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Sustainable Building Materials In French Polynesia

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Abstract – **Developing island economies, such as French Polynesia, are heavily reliant on imported goods. Shipping materials around the world is very energy intensive and contributes to global environmental pollution. A system for the local manufacturing of sustainable building materials offers numerous environmental and economic incentives. From a global perspective, reductions in energy demand and pollution generation are major environmental benefits. Local incentives include invigorating the economy, creating jobs, reducing waste, and supporting self-sufficiency. Possible sustainable materials investigated included palm oil fuel ash, cement composites reinforced with coir fiber, recycled plastic products, three-dimensional engineered fiberboard, and local forestry products. Research revealed coir binderless boards to be the most appropriate material to meet design, economic, and sustainability criteria in French Polynesia. A system-wide analysis of carbon dioxide and energy expenditure shows that coir binderless boards are dramatically favorable over existing technologies. In addition, a cost comparison strengthens the argument in favor of the coir binderless board. Finally, an implementation strategy is presented with recommendations for future research.**

Index Terms – carbon dioxide, coir, French Polynesia, sustainable materials.

INTRODUCTION

Sustainability is the capacity to balance economic, ecologic, and human resources to enable continual growth and development without compromising the integrity of each account. This principle has diverse applications and can be implemented on several levels if the proper care and attention is given. In the case of a developing economy that relies heavily on imported goods, such as French Polynesia (FP), the introduction of a sustainable system in their infrastructure has many benefits. A system for sustainable building materials has great potential to reduce global energy use and pollution from energy intensive processes and shipping. Locally such a system can provide suitable housing, invigorate the economy, add jobs, divert current waste flows, and enable a greater level of self-sufficiency.

BACKGROUND

French Polynesia is the formal name for the territory of French overseas lands, which are comprised of a large cluster of islands and atolls located in the South Pacific Ocean. Its primary industries are tourism, pearl farming, deep-sea fishing and agriculture. The average income is $17,500 US; however, the average cost of a single-family home is $600,000 US.[i]

The climate is tropical, yet moderate. French Polynesia is susceptible to hurricanes, typhoons and tropical storms. In 1983, Cyclone Veena destroyed much of the housing on many of the islands. The French government responded to this crisis by developing emergency, hurricane-resistant kit-homes. With the aid of this program, 600 homes were constructed. When typhoon William hit in 1992, the kit-homes were some of the only residencies to survive. Shortly thereafter the program was revitalized with the introduction of the MTR II model. As of 1995 the MTR has been sold commercially, the current design and materials cost around $60,000US[i], as a type of affordable housing for French Polynesians. The French government continues to subsidize 350 homes, now known as the OPH House (Office of Polynesian Housing), per year and sells an additional 150 homes without subsidies.[i]

In a previous course, Energy & Resources 291, at the University of California at Berkeley (UCB) students focused on the climatic performance of the kit homes. Users of the kit homes stated that the residences were too hot to remain inside during warm weather. Specific design improvements were implemented to gain an understanding how ventilation could increase performance without making drastic changes to the original design. From this data, Madelaine Fava (Project Architect) has designed a fourth prototype and enlisted the aid of the authors to provide sustainable replacements for current building materials.

The initial directive to replace materials used in the kit homes with sustainable substitutes was the starting point for the research conducted for this report. However, during the course of the research the project scope was expanded to focus on the broader topic of sustainability. An economically sustainable material cannot be limited to one application (such as the kit homes). Further, the key concerns of French Polynesia are unemployment, loss of traditional livelihoods and reliance on foreign goods.[ii,iii] To address these issues with the principles of sustainability, the research project focused on finding a regionally available and renewable material that would be appropriate in numerous applications and that could be locally manufactured. Thus the economic, ecologic and human concerns of French Polynesian society would be concurrently addressed.

APPROACH

The final project scope resulted from an iterative approach to the problem statement. An element matrix was created to organize the information, properties and applications, for all materials investigated. The materials in the matrix were then evaluated based upon the resources available in French Polynesia and other site specific factors (e.g. humidity and cultural preference). For example, the OPH project architect and the authors were initially interested in utilizing recycled household plastics for making interior panels, non-structural frames, roofs, and waterproof bathroom and kitchen paneling.[iv] As the plastics are currently exported to Singapore for recycling, the reuse scheme would have eliminated the need to export waste and import some building materials. During the research trip to French Polynesia, the authors discovered that insufficient quantities of these plastics exist for even a small scale production.[v] As the team was concurrently pursing other material sources, this development did not require a new start for the research. The following diagram best illustrates this approach:

