.36E+04	1.13E+10	[3]	1.54E+14
9	Human labour	years	1.21E-01	6.32E+16	[5]	7.62E+15
10	Annual services	US$	2.44E+02	5.26E+12	[5]	1.29E+15
Products and by-products						
11	Coconuts produced	kg	2.19E+04	8.03E+11	[6]	1.76E+16
		J	2.45E+11	7.17E+04	[6]	1.76E+16
COCONUT TRANSPORT						
Non-renewable inputs						
12	Steel for machinery	kg	1.53E+01	1.13E+13	[4]	1.73E+14
13	Diesel	J	1.46E+09	1.11E+05	[4]	1.62E+14
14	Labour	yrs	3.98E-03	1.07E+16	[4]	4.26E+13
15	Annual services	USD	1.80E+01	5.26E+12	[6]	9.46E+13
Products and by-products						
16	Coconuts transported	kg	2.19E+04	8.25E+11	[6]	1.80E+16
		J	2.45E+11	7.36E+04	[6]	1.80E+16
COPRA PRODUCTION and OIL EXTRACTION						
Non-renewable inputs						
17	Steel for machinery	kg	3.65E-01	1.13E+13	[4]	4.13E+12
18	Cement in plant construction	kg	3.55E-01	3.47E+12	[4]	1.23E+12
19	Iron in plant construction	kg	1.45E-02	1.13E+13	[4]	1.64E+11
20	Diesel	J	2.89E+09	1.11E+05	[4]	3.21E+14
21	Electricity	J	3.92E+08	2.77E+05	[7]	1.09E+14
22	Process and cooling water	J	1.30E+07	4.28E+05	[8]	5.56E+12
23	Chemicals	kg	7.00E+00	6.08E+12	[7]	4.26E+13

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[18] Numbers in this study are given in the scientific notation; e.g. 6.58E+05 = 6.58 x 10^5 = 658,000

#	ITEM	UNITS	AMOUNT (ha-1 yr-1)[18]	SPECIFIC EMERGY (seJ unit-1)	REF. FOR SPECIFIC EMERGY	EMERGY (seJ ha-1 yr-1)
24	Labour	yrs	3.82E-04	1.07E+16	[4]	4.09E+12
25	Annual services	USD	2.11E+02	5.26E+12	[6]	1.11E+15
Products and by-products						
26	Oil	kg	2.26E+03	8.68E+12	[9]	1.96E+16
		J	8.52E+10	2.30E+05	[9]	1.96E+16
27	Oil Cake	kg	1.39E+03			
		J	2.17E+10			
BIODIESEL CONVERSION						
Non-renewable inputs						
28	Steel for machinery	kg	5.19E+00	1.13E+13	[4]	5.87E+13
29	Cement in plant construction	kg	1.51E+00	3.47E+12	[4]	5.22E+12
30	Iron in plant construction	kg	3.13E-02	1.13E+13	[4]	3.53E+11
31	Diesel	J	5.42E+09	1.11E+05	[4]	6.01E+14
32	Methanol	J	6.79E+09	1.89E+05	[6]	1.28E+15
33	Catalyst	kg	2.42E+01	2.48E+13	[4]	5.99E+14
34	Electricity	J	7.19E+06	2.77E+05	[7]	1.99E+12
35	Water	J	5.73E+06	4.28E+05	[10]	2.45E+12
36	Labour	yrs	7.99E-04	1.07E+16	[4]	8.55E+12
37	Annual services	USD	7.10E+01	5.26E+12	[6]	3.73E+14
Products and by-products						
38	Biodiesel	kg	2.66E+03	8.48E+12	[9]	2.26E+16
		J	8.52E+10	2.65E+05	[9]	2.26E+16
39	Glycerin	kg	1.96E+02			
40	Soap stock	kg	1.21E+02			
BIODIESEL TRANSPORT						
Non-renewable inputs						
41	Steel for machinery	kg	1.86E+00	1.13E+13	[4]	2.11E+13
42	Diesel	J	1.78E+08	1.11E+05	[4]	1.97E+13
43	Labour	yrs	4.84E-04	1.07E+16	[4]	5.18E+12
44	Annual services	USD	2.19E+00	5.26E+12	[6]	1.15E+13
Products and by-products						
45	Biodiesel produced	kg	2.66E+03	8.50E+12	[9]	2.26E+16
		J	8.52E+10	2.65E+05	[9]	2.26E+16

References for Specific Emergy:

[1] Definition.
[2] Bargigli & Ulgiati (2003).
[3] Lapp (1991).
[4] Brown & Ulgiati (2004).
[5] Ulgiati (2003)
[6] Cavalett & Ortega (2010).
[7] Odum (1996).
[8] Bastianoni *et al.*. (2001).
[9] Calculated by author.
[10] Bastianoni & Marchettini (2000).

Notes for Table 18

1. Item#1: Transformity of Sunlight = 1 by definition. Global solar insolation incident on a horizontal surface for Fiji (Latitude 18 deg S, Longitude 175 deg E) = 5.47 kWh/m^2/day (NASA,

2014). Albedo of coconut palm plantations taken equal to oil palm plantations = 8.8% (Caiazzo *et al.*, 2014). Annual energy of Sunlight = (Average total annual insolation kWh/m^2/day)(365 days/yr)(3.6E6 J/kWh)(1E4 m^2/ha)(1 – albedo) = (5.47 kWh/m^2/day)(365 days/yr)(3.6E6 J/kWh)(1E4 m^2/ha)(1 – 0.088) = 7.19E13 J/ha/yr.

2. Item#2: Rain, chemical potential energy = (area)(rainfall)(% evapotrans)(Gibbs free energy) = (10,000 m^2/ha)(2.62 m)(0.50)(1000 kg/m^3)(4.94E+3 J/kg) = 6.48E10 J/ha/yr.

3. Item#3: Transformity for organic soil 7.38 E4 sej/J (Odum, 1996) corrected by factor of 1.68 (Odum *et al.*, 2000). Soil erosion rate in mature coconut palm plantation taken equal to mature oil palm plantations, estimated at 28 tons/ha/yr (Hartemink, 2006) with 0.04% organics in soil. The energy content in organic soil is 5.4 kcal/g (Ulgiati *et al.*, 1992). The energy of soil used = (area)(erosion rate)(% organic)(5.4 kcal/g)(4186 J/kcal) = (10,000 m^2/ha)(28,000 kg/ha/yr)(0.04)(5.4)(4186) =2.53E10 J/ha/yr.

4. Item#5-10: Non-renewable inputs for '*Coconut Production*' (Items 5-10) have been derived from values given in Tables 28 – 33.

5. Item#11, 16: Energy Contents of Whole Coconut = 11.2 MJ/kg coconut (after Raghavan, 2010).

6. Item#12-15: Weight of Coconuts transported to Oil Mill has been estimated from the quantity of copra (dried coconut kernel): Average weight of one mature coconut = 1.2 kg which gives 0.2 kg of dried copra (Raghavan 2010). Weight of mature coconuts transported = (1.2/0.2) = 6 x Weight of copra processed = 6 x (2,260/62%) = 21,871 kgs/ha. Average distance for Round Trip = 300 kms (from field work).

7. Item#17-25: Non-renewable inputs for '*Oil Extraction*' have been derived from values given in Cavalett & Ortega (2010) for production of oil from soya bean, since the same Oil Mill can be used for both oil seeds. However, the capacities of the Oil Mill for processing coconuts from a 1 hectare plantation have been determined by taking the following multiplication factors:
   Soya Oil extraction = 18% of oil seed (Cavalett & Ortega, 2010);
   Coconut Oil extraction = 62% of copra (Tinytech, 2014);
   Scale-up Ratio for Oil Mill capacity: kgs Copra / kgs Soybean
   = (2,260/510)/(62%/18%) = 1.29

8. Item#26: Energy Content of Coconut Oil = 37.7 MJ/kg (Raghavan, 2010).

9. Item#27: Energy Content of Oil Cake = 15.7 MJ/kg (Raghavan, 2010).

10. Item#28-45: Non-renewable inputs for '*Biodiesel Conversion*' and '*Biodiesel Transport*' have been derived from values given in Cavalett & Ortega (2010) for production of biodiesel from soybean, since the same Biodiesel Plant can be used for esterification of both soybean oil and coconut oil. However, the capacities of the Biodiesel Plant for processing coconuts from a 1 hectare plantation have been determined by taking the following multiplication factors:
    Soya Oil from 1 ha = 510 kgs (Cavalett & Ortega, 2010);
    Coconut Oil from 1 ha = 2,260 kgs (Uriarte, 2010);
    Scale-up Ratio for Biodiesel Plant capacity: Coconut Oil / Soybean Oil
    = 2,260/510 = 4.44.

11. Item#10, 15, 25, 37, 44 (Specific Emergy for Annual Services): Emergy/Money Ratio has been calculated according to the method of Odum (1996). Emergy/ Money Ratio for Fiji in 1983 = 1.49E13 sej/$, taken equal to Dominica, a Small Island Developing State with a similar level of development (Odum, 1996). GDP of Fiji in 1983 = 1.12E9 US$/yr, GDP in 2010 = 3.17E9 $/yr (http://www.indexmundi.com/facts/fiji/gdp). Fiji's Oil Imports in 2010 = 6.36E8 $/yr (International Monetary Fund, 2010). Emergy/ Money Ratio for Fiji in 2010 = (1.49E13 x 1.12E9 + 6.36E8) / 3.17E9 = 5.26E12 sej/$.

3.1.4 Emergy Performance Indicators

Table 19 gives a summary of the Emergy flows from which the emergy performance indicators are calculated.

Table 19 Summary of Emergy Analysis for Coconut Biodiesel

#	PROCESS	R	N	F
1	Coconut Production	2.36E+15	3.14E+15	1.21E+16
2	Coconut Transport			4.72E+14
3	Copra Production and Oil Extraction		5.56E+12	1.58E+15
4	Biodiesel Conversion		2.45E+12	2.93E+15
5	Biodiesel Transport			5.75E+13
	TOTAL	2.36E+15	3.15E+15	1.71E+16

- N is the free *non-renewable* resource EMERGY from local environment; e.g. coal.
- R is the free *renewable* EMERGY of environmental inputs, e.g. sun, wind, rain.
- F is the purchased goods and services, e.g. human services, machinery, fertilizers.

Performance indicators (Table 20) are calculated according to the following equations:

- Yield: $Y = R + N + F$
- % Renewable Energy: $\%REN = R / Y$
- Emergy Yield Ratio: $EYR = Y / F$
- Environmental Loading Ratio: $ELR = (F + N) / R$
- Emergy Index of Sustainability: $EIS = EYR / ELR$

Table 20 Performance Indicators for Coconut Biodiesel

#	PERFORMANCE INDICATORS	SYMBOL	VALUE
1	Yield	Y	2.26E+16
2	Percent Renewable Emergy	%REN	10%
3	Emergy Yield Ratio	EYR	1.32
4	Environmental Loading Ratio	ELR	8.57
5	Emergy Index of Sustainability	EIS	0.15

3.2 EMBODIED ENERGY ANALYSIS

Embodied Energy Analysis (EEA) has been carried out according to the methodology explained in Section 2.3. Commercial energy required directly or indirectly for making goods or services are accounted for as fossil oil equivalent. Human labour, services and free environmental resources (rain, topsoil, etc.) are not accounted for in the EEA (Table 21).

Table 21 Embodied Energy Analysis for Biodiesel Production from Coconuts

#	ITEM	UNITS	AMOUNT (unit ha-1 yr-1)[19]	OIL EQUIV. PER UNIT (kg oil unit-1)	REF. FOR OIL EQUIV.	EMBODIED ENERGY (kg Oil Equivalent)	EMBODIED ENERGY (Joules)	CARBON DIOXIDE EMISSIONS (kg CO_2)
COCONUT PRODUCTION								
Renewable inputs								
1	Sunlight	J	7.19E+13					
2	Rain water	J	6.48E+10					
3	Earth cycle	J	3.00E+10					
Non-renewable inputs								
4	Topsoil used up	J	2.53E+10					
5	Fertilizer	kg	2.15E+02	1.77	[1]	3.81E+02	1.64E+10	1.22E+03
6	Pesticides	kg	3.58E+01	1.27	[1]	4.55E+01	1.96E+09	1.46E+02
7	Diesel	kg	1.55E+02	1.10	[1]	1.70E+02	7.34E+09	5.45E+02
8	Steel	kg	1.36E+01	1.65	[1]	2.24E+01	9.67E+08	7.18E+01
9	Human labour	yrs	1.21E-01					
10	Annual services	US$	2.44E+02					
Products and by-products								
11	Coconuts produced	kg	2.19E+04					
		J	2.45E+11					
COCONUT TRANSPORT								
Non-renewable inputs								
12	Steel	kg	1.53E+01	1.65	[1]	2.52E+01	1.09E+09	8.07E+01
13	Diesel	kg	3.38E+01	1.10	[1]	3.72E+01	1.60E+09	1.19E+02
14	Labour	yrs	3.98E-03					
15	Annual services	USD	1.80E+01					
Products and by-products								
16	Coconuts transported	kg	2.19E+04					
		J	2.45E+11					
COPRA PRODUCTION and OIL EXTRACTION								
Non-renewable inputs								
17	Steel	kg	3.65E-01	1.65	[1]	6.03E-01	2.60E+07	1.93E+00
18	Cement	kg	3.55E-01	0.07	[1]	2.49E-02	1.07E+06	7.95E-02
19	Iron	kg	1.45E-02	0.02	[2]	2.91E-04	1.25E+04	9.30E-04

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[19] Numbers in this study are given in the scientific notation; e.g., 6.58E+05 = 6.58 x 10^5 = 658,000

#	ITEM	UNITS	AMOUNT (unit ha-1 yr-1)[19]	OIL EQUIV. PER UNIT (kg oil unit-1)	REF. FOR OIL EQUIV.	EMBODIED ENERGY (kg Oil Equivalent)	EMBODIED ENERGY (Joules)	CARBON DIOXIDE EMISSIONS (kg CO_2)
20	Diesel	kg	6.72E+01	1.10	[1]	7.39E+01	3.18E+09	2.36E+02
21	Electricity	J	3.92E+08	7.17E-08	[1]	2.81E+01	1.21E+09	9.00E+01
22	Water	kg	2.63E+03	1.43E-04	[3]	3.76E-01	1.62E+07	1.20E+00
23	Chemicals	kg	7.00E+00	1.27	[1]	8.89E+00	3.83E+08	2.84E+01
24	Labour	yrs	3.82E-04					
25	Annual services	USD	2.11E+02					
Products and by-products								
26	Oil	kg	2.26E+03					
		J	8.52E+10					
27	Oil Cake	kg	1.39E+03					
		J	2.17E+10					
BIODIESEL CONVERSION								
Non-renewable inputs								
28	Steel	kg	5.19E+00	1.65	[1]	8.57E+00	3.69E+08	2.74E+01
29	Cement	kg	1.51E+00	0.07	[1]	1.05E-01	4.54E+06	3.37E-01
30	Iron	kg	3.13E-02	0.02	[2]	6.25E-04	2.69E+04	2.00E-03
31	Diesel	kg	1.26E+02	1.10	[1]	1.38E+02	5.96E+09	4.42E+02
32	Methanol	kg	3.45E+02	0.60	[4]	2.07E+02	8.92E+09	6.62E+02
33	Catalyst	kg	2.42E+01	n.a.				
34	Electricity	J	7.19E+06	7.17E-08	[1]	5.16E-01	2.22E+07	1.65E+00
35	Water	kg	1.16E+03	1.43E-04	[3]	1.66E-01	7.15E+06	5.31E-01
36	Labour	yrs	7.99E-04					
37	Annual services	USD	7.10E+01					
Products and by-products								
38	Biodiesel	kg	2.66E+03					
		J	8.52E+10					
39	Glycerin	kg	1.96E+02					
40	Soap stock	kg	1.21E+02					
BIODIESEL TRANSPORT								
Non-renewable inputs								
41	Steel	kg	1.86E+00	1.65	[1]	3.08E+00	1.33E+08	9.85E+00
42	Diesel	kg	4.12E+00	1.10	[1]	4.53E+00	1.95E+08	1.45E+01
43	Labour	yrs	4.84E-04					
44	Annual services	USD	2.19E+00					
Products and by-products								
45	Biodiesel produced	kg	2.66E+03	0.43	[5]	1.15E+03	4.94E+10	3.67E+03
		J	8.52E+10					
TOTAL						1.15E+03	4.94E+10	3.67E+03

References for Oil Equivalent:

[1] Biondi *et al.* (1989); taken from Cavalett and Ortega (2010).

[2] Boustead and Hancock (1979).

[3] Smil (1991).

[4] Ulgiati (2001).

[5] Calculated by author.

3.2.1 Embodied Energy Performance Indicators

Embodied Energy of Biodiesel

For producing coconut biodiesel:

Total Embodied Energy Demand = 1.15E+03 kg Oil Equivalent;
Quantity of Biodiesel produced = 2.66 E+03 kgs;
Embodied Energy of Biodiesel = 1.15E3 / 2.66E3
= 0.43 kg Oil Equivalent / kg Biodiesel;

Energy Return on Energy Invested (EROEI)

In the agricultural and industrial phases of the biodiesel production process, fossil oil is used directly as diesel fuel or indirectly the oil goes into producing the other inputs such as electricity, fertiliser, methanol, steel, cement, etc. The total energy invested is calculated by the Embodied Energy Analysis as 1.15E+03 kg oil equivalent per hectare. The returns from one hectare are 2,660 kgs of biodiesel and 1,390 kgs of oil cake.[20] The Energy Return on Energy Invested (EROEI) has been calculated as follows:

Energy Return:

Energy content of 2,660 kgs of biodiesel = 2,660 x 37.8 MJ/kg = 1.01E11 J
Energy content of 1,390 kgs of oil cake = 1,390 x 15.7 MJ/kg = 2.17E10 J
Total energy content of products = 1.22E11 J

Energy Invested:

Energy content of 1.15E3 kg oil equivalent = 1.15E3 x 4.31E7 = 4.94E10 J

Energy Return on Energy Invested = 1.22E11 / 4.94E10 = 2.47

Carbon Dioxide Emissions

Total CO_2 Emissions = 3.67E+03 kgs CO_2 / ha;
Quantity of Biodiesel produced = 2.66 E+03 kgs;

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[20] Large scale biodiesel production has led to the over production of glycerin that has lowered its market value to a level that it can be considered as an industrial waste (Cavalett & Ortega, 2010). Therefore, it has not been considered as a co-product.

Specific CO_2 Emission = 3.67E3 / 2.66E3

= 1.38 kg CO_2 / kg biodiesel.

= 36 g CO_2 / MJ biodiesel.

3.3 SUMMARY OF RESULTS

To analyse the sustainability of coconut biodiesel in a holistic manner, two different Environmental Accounting methods have been used: i) Emergy Analysis and ii) Embodied Energy Analysis.