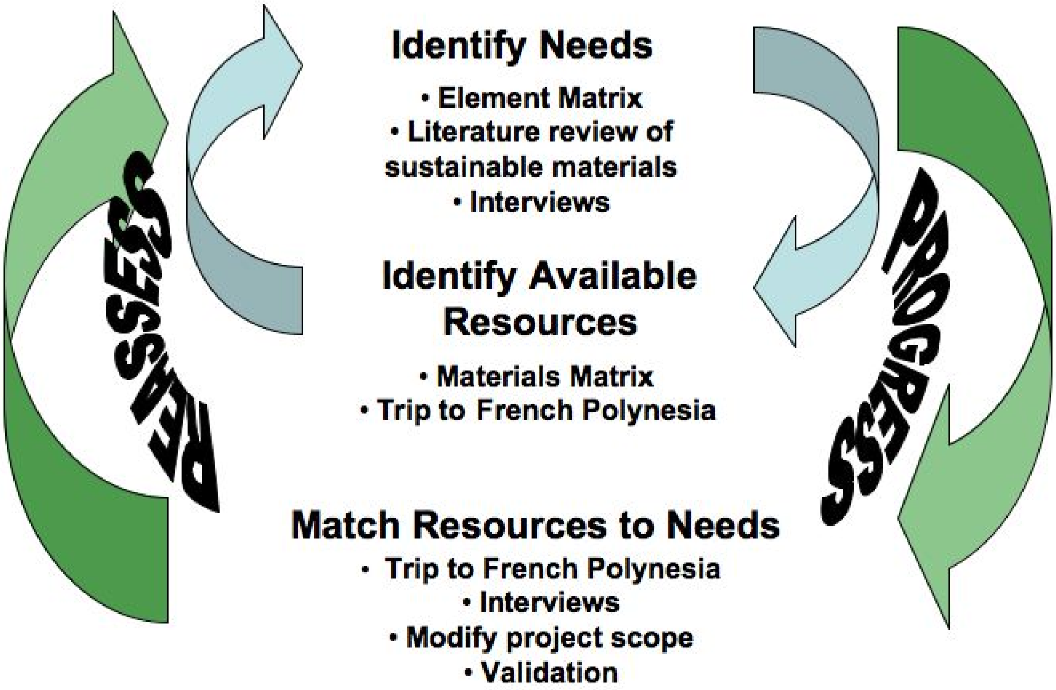

FIGURE 1
PROJECT APPROACH.

The approach used by the authors has enabled a flexibility of project deliverables and thereby has permitted a change in scope from the initially confined assignment of finding sustainable materials for kit homes. The criteria for the project were realizable solutions, minimal environmental impact, satisfaction of user needs, high performance materials, and a system-wide approach to sustainability in French Polynesia. A literature review was conducted for all possible sustainable materials.[iv,vi,vii,viii,ix,x] Non-sustainable materials were not investigated as they were already in use in French Polynesia and would not have required any shift in current practice. The authors' are recommending the most viable sustainable construction material technology and a manufacturing process that will provide the most local benefit.

GOALS

The objective of the research was to find materials that addressed the needs of the local community and satisfied a system-wide approach to sustainability. Focusing on a holistic solution to sustainable materials allowed the authors to address the issues of environmental impact, local livelihoods, local production, and an expanded market base for the chosen products. The research conducted and the deliverables addressed within the scope of the project are as follows:

TABLE I
GOALS

Task	**Level of Goal**
Identify appropriate technologies	Minimum
Prepare support package • Reviewed material to support next group	Minimum
Quantify environmental indicators • Compare current and proposed systems • Include embodied energy content (EEC), greenhouse gas (GHG) and transportation emissions.	Maximum
Cost analysis • Use available information to provide a comparison between current products and those proposed.	Maximum
Develop schematic feasibility plans: • One island vs. multi-island plans • Alternative energy plan.	Minimum/ Maximum
Suggest new scope for contract between UCB and FP for testing of proposed material.	Maximum (Future project)
Outreach • Find champions and sustainable partnerships.	Minimum/ Maximum (Future project)
Future Implementation • Test program • Pilot scale plant	Maximum (Future project)

MATERIALS CONSIDERED AND EVALUATED

A review of sustainable materials was undertaken to assess the performance, feasibility of use, and environmental impact of each proposed material. Following the reconnaissance trip to French Polynesia these options were accordingly re-evaluated.

Palm Oil Fuel Ash- a supplementary cementitious material

Palm oil is extracted from the fruit, copra, of the palm oil tree (see Figure 2). The oil extraction process is powered by electricity, if electricity is not available then the needed electrical energy can be generated by burning the palm oil tree byproducts in a steam turbine. The ash generated by burning the byproducts, palm oil fuel ash (POFA), is 5% by weight of the original solid materials. As with other ash byproducts (*e.g.* blast furnace slag and fly ash), POFA can be used as a supplementary cementitious material due to its pozzolanic properties.[vii] It has also been shown that POFA mitigates the expansive forces of alkali-silica reaction, a common chemical attack in concrete structures.[vii] In Tahiti, the fruit of the coconut palms are used to produce coconut oil. Unfortunately, the sole Tahitian coconut oil producer uses electricity to power the extraction process so no ash is generated at the factory.