Emergy Analysis gives the following results:

1. Transformity of coconut biodiesel is 2.65E+05 sej/J, of which 37% is from diesel fuel and another 37% from fertilizer and pesticides.
2. Percent Renewable Energy is 10%, so 90% is from non-renewable energy sources.
3. Emergy Yield Ratio is 1.32, indicating a low ability to exploit local resources efficiently.
4. Environmental Loading Ratio is 8.57, implying that biodiesel production causes significant environmental or ecosystem stress.
5. Emergy Index of Sustainability is 0.15, indicating a low contribution to the economy per unit of environmental loading and a very high degree of environmental stress per unit of emergy yield.

Embodied Energy Analysis gives the following results:

1. Energy Returned on Energy Invested is 2.47, which means that it is not worth the effort in energetic terms.
2. Carbon dioxide Emissions due to the direct and indirect use of fossil fuels during the production of coconut biodiesel is 1.38 kg CO_2 per kg biodiesel or 36 g CO_2 per MJ of energy delivered, showing that biodiesel is not a carbon neutral fuel.
3. To produce biodiesel without using fossil fuels, an additional 68% biodiesel has to be produced which will be used to substitute fossil fuels for the production process.

4 DISCUSSION AND CONCLUSIONS

This thesis has presented information on the alternatives Pacific Island Countries have with respect to energy technologies, and has provided and demonstrated an approach for analysing the potential of a specific energy source — coconut biodiesel — for replacing expensive and unsustainable fossil fuels.

4.1 EMERGY ANALYSIS

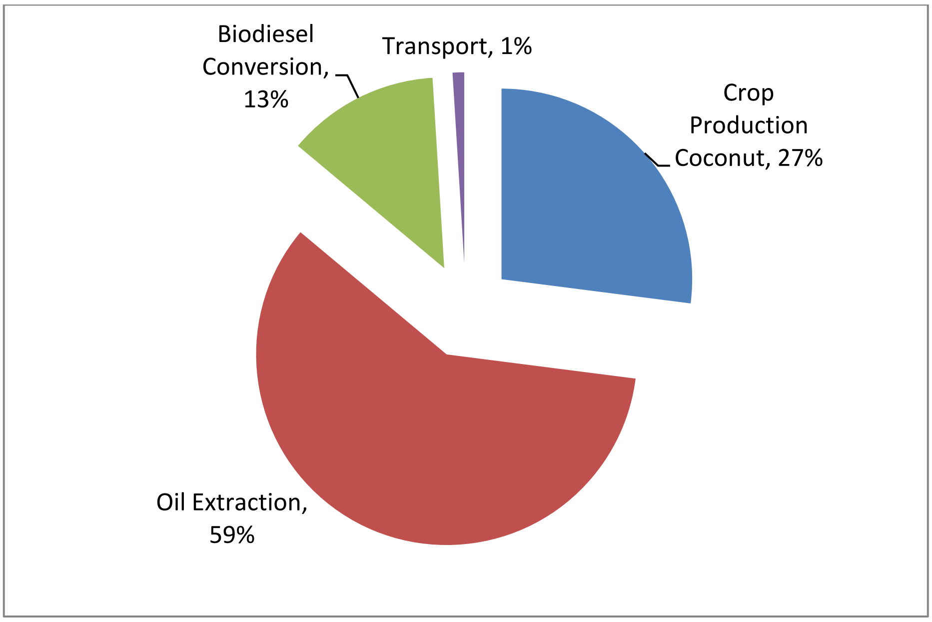
4.1.1 Transformity

The transformity of a fuel is a useful yardstick for choosing the better alternative. If the transformity of a fuel is lower, that means that the total amount of solar energy in sej (solar emjoules) that went into the fuel is less and therefore the process of producing the fuel in its final form is more efficient. The transformity of oil extracted from coconuts is 2.30E+05 sej/J, whereas the transformity of biodiesel produced from the coconut oil is greater, i.e. 2.65E+05 sej/J. The increase in transformity at each of the four main steps in the production of coconut biodiesel is given in Table 22, in comparison with soybean biodiesel. The share of additional transformity attributed to each process is shown in Figure 17.

Table 22 Transformity Increase at each Stage of Biodiesel Production
(Source: a) Calculated by author; b) Cavalett and Ortega, 2010)

		a) Coconut biodiesel		b) Soybean Biodiesel	
#	Process	Additional Transformity (sej/J)	% of Total	Additional Transformity (sej/J)	% of Total
1	Crop Production: Coconut / Soybean	7.17E+04	27%	1.01E+05	26%
2	Oil Extraction	1.57E+05	59%	2.39E+05	61%
3	Biodiesel Conversion	3.43E+04	13%	4.90E+04	13%
4	Transport	2.60E+03	1%	1.00E+03	0.3%
	TOTAL	2.65E+05		3.90E+05	

Figure 17 Transformity Increase at each Stage of Biodiesel Production



In the production of coconut biodiesel, oil extraction (including copra production) contributes more than half the increased transformity. The agricultural phase, i.e. production of coconuts, is the second highest. The biodiesel conversion process itself contributes a modest increase in transformity while transportation contributes only 1%. A comparison with production of biodiesel from soybeans (Table 22) shows almost the same transformity increases from the four processes. This clearly indicates that nearly three-quarters of the increase in transformity is due to the flows of Emergy that support the industrial processes of copra production, oil extraction and biodiesel conversion; the remaining one-quarter supports the agricultural phase.

In Table 23, the transformities of the most widely used fossils fuels and biofuels are compared to that of coconut oil and biodiesel. The table also gives the key Emergy Performance Indicators of these fuels.

The transformity of all biofuels are higher than fossil fuels such as coal (6.71E+04), natural gas (8.05E+04), crude oil (9.06E+04), and motor fuels (1.11E+05) evaluated by Odum (1996). This is because natural processes have taken millions of years to form fossil fuels whereas all biofuels are grown by using a less efficient process of photosynthesis over a very much shorter time period. The higher transformity of biofuels is also because biofuel crops have a higher demand for direct and indirect environmental support, and because of inputs to the industrial processes of copra production, oil extraction and biodiesel conversion.

Table 23 Performance Indicators of Biofuels and Fossil Fuels (Sources: given below Table)

#	ITEM	TRANSFORMITY (sej / J)[21]	EYR	%REN	ELR	EIS
THIS STUDY						
1	Coconut Oil	2.30E+05				
2	Coconut biodiesel	2.65E+05	1.32	10%	8.57	0.15
FOSSIL FUELS						
3	Coal	6.71E+04	10.5			
4	Natural Gas	8.05E+04	10.3			
5	Crude Oil	9.06E+04	3.2 - 11.1			
6	Diesel, Gasoline	1.11E+05				
BIOFUELS						
7	Soybean Oil	3.40E+05				
8	Sunflower Oil	2.78E+05				
9	Sunflower Biodiesel	2.31E+05				
10	Soybean Biodiesel	3.90E+05	1.62	30%	2.26	0.72
11	Rapeseed Biodiesel	1.36E+05	1.27	11%	8.23	0.15
12	Sugarcane Ethanol	7.07E+04	1.38	19%	4.30	0.32
13	Sugarcane Ethanol	1.86E+05 to 3.15E+05				
14	Ethanol from Corn	1.89E+05				
15	Ethanol from Wheat	9.19E+04	1.15	12%	7.05	0.16
16	Methanol from Willow	6.06E+04	1.11	10%	8.80	0.13
17	Biodiesel from Algae	5.04E+05	6.44	84%	0.18	35.0
18	Biogas from Algae	9.12E+04	3.66	67%	0.49	7.4

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[21] Numbers in this study are given in the scientific notation; e.g., 6.58E+05 = 6.58 x 10^5 = 658,000

Sources for Item#:

1. Calculated by author
2. Calculated by author
3. Odum, 1996; Odum *et al.*, 2000[22]
4. Odum, 1996; Odum *et al.*, 2000[22]
5. Odum, 1996; Odum *et al.*, 2000 [22]
6. Odum, 1996; Odum *et al.*, 2000 [22]
7. Cavalett & Ortega, 2010
8. Bastianoni *et al.*., 2008
9. Giampietro & Ulgiati, 2005
10. Cavalett & Ortega, 2010
11. Cavalett & Rydberg, 2010
12. Cavalett & Rydberg, 2010
13. Giampietro & Ulgiati, 2005
14. Giampietro & Ulgiati, 2005
15. Cavalett & Rydberg, 2010
16. Cavalett & Rydberg, 2010
17. Jarméus, 2013
18. Jarméus, 2013

The transformity of ethanol from various feedstocks (wheat, corn, sugarcane) varies between 9.19E+04 and 3.15E+05. The transformity of coconut biodiesel calculated in this study (2.65E+05) is higher than rapeseed biodiesel (1.36E+05)(Cavalett & Rydberg, 2010) and sunflower biodiesel (2.31E+05)(Giampietro & Ulgiati, 2005) but is lower than soybean biodiesel (3.90E+05)(Cavalett & Ortega, 2010). The yield of coconut oil per hectare is more than five times the yield of soybean oil (Table 24), so one can expect the environmental support for one litre of coconut oil to be less than for one litre of soybean oil. This may explain why the transformity of coconut biodiesel is higher. However, the yields of rapeseed and sunflower are also much lower than coconut but their transformities are also lower, so there are other factors that are not so evident. Rain is the largest renewable input for the coconut palm as well as other biofuel crops (Cavalett & Ortega, 2010), and the high rainfall in Fiji (2,625 mm/yr) could be one of the factors behind the higher transformity of coconut oil.

Table 24 Typical Yields of Oilseed Crops (Uriarte, 2010)

CROP	LITRES OIL per hectare
Soybean	446
Sunflowers	952
Rapeseed	1,190
Coconut	2,689
Oil Palm	5,950

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[22] Transformities given by Odum (1996) have been scaled up by a factor of 1.68 = 15.83E24 / 9.44E24, based on a recalculation of the Global Emergy Base of Reference done by Odum *et al.* (2000).

4.1.2 Percent Renewable Energy

The Percent Renewable Energy (%REN) of coconut biodiesel is only 10.4%. This is very close to values obtained by Cavalett & Rydberg (2011) for rapeseed biodiesel (11%), ethanol from wheat (12%) and methanol from willow (10%). This means that nearly 90% of the resources used in producing these biofuels are non-renewable. The production of oil crops and their conversion to biofuels depend on fossil fuels for energy, fertiliser, chemicals and other materials.

Ethanol from sugarcane shows a higher %REN of 19% probably because all the heat and electricity required for producing sugar and ethanol comes from burning bagasse, which is a by-product of the sugarcane itself.[23]

In order to produce biodiesel in a more sustainable way, methods to increase the renewability of the agricultural and industrial processes have to be found. Nevertheless, the renewability of biofuels is far better than fossil fuels, which are considered totally non-renewable because they are used at a much faster rate than the millions of years required by nature to replenish them.

4.1.3 Emergy Yield Ratio

The Emergy Yield Ratio (EYR) is a measure of how efficiently the fuel production process exploits local resources and contributes to the main economy. The EYR of coconut biodiesel is 1.32 and this is comparable to other biofuels (1.1 to 1.5)(Cavalett & Rydberg, 2011). The EYR for fossil fuels ranges from 3 to 11 (Odum, 1996). Biofuels therefore have a low ability to exploit and deliver local resources in the form of liquid motor fuels such as biodiesel and ethanol.

Ethanol from sugarcane has a higher EYR value than ethanol from wheat, indicating a higher ability to utilise local resources and a lesser dependence on external inputs. This

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[23] Sugarcane juice is squeezed out of the stalks in sugar mills. The fibrous part of the stalk left over after the juice has been squeezed out is called bagasse. It is burned in co-generation plants to produce heat and electricity required at the sugar mill, and the excess electricity is sold (Binger *et al.*, 2005).

is partly because the ethanol from sugarcane production utilises sugarcane bagasse for all its energy needs. Brazilian sugarcane also uses cheap labour intensively (Cavalett & Rydberg, 2011).

4.1.4 Environmental Loading Ratio

The Environmental Loading Ratio (ELR) for coconut biodiesel is found to be 8.57. This is similar to evaluations by Cavalett & Rydberg (2011) for rapeseed biodiesel (8.23), ethanol from wheat (7.05) and methanol from willow (8.80), but is higher than the ELR of ethanol from sugarcane (4.30) also obtained by Cavalett & Rydberg (2011) and biodiesel from soybean (2.26) obtained by Cavalett & Ortega (2010). The high ELR of coconut biodiesel and other biofuels is due to a high ratio of non-renewable and imported Emergy use to renewable Emergy use. This indicates that the whole biodiesel production chain causes significant pressure on the environment and a great deal of ecosystem stress.

4.1.5 Emergy Index of Sustainability

The Emergy Index of Sustainability (EIS) for biodiesel in this study is 0.15. Such a low EIS has also been obtained by Cavalett & Rydberg (2011) for biodiesel from rapeseed (0.15), ethanol from wheat (0.16) and methanol from willow (0.13). The low EIS is due to a low value of the Emergy Yield Ratio combined with a high value of the Environmental Loading Ratio. This indicates that the potential contribution of the biodiesel production process to the economy per unit of environmental loading is very low. A low EIS can also been seen as a high degree of environmental loading or ecosystem stress per unit of Emergy yield from the use of local resources to produce biodiesel.

Even though Cavalett & Ortega (2010) have not provided a value for EIS, their values for EYR (1.62) and ELR (2.26) were used to calculate the EIS for soybean biodiesel to be 0.72. This is much higher than the EIS for coconut biodiesel obtained in this study (0.15). It is not clear why, for soybean biodiesel, Cavalett & Ortega (2010) have obtained higher values of EIS (0.72) and %REN (30%), and a lower value of ELR (2.26) than this study.

However, the EYR, ELR and EIS values obtained in this study are very close to the values for the same three performance indicators reported by Cavalett & Rydberg (2011) for the biofuel technologies they evaluated: biodiesel from rapeseed, ethanol from wheat and methanol from willow (Table 23).

4.2 EMBODIED ENERGY ANALYSIS

The Embodied Energy Analysis complements the Emergy Analysis by providing additional performance indicators that give insights useful for assessing the sustainability of biodiesel:

1. Embodied Energy of biodiesel and its inputs;
2. Energy Return on Energy Invested;
3. Carbon dioxide emissions.

4.2.1 Embodied Energy of Biodiesel and its Inputs

The Embodied Energy of biodiesel produced from a one hectare coconut plantation is 1.15E+03 kg oil equivalent which equals 0.43 kg oil equivalent per kg biodiesel. Embodied Energy of all inputs used in the biodiesel process is given in Table 31.

Table 25 Embodied Energy of Inputs for Biodiesel Production

#	ITEM	EMBODIED ENERGY (kg Oil Equivalent)	% OF TOTAL
1	Diesel	4.24E+02	37%
2	Electricity	2.87E+01	2%
3	Fertilizer	3.81E+02	33%
4	Pesticides	4.55E+01	4%
5	Methanol	2.07E+02	18%
6	Steel, Cement, Iron	6.00E+01	5%
	TOTAL	1.15E+03	100%

Diesel fuel accounts for 37% of the Embodied Energy in biodiesel, while fertilizer (33%) and pesticides (4%) together account for another 37%. The third major contribution is by methanol (18%). Steel, cement and iron used in plant construction and transportation form 5% of the Embodied Energy in biodiesel, and electricity is only 2%.

4.2.2 Energy Return on Energy Invested

The Energy Return on Energy Invested (EROEI) for coconut biodiesel is 2.47. This is almost the same as the EROEI for soybean biodiesel (2.48) obtained by Cavalett & Ortega (2010). Heinberg (2009) reports that EROEI of soybean biodiesel from soybean varies from a low of 1.93 to a high of 3.5, while the highest EROEI for biodiesel is 9 produced from palm oil. This could be because the yield of palm oil (5,950 L/ha) is the highest of all biofuel crops. The yield of palm oil is more than twice that of coconut oil (2,689 L/ha), more than five times that of rapeseed oil (1,190 L/ha) and more than ten times that of soybean oil (446 L/ha) (Table 24).

The EROEI of ethanol from corn in the USA lies between 1 and 1.25, whereas ethanol from sugarcane in Brazil has an EROEI between 8 and 10 (Heinberg, 2009). However, all the biofuels are much lower than the EROEI of fossil fuels with coal at 50, crude oil at 19 and natural gas at 10. The EROEI for syncrude oil from tar sands found in Alberta and Venezuela has been estimated between 5.2 and 5.8.

Giampietro & Mayumi (2009) suggest that an EROEl below 3.0 is not worth the effort in energetic terms. Heinberg (2009) also rules out both biodiesel and ethanol as alternatives to fossil fuels not only because of their low EROEI but also because of limits to land and water required for their large scale production.

Instead of using fossil fuel, it is possible to use a part of the biodiesel produced to provide the energy requirements of the biodiesel production process. Since the EROEI of biodiesel is 2.47, only 1.47 litres of biodiesel will be available as the final product because the remaining 1.0 litre has to be used as energy for the process. In other words, for every one litre of biodiesel product, another 0.68 litres (= 1/1.47) of biodiesel has to be produced to supply the energy for the production process. This would mean that the land area and all the process equipment has to be scaled up by 68% to make the process independent of external energy sources. This in turn will increase the environmental loading and ecosystem stress by 68%.

4.2.3 Carbon Dioxide Emissions

Carbon dioxide (CO_2) emitted as a result of the production of coconut biodiesel is 3.7 tons CO_2 per hectare of coconut plantation, 1.38 kg CO_2 per kg biodiesel burned, and 36 g CO_2 per MJ of energy delivered. In comparison, production and use of petroleum diesel would release around 100 g CO_2 per MJ of energy delivered (Cavalett & Ortega, 2010). Therefore, the use of coconut biodiesel releases 64% less greenhouse gases than the use of petroleum-based diesel fuel.

Even though all the carbon dioxide released by burning biodiesel has been captured by the coconut plant from the atmosphere, biodiesel cannot be called a *net zero* emitter of greenhouse gases or *climate neutral* because of the CO_2 released by fossil fuels used directly or indirectly during the production process. In addition, production of biofuels releases nitrous oxide gas whose global warming potential is more than 300 times that of carbon dioxide (Crutzen *et al.,* 2007). Crutzen *et al.* have estimated that any cooling due to fossil fuel savings from the use of biodiesel and bioethanol would be nullified by the additional global warming due to nitrous oxide emissions.

4.3 COMPARATIVE COSTS

The typical range of capital costs for Renewable Energy Technologies (RETs) are given in Table 26 and Figure 18. Levelised Cost of Electricity[24] (USD/kWh) from RETs for Pacific

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[24] Levelized Cost of Electricity (LCOE) is the unit cost of electricity generation (in $/kWh) over the life of a power plant. LCOE reflects all costs needed to build and operate a power plant over its economic life, normalized over the total net electricity generated.

island countries is given in Table 26 and Figure 19. While the price of fossil fuel power in the OECD[25] countries ranges from 5 to 10 US cents/kWh, typical electricity prices on islands are much higher and range from 20 to 55 US cents/kWh (Figure 19). The high power tariff on islands is largely due to the use of diesel power plants; diesel generation costs can be as high as 2.00 USD/kWh in remote, small-scale applications.