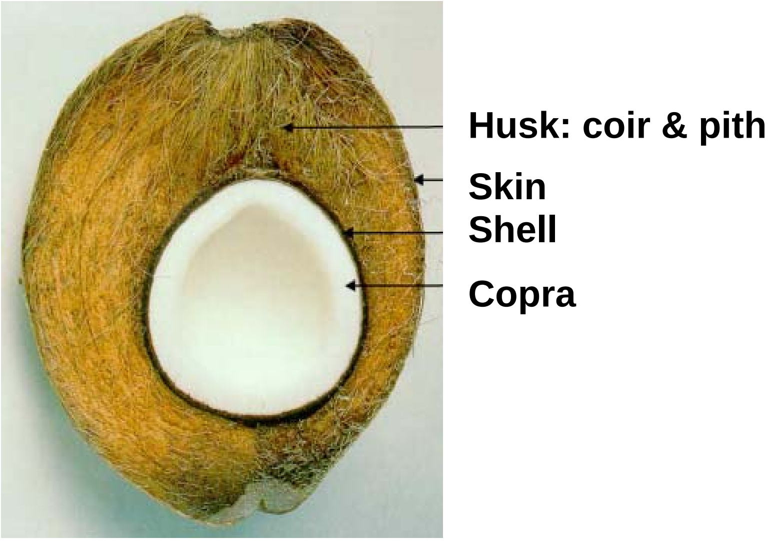

FIGURE 2
CROSS SECTION OF A COCONUT. (COURTESY OF AGROTECHNOLOGY)

Cement Composites Reinforced with Coir Fiber

The use of vegetable fibers for reinforcing offers a unique solution to increase structural performance at a low cost with widely available materials. Fiber composite materials offer increased ductility, toughness, and post-cracking flexural strength. Coir fiber, also known as the coconut husk, is widely available in French Polynesia.

The kit-homes were found to utilize exterior and interior fiber cement panels of 0.5 and 0.125 inch thickness respectively. From conversations with the general contractor of the kit homes these panels can be used in a wide range of construction applications.[xi] The initial interest in composite cementitious materials was based upon the assumption that significant amounts of material were being used similar to fiber reinforced concrete structures, which are often several feet thick. The minimal material requirements of the panels, fractions of an inch thick, indicate that the replacement of the imported fiber with locally available fiber would not create a significant change in the current material importation scheme. Therefore, this technology was not seen as sufficient in developing a sustainable material system in French Polynesia.

Recycling in French Polynesia

Assuming a sufficient amount of recyclable input materials is available the utilization of recyclable wastes offers one possible solution for sustainable materials in French Polynesia. Such a system could reduce imports by manufacturing building materials from recycled waste generated on the islands. The additional benefit of this scheme would be the elimination of extensive shipping currently used to send the recyclables to other countries for processing. Finally recycled plastic materials are well understood and have desirable performance properties.

Recycled Plastic Products: Polymeric Panels

One useful product made from recycled plastics is polymeric panels. Polymeric panel is a term utilized to describe panels that are composed from a mix of common recycled plastic wastes such as polypropylene, polystyrene, and polyethylene. This technology can be utilized for the production of interior panels used in the construction of affordable housing units.[iv]

Recycled Plastic Products: Cement Tiles from Recycled Plastic Wastes

Plastic wastes are a viable component of cementitious tiles used for flooring in kitchens and bathrooms. The plastic wastes used in this technology are common recyclables, including LDPE (low density polyethylene), HDPE, and polystyrene with small amounts of PET (Polyethylene Terephthalate).

Unfortunately, the use of recycled waste to generate building materials was not seen as an appropriate scheme for several reasons. The major drawback to such a system is the limited amount of recyclables generated in French Polynesia (see Table II). When a materials production scheme was proposed to the sole recycling organization, Société Environment Polynesien, they stated that French Polynesia did not produce sufficient quantities for such a program.[xii] Currently, recyclable plastics in French Polynesia are collected over a period of three months before large enough quantities can be accumulated to justify shipping to Singapore where they are recycled (see Figure 3).[xii] Therefore, polymeric panels and cement tiles from recycled plastic wastes are not feasible solutions.

TABLE II

AMOUNT OF RECYCLABLES (PAPER, CARDBOARD, PLASTIC BOTTLES, ALUMINUM CANS, AND METAL TIN) COLLECTED FROM VARIOUS SOURCES (TONS).[XII]

	2001	2002	2003	2004	2005	2006
Industry	1633	1989	2292	2471	2326	2653
Municipality	0	492	627	924	1065	821
Residential	1241	1935	2474	3039	2920	3102
Total	2874	4416	5393	6434	6311	6576

FIGURE 3
BALES OF SORTED PAPER WAITING FOR SUFFICIENT QUANTITIES TO FILL A CARGO VESSEL.[xiii]

Three-Dimensional Engineered Fiberboard

The United States Forest Products Laboratory (FPL) has been investigating the application of agricultural, wood, and paper fibers for use in building materials for decades. The product can be shaped in a variety of ways. The sheets and molded parts are made through a versatile production process that can utilize nearly any bio-fiber resource. A specific study had not yet been done using coconut husk.