Table 26 Capital Costs and Levelised Cost of Electricity for Renewable Energy Power Generation (IRENA, 2013)

#	TECHNOLOGY	CAPITAL COST (USD/kW)	LEVELISED COST OF ENERGY (USD/kWh)
1	Small Hydropower	1,300 – 5,000	0.03 - 0.07
2	Large Hydropower	1,050 – 4,215	0.03 - 0.06
3	Biomass	660 – 1,860	0.05 - 0.06
4	Gasification	2,140 – 5,700	
5	Anaerobic Digester	2,570 – 6,100	
6	Geothermal	2,000 - 5,900	0.05 - 0.09
7	Onshore Wind	1,500 – 2,200	0.08 - 0.12
8	Offshore Wind	4,000 – 4,500	
9	Utility-scale Solar PV	1,720 – 2,160	0.15 - 0.31
10	Residential Solar PV	3,100 – 3,400	
11	CSP - parabolic trough	3,500 - 4,600	0.14 - 0.36
12	CSP - solar towers	6,300 – 10,500	0.17 - 0.29
13	Typical Island Electricity Prices		0.20 - 0.55

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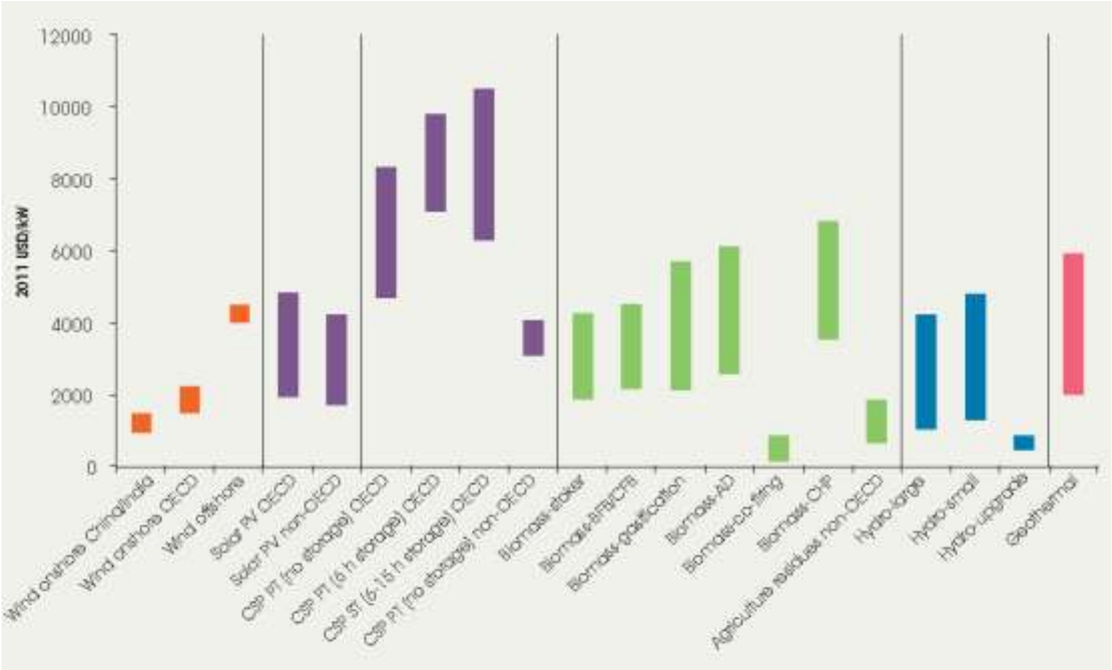
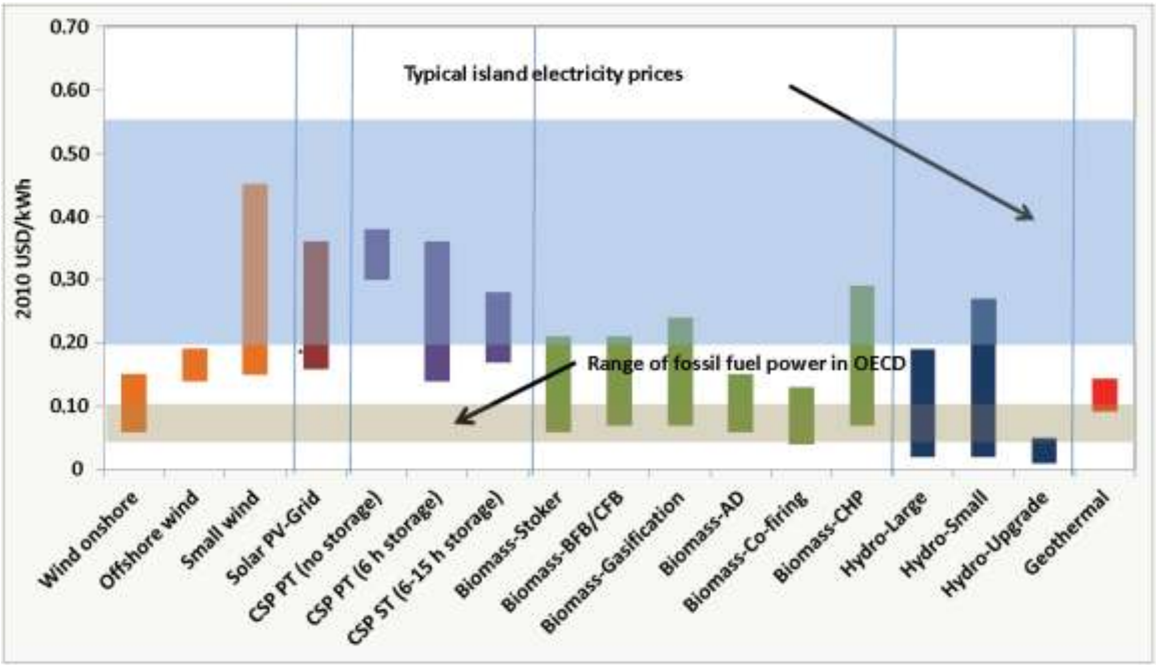
[25] The Organisation for Economic Co-operation and Development (OECD) consists of 34 member countries that include many of the world’s most advanced countries but also emerging countries like Mexico, Chile and Turkey.

Figure 18 Typical Capital Cost Ranges for Renewable Energy Technologies (IRENA, 2013)



Note: CSP = Concetrated Solar Power, PT = Parabolic Trough, ST = Solar Tower, BFB/CFB = Bubbling Fluidised Bed/Circulating Fluidised Bed, AD = Anaerobic Digester, CHP = Combined Heat And Power.

Figure 19 Price of Renewable Power (USD/kWh) Compared to Typical Prices of Electricity in Pacific Islands and OECD countries (IRENA, 2012a)



Note: Assumes the Cost of Capital is 10%.CSP = Concetrated Solar Power, PT = Parabolic Trough, ST = Solar Tower, BFB/CFB = Bubbling Fluidised Bed/Circulating Fluidised Bed, AD = Anaerobic Digester, CHP = Combined Heat And Power.

Because of the high price of electricity on Pacific Islands (0.20 – 0.55 USD/kWh), the cost of electricity generated from biomass, hydropower and geothermal generation technologies are cheaper than power from fossil fuels and therefore financially viable. If the wind and solar resources are good, then wind generators and solar photovoltaics are also cost competitive and financially viable.

4.4 SUPPORTIVE ENERGY POLICY ON SMALL ISLANDS

4.4.1 Overarching Considerations

There are several overarching considerations that should be incorporated into the planning of a sustainable energy supply on islands. The human resources often include a strong sense of place and community – valuable resources for collective action. Focussed efforts to engage the local population will encourage a sense of involvement in the projects and help islanders feel empowered to improve their own future. Moreover, the developmental benefits of the energy project should improve quality of life on the islands in an equitable and practical way. My experience with energy projects in SIDS has taught me that when planning a sustainable energy supply for islands, there are some important considerations:

Community involvement

A community involvement approach from the early stages of the project may be better than a top-down approach in which an external agency (governmental or non-governmental) pre-determines the parameters of the project. Public education is an important step. The island community should be made aware of the benefits of energy efficiency measures and renewable energy technologies. In order to encourage the local enthusiasm for an energy project, the environmental and economic benefits and drawbacks of available energy sources should be explained and discussed at public meetings.

It is very important to recognize the realities of life and work in a small island context, and to give due consideration to the real needs and priorities of the people. The community should be given a say in how the quality of their lives could be improved and what is required to do it, thereby giving them the self-confidence to help themselves. The success of the energy project can be further ensured through community participation in the installation, operation and maintenance of energy infrastructure, so that they feel a sense of ownership in the project and have an incentive to take good care of the energy system.

Technical Maturity

To ensure successful projects, only mature technologies should be used on islands. Technologies that are still under development should not be considered because solving teething problems in remote locations is difficult and expensive. Only those options that are fully commercialised and well proven under field conditions should be selected.

Reliability is more important than efficiency

People on small islands have no hinterland of alternative resources to draw upon. When a system fails the results may literally spell life or death. A very important consideration is therefore the reliability of the equipment and of the energy system as a whole. Extended warranties should be negotiated with the manufacturers and suppliers. It is far better to have a reliable system than to have a more efficient system that is less reliable.

Suitability to local conditions

System design and equipment selection has to take into consideration the limited infrastructure, human resources and geographical scale of many small islands, such as the maximum capacity of roads and bridges, and handling capacity of the ports. Equipment should be able to operate successfully over its entire lifetime in the harsh tropical marine environment found on most Pacific islands. Equipment with a successful track record of long term operation in similar conditions is preferable.

Ease of Installation, Operation & Maintenance

Technical skills will develop over time, but at the early stages, equipment has to be easy to install, operate and maintain under local island conditions. High capacity cranes may not be available on the islands to lift and install heavy equipment such as large wind turbines. Smaller wind turbines and alternate installation techniques such as tilt-up towers can be used instead. This will make it possible to lower the wind turbine towers before the devastating cyclonic storms that hit the Pacific island countries once every few years.

4.4.2 Local Benefits

Capacity-Building and Training

Capacity building of in-country manpower is essential so that they can handle the whole project cycle including energy planning, production, distribution and usage. Training in installation, operation and maintenance of the equipment may be imparted at manufacturers' facilities, on existing RE project sites and/or during installation of the systems. Project management capabilities may have to be built up or up-graded. Capacity building is an on-going process because new skills may be required or new employees trained.

Technology Transfer and Local Manufacture

Table 27 gives a list of RE technologies that are suitable for local manufacture in Pacific Island Countries. Local manufacturing creates jobs, benefits the local economy and makes the island countries more self sufficient. Although some manufacturing can be carried out in existing mechanical workshops, additional machinery and training may be necessary.

A technology transfer arrangement with the supplier should include training in manufacturing processes, installation, operation and maintenance, as well as quality assurance. For production volumes to be financially viable, exports to regional and international markets may be necessary.

Table 27 Technologies Suitable for Local Manufacture in Pacific Island Countries (Raghavan, 2003)

ENERGY RESOURCE	TECHNOLOGIES
Hydro power	• Cross-flow turbines • Pelton turbines
Biomass	• Biogas plants • Gasifiers • Plant Oil production & usage
Wind energy	• Wind Electric Generators • Mechanical Windpumps
Solar energy	• Heaters • Driers • Cookers • Solar Photo Voltaic module assembly

Productive Uses of Energy for Income Generation

The quality of life on the islands can be improved by utilising the RE power supply for productive activities in the daytime. Such income generating activities include sawmills, oil mills, weaving, handicrafts, and processing of locally available produce. Utilization of power in the daytime will increase the capacity utilization factor of the RE power plant, thereby improving its financial viability.

To facilitate the rapid growth of small and medium scale enterprises (SMEs), business development skills of the local entrepreneurs may need to be upgraded in several key areas:

1. Preparation of business plans
2. Loan applications
3. Small enterprise management
4. Equipment selection and procurement
5. Marketing.

One of the major challenges faced by the governments of the Fiji Islands and other Pacific Island Countries is the continuing migration of islanders from the smaller outer islands to larger islands, and from rural areas to towns, especially national capitals. The predominantly rural society of the Fiji Islands is likely to be transformed into a predominantly urban society within 20 years (Russell 2009). On islands worldwide, this trend has negative impacts on cultural survival, retention of important traditional knowledge and food security, and stresses urban infrastructure and services (Novaczek *et al*., 2001). By providing employment opportunities on the smaller islands, energy projects may raise the income levels and quality of life of the people, thereby reducing their migration to the larger islands and urban centres. Health and educational facilities on the islands can be significantly improved by providing a reliable power supply to schools and hospitals.

4.5 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

4.5.1 Conclusions

A holistic evaluation of coconut biodiesel using Emergy analysis and Embodied Energy Analysis clearly indicates that this renewable energy resource is not a sustainable alternative to fossil fuels. The Environmental Loading Ratio (8.57) of coconut biodiesel is very high and the Emergy Index of Sustainability (0.15) is very low. Moreover, biodiesel is not carbon neutral because the production process emits 1.38 tons CO_2 per ton of biodiesel (36 g CO_2 per MJ of biodiesel). From a holistic perspective, biofuels are not the answer to the search for sustainable alternatives to fossil fuels.

The idea that renewable energy can solve the whole problem of sustainability and sustainable development is not valid. In the hype surrounding ‘green’ renewable energy as the solution to all our energy problems, perhaps we are missing something. It is necessary to take a step backwards and recognise that the root cause of the vulnerability of small island countries is the increasingly high dependence on energy in their development and economic growth paradigms. There is no magic bullet in the form of renewable energy or biofuels that will satisfy this ever growing hunger for energy. What is required is a shift in the development paradigm that can delink the natural human urge towards a better quality of life and happiness from the energy intensive strategies that are currently being pursued.

After all, when European explorers first discovered Polynesia barely three centuries ago, they found that the Pacific islanders were some of the happiest people in the world, living a low energy lifestyle without using any fossil fuels. The highly energy-intensive lifestyle of people in the developed countries, based primarily on fossil fuels, is slowly destroying our planet. A different development pattern that is based on less energy usage is necessary. The whole issue of sustainable energy has to be revisited.

> Ecologists Howard T. Odum and Elisabeth C. Odum, in their groundbreaking book Prosperous Way Down (Odum & Odum, 2001) describe the undesirable consequences of our current, unsustainable path, and lay the foundation for avoiding a crash in the human economy and human civilization. Odum & Odum point out that most populations of organisms, including many human civilizations, have taken the natural, efficient path of apocalyptic downfall. But they also demonstrate how, with some thought and foresight, we can pursue an alternative path: They show us a prosperous way down from the world's economic peak. . . . Odum & Odum provide myriad specific solutions for the impending descent, ranging from reorganization of cities to restoration of waters and from ubiquitous transmission of knowledge to universal appreciation for alternative lifestyles (i.e. those that are not based on procreation and conspicuous consumption). (McPherson, 2005, p. 118)

"There has been a growing consensus that the collapse of Easter Island is an alarming example of the dependence of human societies on their environment and of the devastating consequences of irreversibly damaging that environment" (Nagarajan, 2006, p. 297). "The people of Rapa Nui (Easter Island) disappeared leaving only their monuments as an example to the world of what happens when culture cannot downsize to fit its environmental production" (Odum, 2007, p. 393). Unless our civilisation takes timely action, our fragile *earth island* could very well meet a dreadful fate similar to that of Rapa Nui.

4.5.2 Recommendations for Future Work

It is essential to get off fossil fuels. Since some level of energy is required, other local energy resources have to be studied and compared to find alternatives that are more sustainable than coconut biodiesel. These could be other, more sustainable ways of using coconuts for power generation, or other renewable energy resources. It is therefore recommended that a thorough Emergy analysis and Embodied Energy Analysis should be carried out for the following alternate methods of generating power, so that their sustainability can be compared with the use of coconut biodiesel and petroleum diesel:

1. The husk & shell of coconuts, which are by-products, can be burned in a biomass gasifier. The fuel gas from the biomass gasifier (called *producer gas*) can be used to generate electricity in a gas engine generator or a diesel engine generator[26]. The transformity of shell & husk will be lower than that of coconut biodiesel but the additional transformity of the biomass gasifier has to be accounted.

2. Pure coconut oil can be used as fuel in a diesel engine instead of converting the oil to biodiesel. The advantages of using pure coconut oil as a fuel are: a) coconut oil is cheaper than coconut biodiesel because of the additional cost of biodiesel conversion; and b) chemicals (alcohol and catalyst) are not necessary. However, coconut oil is more viscous than petroleum diesel and its combustion properties are different. To prevent damage to the diesel engine, the use of coconut oil will require proper engine adaption / modification that will depend on the type of engine (direct injection or indirect injection) and the usage (stationary engine for power generation or automotive engine for transport). The transformity of coconut oil is lower than that of coconut biodiesel, but the emergy of the materials and labour required for engine modification have to be accounted.

   Similarly, the oil and biodiesel from other biofuels crops such as Jatropha should be evaluated using Emergy Analysis.

3. Sustainability of technologies that harness other renewable energy resources in small islands need to be studied, such as solar, wind, wave power, ocean thermal energy conversion (OTEC) and geothermal. Some technologies have very useful

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[26] A gas engine generator has spark ignition; it can therefore operate on 100% producer gas. A diesel engine generator has compression ignition; therefore it can operate only on around 80% producer gas, because it needs around 20% diesel fuel to ignite the fuel air mixture (Raghavan, 2010).

co-products that have a high value on many small islands. For example, in addition to electricity, OTEC produces fresh drinking water that is scarce on some islands and has to be imported using tankers. OTEC also brings in nutrient rich ocean water that can be used for aqua-culture. The profitability as well as the sustainability issues of the by-products have to be accounted.

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6 APPENDIX

Financial data for the agricultural and industrial phases in the production of coconut biodiesel is given in the following tables and figures:

- Break-down of costs and returns are in Tables 28 to 31, and Figures 20 to 23.
- Net profits are given in Table 32, and Figures 24 and 25.
- Value added by intermediate products are in Table 33, and Figures 26 and 27.