The major concern regarding three-dimensional engineered fiberboard is the high humidity levels in French Polynesia. During the humid season, November to April, the humidity ranges from 80-90%. This level of humidity greatly exceeds the optimal range, 35-55% relative humidity, for an indoor environment. In the dry season, May to October, the humidity levels decrease but still will pose a performance issue for three-dimensional engineered fiberboard. The lack of residential air conditioning further compounds these issues. Currently there has yet to be scientific study ensuring the mechanical and architectural properties of three-dimensional engineered fiberboard in extreme humidity conditions. Therefore, this material requires significant testing and analysis before it can be seen as an appropriate technology in French Polynesia.

Forestry in French Polynesia

The construction industry in French Polynesia currently utilizes significant amounts of wood imported from the United States and Canada. Kit homes in Moorea were found to utilize both Douglas fir and pine.[xiv] The abundance of coconut trees is seen by some government officials as a viable material source that would provide jobs and an end product in the outer atolls.[xv] However, experts in the wood industry suggested that a production mill would not be financially viable supporting more than a few workers.[xvi] Further, the wood obtained from the coconut trees would only be appropriate as a finish material and not structural elements.

The Caribbean Pine is an alternative. Plantations of Caribbean Pine were started in 1977 to create a source of locally grown wood, however the results are not overwhelmingly positive.

Contractors in the building industry state that these products are difficult from a workability perspective.[xi] However, in outdoor settings where durability is a crucial concern this material has been proven appropriate in French Polynesia. Despite workability concerns, Caribbean Pine is currently utilized for outdoor decking in the kit homes due to its extreme resistance to terminates, weather, and aging (see Figure 4).[v,xi]

FIGURE 4

CARRIBEAN PINE USED AS A DECKING MATERIAL IN A KIT-HOME IN FRENCH POLYNESIA.[XIII]

Finally, the authors investigate other local woods and bamboo. Various additional woods exist, but are only suitable for handcrafts due to their low strength and durability.[xvi] Bamboo, a member of the grass family, is not seen as a desirable material by the majority of the population, due to the frequent maintenance needs, short life span, poor durability, termite concerns, and the desire for modern housing materials.[i,v,xi] Overall the lack of demand indicates that bamboo is an inappropriate solution.

CHOSEN MATERIAL: COIR BINDERLESS BOARD

During the extensive literature review[i,iv,vi,vii,viii,ix,x,xvii,xviii] conducted for this report, several systems of panel construction were considered. Of the technologies evaluated, one particular coconut husk construction board seemed especially promising. Coconut husk construction board is a relatively mature technology; a feasibility study for large-scale production of a similar product and manufacturing was performed in Sri Lanka in 1978.[xix] The most recent version of the coir board product was developed by the Agrotechnology laboratory in Wageningen, The Netherlands under the direction of Dr. Jan Van Dam. Funding was provided by the United Nations (UN) via the Common Fund for Commodities and was administered through the Food and Agriculture Organization (FAO). Currently, manufacturing facilities are in the advanced planning stages for the Philippines and Indonesia.

The material science technology of the board is very simple and elegant. Coconuts are about 35% coir (or coconut husk) by weight (see Figure 2). This is a heterogeneous material made up of about 30% fiber and 70% pithe intermingled. The pithe is rich in lignin which when heated under pressure exhibits thermosetting behavior. Therefore it makes a strong, stable, and resin-like binder. The coir contains both of the elements, pithe and fibers, needed for a strong, dense building panel.[viii]

The manufacturing process is simple as shown in Figure 5. Coir is dried and ground to yield fibers within a certain range of length. The ground material is formed into molds for the desired product shape. Heat and pressure are applied to bind the material together. Maximum strength is achieved using a temperature of 180°C. A variety of densities can be formed on the same equipment simply by altering the temperature, pressure and hold times. Low density boards (1050 kg/m^3) are applicable for interiors, while the high density boards (1350 kg/m^3) are strong and durable enough for exterior use. Table III summarizes the key material properties.

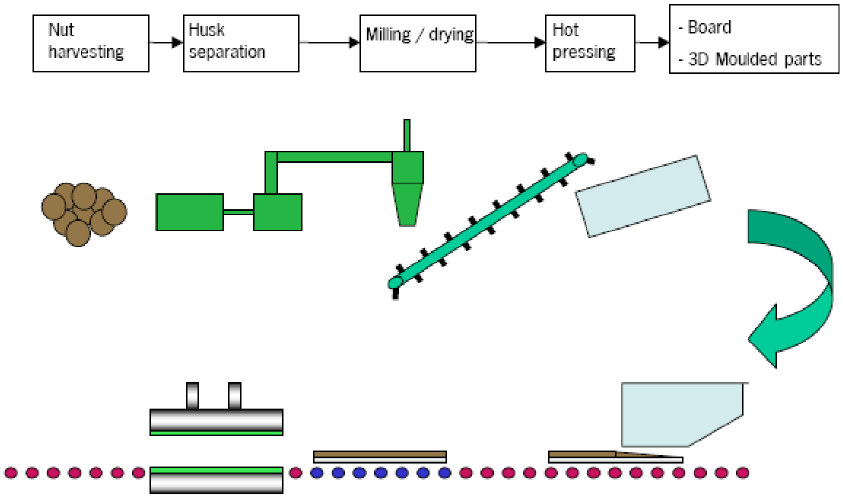

FIGURE 5
COIR BOARD MANUFACTURING PROCESS. (COURTESY OF AGROTECHNOLOGY)