Table 28 Production of Mature Coconuts (Compiled from data in ERIA, 2010)

ITEMS	QUANTITY		COST	% of Total
	Quantity	Units	USD / ha	
Fertilizer, Chemicals	1	bag /yr	26	8%
Weeding, Fertilizing, Maintenance	12	person days /yr	66	21%
Harvesting, Dehusking, Hauling	8	harvests /yr	177	55%
Transportation, Delivery	8,000	nuts	53	16%
TOTAL COST of Dehusked Nuts			322	100%

NOTES:
For a one hectare plantation.
8 harvests per year (once every 45 days)
Average yield = 10 nuts /tree /harvest
Average weight of whole nut = 1.2 kgs
Dehusked nut = 67% by weight of whole nut

Figure 20 Cost Break-down for Production of Mature Coconuts (ERIA, 2010)

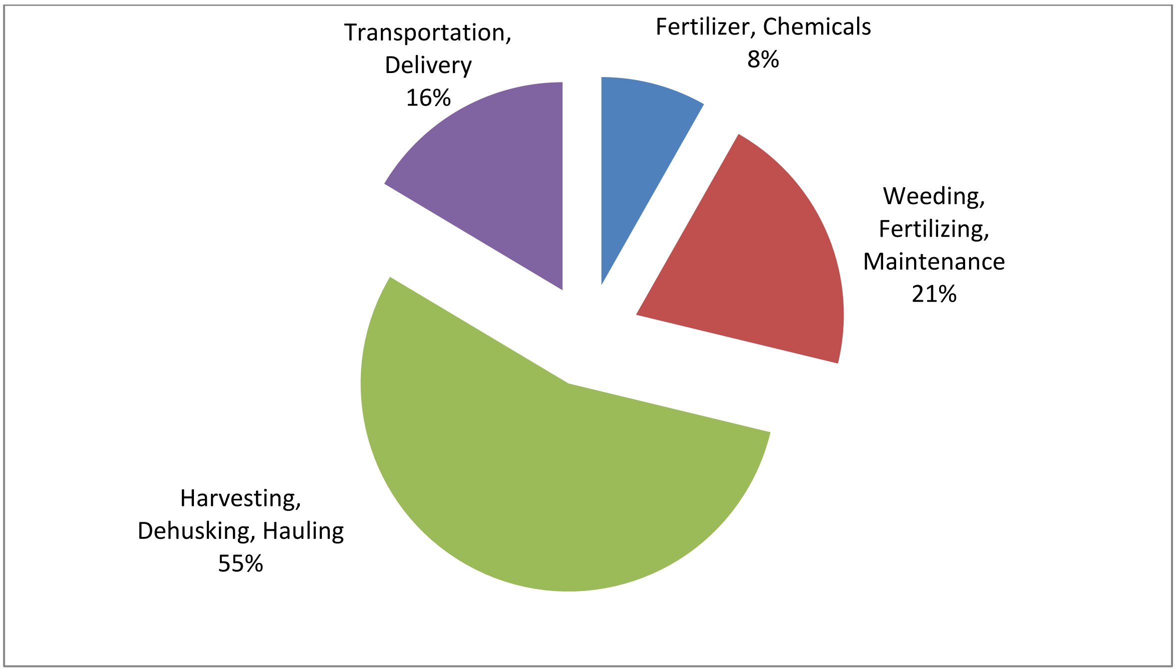

Table 29 Production of Copra from Mature Coconuts (Compiled from data in ERIA, 2010)

COSTS

ITEMS	QUANTITY		COST	% of Total
	Quantity	Units	USD / ha	
Mature Dehusked Coconut Input	6,432	kgs /ha	639	89%
Labour	6	person days	40	6%
Transportation	2,123	kgs /ha	13	2%
Overheads -fees, taxes, sales, admin.			22	3%
TOTAL COST of Copra	2,123	kgs /ha	714	100%

RETURNS

Selling Price of Copra	2,123	kgs /ha	1,030	
PROFIT from sales of COPRA			317	92%
Byproduct: Coconut Shell	1,441	kgs /ha		
Less - Shell used as fuel	1,000	kgs /ha		
PROFIT from sales of SHELL	441		29	8%
TOTAL PROFIT			346	100%

NOTES:
For a one hectare plantation.
Average copra yield = 33% by weight of dehusked nut
Coconut Shell yield = 22.4% by weight of dehusked nut

Figure 21 Cost Break-down for Production of Copra (ERIA, 2010)

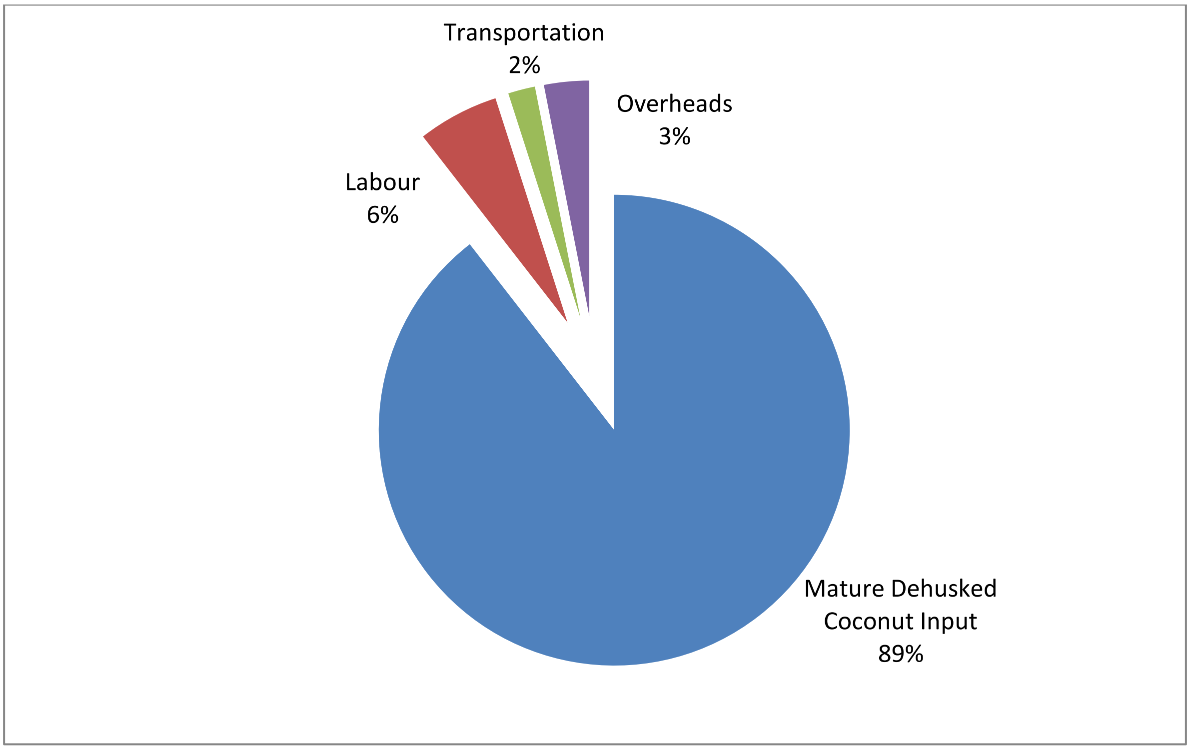

Table 30 Production of Coconut Oil (CNO) from Copra (Compiled from data in ERIA, 2010)

COSTS

ITEMS	QUANTITY		AMOUNT	% of Total
	Quantity	Units	USD / ha	
Copra	2,123	kgs /ha	1031	95%
Chemicals	7	kgs	14	1%
Labour	1	person days		1%
Overheads				3%
TOTAL COST			1086	100%

RETURNS

Selling Price of CNO	1,208	kgs /ha	1119	
PROFIT from sales of CNO	1,208	kgs /ha	33	28%
By-Products: Copra Meal	679	kgs /ha	52	
Fatty Acid .	64	kgs /ha	32	
PROFIT from sales of By-Products			85	72%
TOTAL PROFIT			118	100%

NOTE:

For a one hectare plantation.

Crude CNO yield = 61.5% of Copra; Copra Meal = 32% of Copra by weight

Refined CNO yield = 92.5% of Crude CNO by weight

Fatty Acid = 4.9% of crude CNO by weight

Figure 22 Cost Break-down for Production of Coconut Oil (ERIA, 2010)

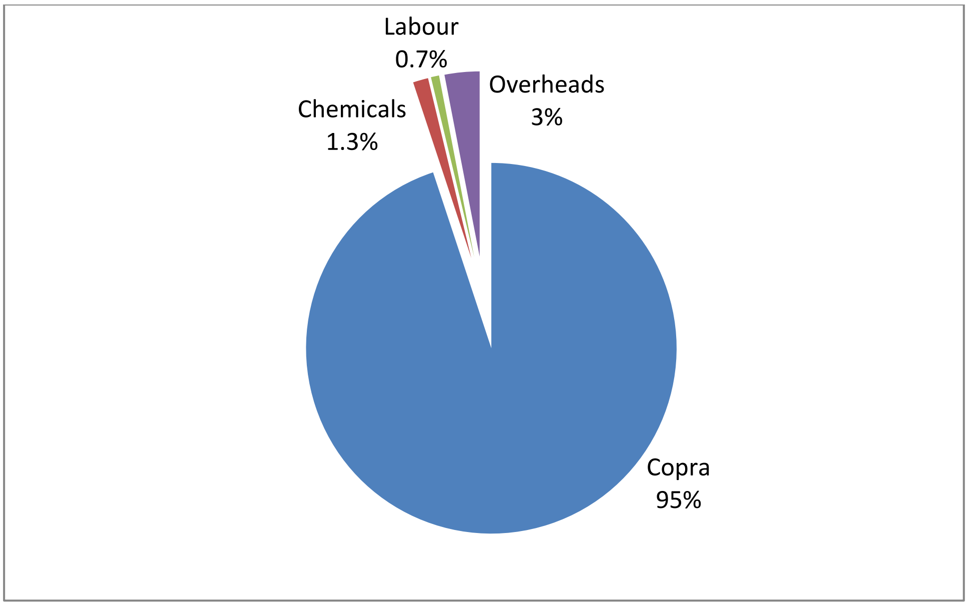

Table 31 Production of Biodiesel from Coconut Oil (Compiled from data in ERIA, 2010)

COSTS

ITEMS	QUANTITY		AMOUNT	% of Total
	Quantity	Units	USD / ha	
Coconut Oil	1,208	kgs /ha		
@ 0.915 kg /litre	1,320	litres /ha	1,119	88%
Methanol, 14.5%	191	litres	80	6%
Catalyst, 0.67%	8.8	litres	7	1%
Labour	1.76	person days	14	1%
Overheads	1,320	litres /ha	58	5%
TOTAL COST			1,278	100%

RETURNS

Selling Price of Biodiesel	1,320	litres /ha	1,282	
Profit from sales of Biodiesel	1,320	litres /ha	4	11%
By-Products: Glycerin, 12.5%	151	litres	27	85%
Acid oil, 0.55%	6.6	litres	1	4%
Profit from sales of By-Products			28	89%
TOTAL PROFIT			31	100%

NOTE: For a one hectare plantation.

Figure 23 Cost Break-down for Production of Biodiesel from Coconut Oil (ERIA, 2010)

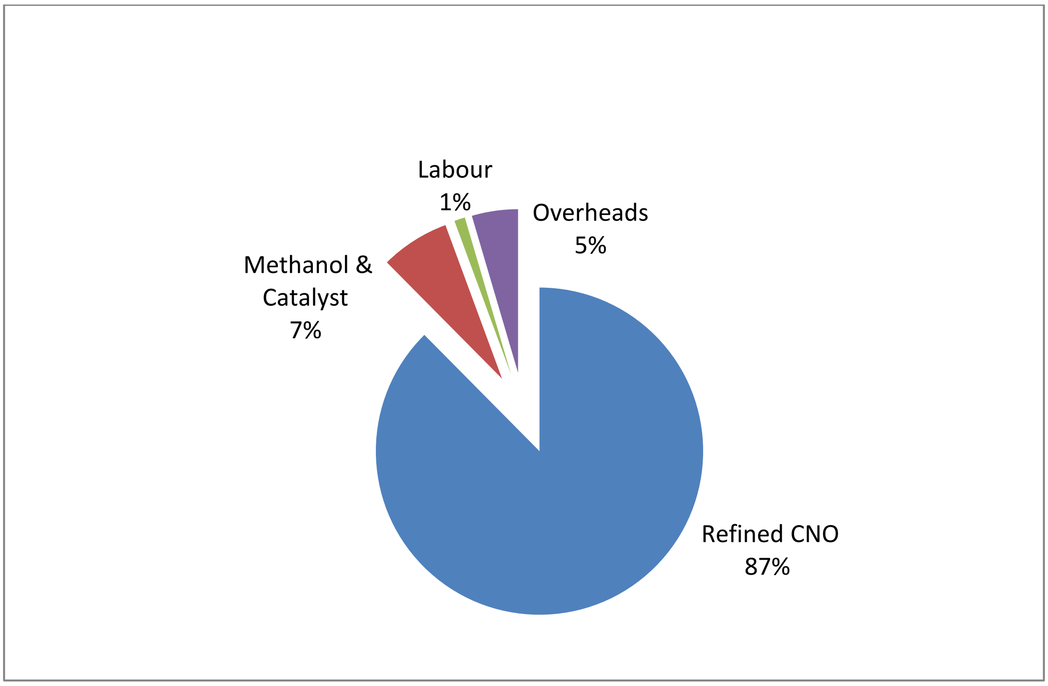

Table 32 Net Profits in Production of Biodiesel (Compiled from data in ERIA, 2010)

PRODUCT	NET PROFIT	BY-PRODUCT SALES	TOTAL PROFIT
	USD /ha	USD /ha	USD /ha
Dehusked Nut	343	-	343
Copra	317	29	346
Coconut Oil - CNO	33	85	118
Biodiesel	4	28	31
TOTAL	697	142	839

NOTE: For a one hectare plantation.

Figure 24 Profits in the Stages of Production of Biodiesel (USD /ha) (ERIA, 2010)

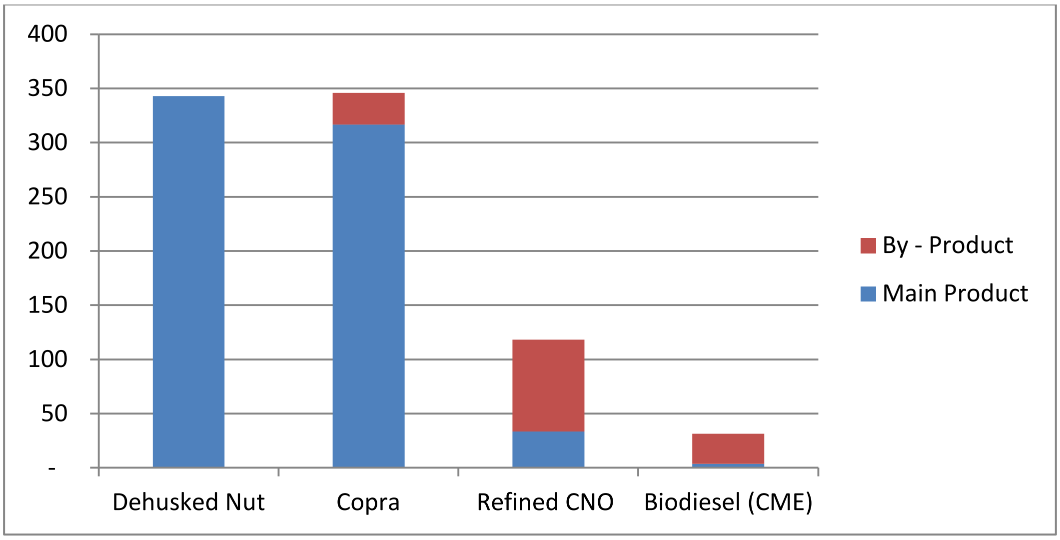

Figure 25 Percent Profits in Biodiesel Value Chain (ERIA, 2010)

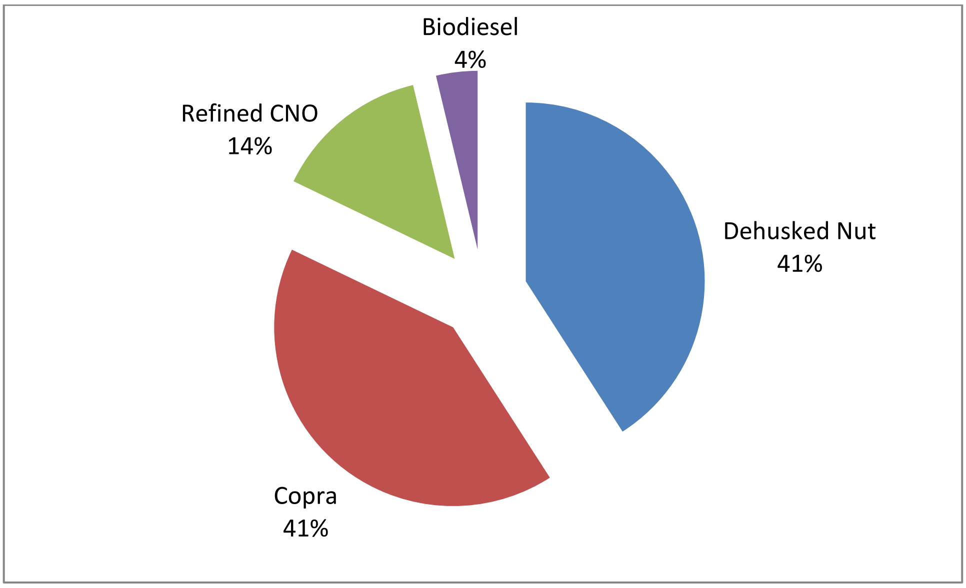

Table 33 Total Value Added for Intermediate Products (Compiled from data in ERIA, 2010)

PRODUCT	TOTAL PROFIT	WAGES PAID	TAX REVENUE	TOTAL VALUE ADDED	% of Total
	USD /ha	USD /ha	USD /ha	USD /ha	%
Dehusked Nut	343	243	exempted	586	45%
Copra	346	40	121	507	39%
Refined CNO	118	8	41	167	13%
Biodiesel	31	14	11	56	4%
TOTAL	839	304	173	1316	100%

NOTE: For a one hectare plantation.

Figure 26 Break-down of Value Addition in Production of Biodiesel (USD/ha) (ERIA, 2010)

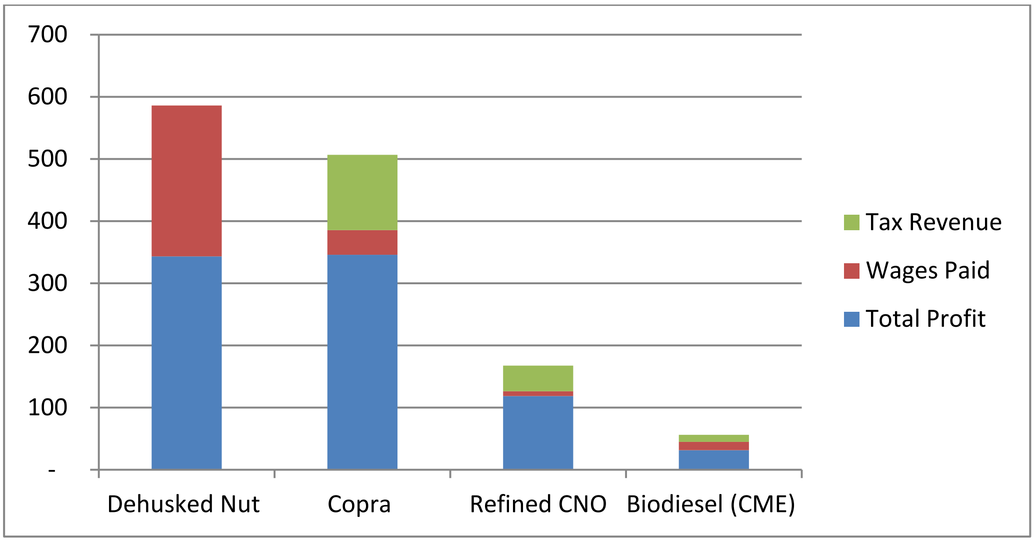

Figure 27 Total Value Addition in Production of Biodiesel (ERIA, 2010)