TABLE III
COIR BOARD PROPERTIES

Coir Binderless Boards*		
	Medium Quality Boards	High Quality Boards
Properties		
Density kg/m^3	1,050	1,350
Moisture content (%)	9	9
Bending Strength (Mpa)	13	47
Bending Stiffness (Gpa)	2	5
Water Resistance	poor	good
Fire Resistance	good	good
Handling & Workability		
Sawing	ok	ok
Sanding	ok	ok
Painting	ok	ok
Drilling	ok	ok
Screwing	ok	after predrilling
Nailing	ok	NO

*Table courtesy of Agrotechnology

ENVIRONMENTAL ANALYSIS OF COIR BINDERLESS BOARDS

The incorporation of sustainable materials into island communities offers the possibility for creating local sustainable livelihoods. As migration to urban centers, mainly Papeete on Tahiti, has grown over the years, keeping local communities in the outer islands of French Polynesia has become a continual challenge for the French Polynesian government.[iii] The main source of employment for numerous people in these remote islands is the production of copra, which is highly subsidized by the French government. The world market price for copra is 20 French Polynesian Francs/kg, but in French Polynesia the rate is 100 French Polynesian Francs/kg.[iii,xvi] Despite the high subsidies, the production of copra in all the island groups has shown significant decline over the past 40 years (see Figure 6). The use of a coconut byproduct would prove instrumental in the revitalization of this industry, while providing local jobs and a value added by-product.

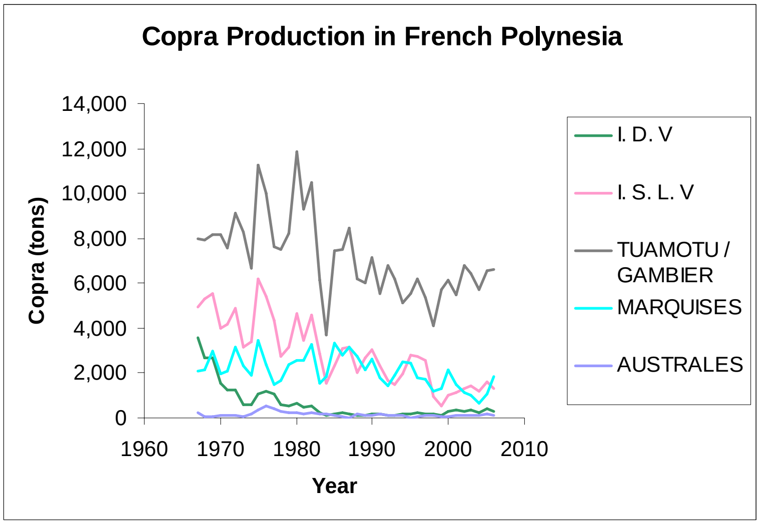

FIGURE 6

PRODUCTION OF COPRA IN THE VARIOUS ISLAND GROUPS OF FRENCH POLYNESIA. (NOTE I.D.V.- ISLES DU VENT, I.S.L.V.- ISLES SOUS LE VENT)[xx]

Comparison to Engineered Woods

The coir binderless panels compare very well on environmental terms to the engineered woods currently imported to French Polynesia. Table IV shows cradle-to-gate[1] GHG emissions data for engineered woods and the coir panel.[ix] The energy requirements of producing coir panels can be provided by either diesel fuel or 100% coconut oil. Even the diesel powered system emits only 13% of the GHGs attributed to the imported engineered panels, when compared by weight. When compared by volume, the percent of average emissions jumps up to 33% which reflects the higher density of coir boards.

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[1] Includes everything involved with acquiring raw materials, transportation to manufacturing unit, and all operations in manufacturing. Gate refers to the gate of the factory.

TABLE IV
EMISSIONS DATA FOR IMPORTED ENGINEERED WOODS AND COIR BOARDS[xx]

Emissions* as CO_2 Equivalent (CO_2e) ** for US manufactured Plywood and Oriented Strand Board (OSB) and local COIR board

Product and source area	Product Density kg/m^3	**CO_2e by volume** kg CO_2E/m^3	**CO_2e by mass** kg CO_2E/kg
Plywood (avg.)	518	332	0.64
Pacific NW	480	235	0.49
South East	555	429	0.77
OSB	651	780	1.2
Total Average	562	**481**	**0.92**
Coir Board using diesel* **	1,356	**157**	**0.12**
Coir values as % of avg	241%	**33%**	**13%**
Coir Board using coconut oil	1,356	**0**	**0**

*Does not include transportation to or within French Polynesia

**Does not include biomass combustion, CO, SO_2

*** 0.75 kg of CO_2 /KWh

Similar to the total GHG data, the embodied energy content (EEC) of the coir binderless boards is much lower than plywood or oriented strand board (OSB). In Table V cradle-to-gate EEC data is presented.[ix] Since the coir panels are made of a waste product, the related EEC is entirely from the process energy required. Both plywood and OSB use large amounts of non-renewable resources in the binders, whereas the coir panel uses none. Comparing the products, the coir panel has only 5% of the EEC attributed to the imported panels, when compared by weight. When compared by volume, the percent of average again jumps up to 11%, which reflects the higher density of coir boards.

TABLE V

EMBODIED ENERGY DATA FOR IMPORTED ENGINEERED WOODS AND COIR BOARDS[xx]

Embodied Energy Content* for US manufactured Plywood and Oriented Strand Board and local COIR board					
Product and source area	Product Density kg/m³	MJ/m³	MJ/kg	KWh/m³	KWh/kg
Plywood (avg.)	518	4,644	8.88	1,290	2.47
Pacific NW	480	3,638	7.58	1,011	2.11
South East	555	5,649	10.18	1,569	2.83
OSB	651	11,145	17.12	3,096	4.76
Total Average	562	**6811**	**11.63**	**1892**	**3.23**
Coir Board**	**1,356**	**751**	**0.55**	**209**	**0.15**
Coir values as % of avg	**241%**	**11%**	**5%**	**11%**	**5%**

*Does not include transportation to or within French Polynesia

**EEC reflects work to manufacture board only as all source material is recovered waste

Current Environmental Costs of Husk Disposal

The burning of waste husk from copra production creates a significant amount of CO_2 emissions. This can be eliminated through the diversion of the waste stream into the production stream of the coir board. The possible reduction of CO_2 by the implementation of coir board plants in French Polynesia was determined by a series of energy conversion calculations combined with stoichiometry. The average energy content of crop wastes (assuming 20% moisture content) was converted to energy per tonne of coal and then translated to CO_2 emissions by balancing the combustion equation of bituminous coal in air.[xxi]

CONVERSION OF HUSK WASTE (KG) TO CO_2 (KG)

$$kg\ husk \times \left[\frac{13\times10^{-3} GJ}{kg}\right](energy\ content\ of\ husk) \times \left[\frac{3.57\times10^{-2} MT\ coal}{GJ}\right](energy\ content\ of\ coal)\ldots$$

$$\times\left[\frac{1000\ kg}{MT}\right]\times\left[\frac{0.44\ kg\ CO_2}{0.16\ kg\ coal}\right](amount\ CO_2\ per\ coal)$$

$$\rightarrow kg\ husk \times 1.276 \Rightarrow kg\ CO_2$$

(where kg is kilograms, GJ is gigajoules, MT is million tonnes)

The conversion rate of 1.276 kg of CO_2 released per every kg of husk burned is utilized in the calculation of emissions saved. The amount of husk burned is calculated based upon quantities of current copra production within French Polynesia (Figure 6).[xvi] From this information, the authors determined that the emissions saved would be based on the husk collected from each proposed shipping route (refer to Section- Implementation Plan for results).

Transportation Factors

Currently, a majority of construction materials are imported to French Polynesia from Oregon, Canada, and France. Thus these materials have high associated emissions and embodied energy costs. The assumed average emission of CO_2 per kilometer traveled per tonne of freight by long haul sea shipping is 0.0175 kg CO_2/km-kg.[xxii] The authors assumed the proposed production output of coir board for one medium sized plant (20,000 tonnes) will displace an equal amount of cargo containing building materials.

TABLE VI

LONG HAUL TRANSPORTATION CONTRIBUTION TO CO_2 EMISSIONS PER CARGO DISPLACED PER PLANT

Route	Distance (km)	CO_2 Emission (MT)
Oregon to Tahiti	7,230	2,530
Canada to Tahiti	8,000	2,800
France via Panama Canal to Tahiti	16,500	5,775

Implementation Plan

The system currently in place for the production of coconut oil is the model for our suggested coir board system. Ferries from Tahiti transport both passengers and cargo to the outer island communities. The main port of French Polynesia is located in Papeete, Tahiti. Copra is collected on the individual islands and then taken to the local port where the individual is paid for their product. The ferry continues along its route collecting copra along the way. Finally, the ferry arrives in Papeete where the oil production takes place. In a similar manner we suggest utilizing the cargo/passenger ferries as a means of transporting the husks.

Contrary to coconut oil production, we suggest that the coir boards are manufactured in the outer islands. This would create a source of employment and reduce the transportation of high volume material. The final boards could be used on the island where they are produced or taken to Tahiti or Moorea to be sold as a building material. As the cost of each manufacturing plant is substantial, $2 million US, it would not be appropriate to build a mill on every island that produces coconuts. Additionally, considerations such as economic status, concerns of local populations, past investments, and many other factors would need to be analyzed in depth before deciding on final plant locations. While analysis and research into the social, cultural, and historic factors is necessary, an initial scheme based upon the quantity of copra production was undertaken.

The island of Tahaa in the island group Iles Sous Le Vent is the dominate producer of copra in French Polynesia with over 770,000 kg produced per year (see Table VII). The majority of the other top five producers are located in the Marquises, which lie around 1450 km away from Tahiti compared to only 523 km for the Tuamotus, and 200 km for Tahaa (see Figure 7). The varied location of these islands does not lend itself easily to one simple route.

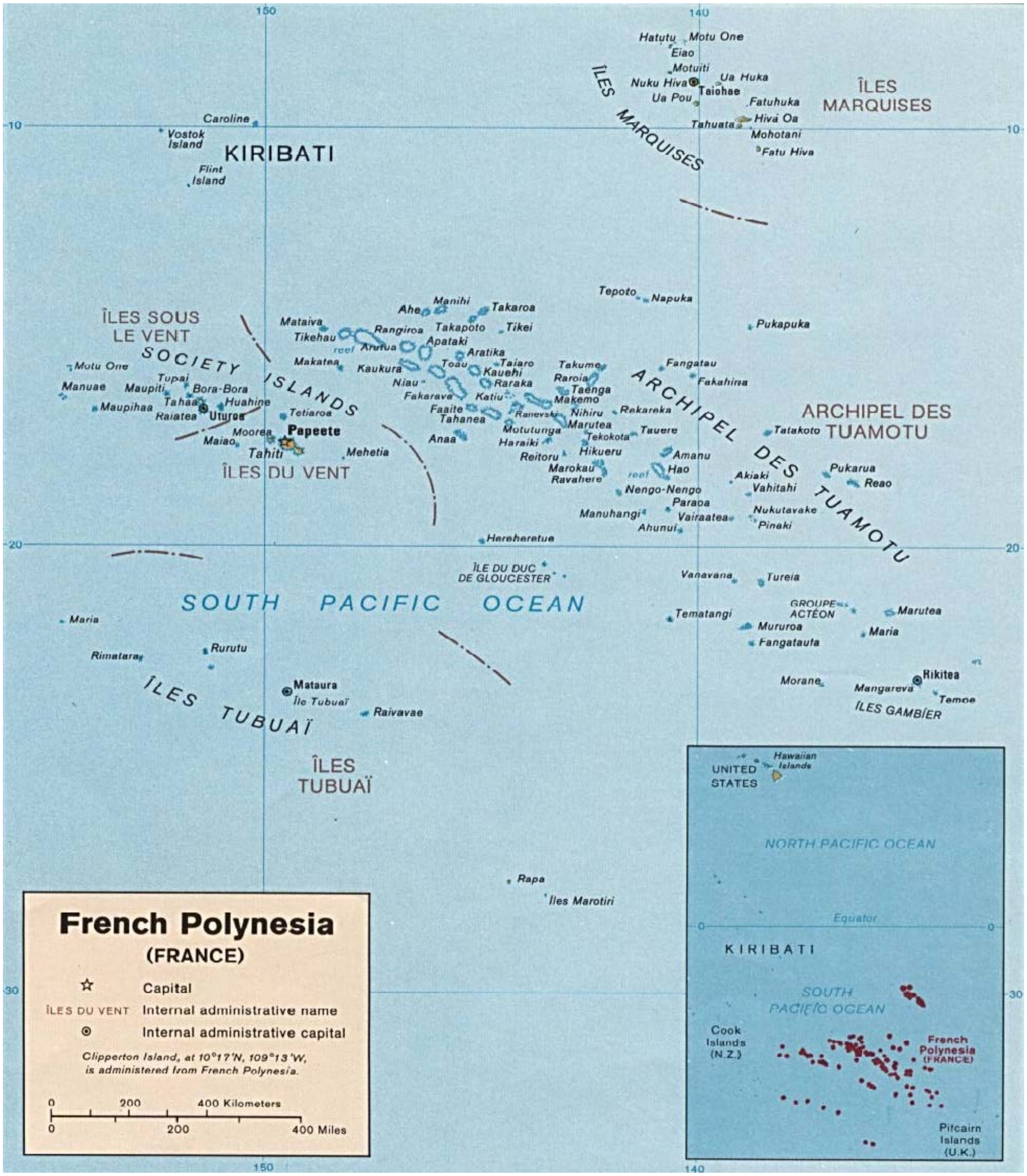

FIGURE 7

MAP OF FRENCH POLYNESIA ILLUSTRATING THE VARIOUS ISLAND GROUPS.[xxiii]

TABLE VII

TOP 5 COPRA PRODUCING ISLANDS IN FRENCH POLYNESIA AS OF 2007

Island Group	Island	Price per kg (French Polynesia Francs)	Value*	Net Weight (kg)
Marquises	HIVA OA	100.00 F	45,033,675 F	442,921
Marquises	NUKU HIVA	100.00 F	39,344,925 F	385,594
Tua Ouest	RANGIROA	100.00 F	40,634,545 F	362,336
ISV	TAHAA	100.00 F	79,996,955 F	773,195
Marquises	UA HUKA	100.00 F	46,175,565 F	442,885

* Total value includes a portion of seconds sold at a lower price

As the goal is to reduce greenhouse gas emissions, short ferry voyages and large quantities of husks acquired per kilometer travel are desirable. Simple routes that focus on the major island groups were thus evaluated to determine the quantity of husks gathered and the required kilometers traveled (see Table VIII). All islands producing more than 100,000 kg of copra per year were included in the analysis. The kilometers traveled assume the beginning and final port is in Tahiti.

TABLE VIII

POSSIBLE FERRY ROUTES FOR ISLANDS PRODUCING MORE THAN 100,000 KG COPRA.[xvi,xx]

Proposed Routes within Island Groups Producing > 100,000 kg of copra						
Route	Island Group	Husk (MT)	Distance (km)	Husk/Distance (MT/ km)	Freight CO_2 (MT)	CO_2 Burning Husks (MT)
1N	IDV/ ISLV	5,018	523	**9.595**	46	6.40
2N	Marquises	6,179	3,258	1.897	352	7.88
3N	Tuamotu Center	2,819	2,092	1.347	103	3.60
4N	Tuamotu East	4,539	3,379	1.343	268	5.79
5N	Tuamotu West	6,974	1,529	**4.561**	187	8.90
6N	Tuamotu North-East	2,326	2,574	0.904	105	2.97

(N- new route)

From the above analysis, Route 1N and 5N offer significant amounts of husk per distance traveled. The higher the ratio of husks to distance traveled, the more favorable the route because the carbon dioxide emitted per unit husk is reduced. Route 1N includes several islands in Iles Du Vent and Iles Sous Le Vent of which Tahaa plays a crucial role. As production levels in Tahaa are high and the distance to Tahiti is short this Route offers significant opportunities. The second best route after 1N is the Tuamotu West route (5N) due to its high husk per distance ratio.

While focusing on local island groups seems logical, it might prove more beneficial in the short term to utilize existing ferry services offered.[xxiv,xxv] Similar to above, the existing routes all begin and end in Tahiti. Thirteen different existing routes were examined and the husk content, miles, and husk per distance traveled were calculated (see Table VIIII). For existing routes the best husk to distance ratio is Route 11E with 2.659 MT/km versus Route 1N with 9.595 MT/km. Although Route 11E has a high husk to distance ratio, only around 2,675 MT of husk would be gathered versus Route 12E where over 10,752 MT would be collected. The larger amount of material collected along Route 12E compared to Route 11E is a more important factor than the marginal difference in the husk to distance ratio of the two routes.

Thus Route 1E, 5E, 6E, 11E, and 12E would be appropriate locations for a manufacturing system based on current ferry routes. Location of the plant(s) could be Ua Huka, Hiva Oa; Rangiroa, Kaukura; Reao, Puka Puka, Fakahina; Rangiroa, Kaukura and Reao, Tataoto, Puka Puka respectively. These choices were made based upon which islands in each respective route produced the most husks. All these plant locations overlap with islands visited on the new suggested routes, creating an appropriate layout for production. Consequently, plants built on one of these locations would prove viable in the short and long term for either the existing or proposed ferry scheme.

TABLE VIIII

CURRENT FERRY ROUTES AND ASSOCIATED HUSK PRODUCTION IN FRENCH POLYNESIA.[XVI,XX,XXII,XXV]

Existing Ferry Routes in French Polynesia					
Route	Husk (MT)	Distance (km)	Husk/Distance (MT/ km)	Freight CO_2 (MT)	CO_2 Burning Husks (MT)
1E	7,887	3,500	**2.253**	483	10.06
2E	1,341	925	1.450	22	1.71
3E	1,800	1,126	1.599	35	2.30
4E	1,285	1,448	0.887	33	1.64
5E	2,676	1,126	**2.377**	53	3.41
6E	10,195	4,143	**2.461**	739	13.01
7E	7,482	3,821	1.958	500	9.55
8E	2,367	3,138	0.754	130	3.02
9E	1,391	925	1.504	23	1.77
10E	1,285	1,448	0.887	33	1.64
11E	2,675	1,006	**2.659**	47	3.41
12E	10,752	4,787	**2.246**	901	13.72
13E	4,340	3,990	1.088	303	5.54

(E- existing route)

PRODUCTION SCENARIOS

Individual Islands Have Husk Milling Capacity and May be Power Independent

This scenario would allow individual farmers to add value to the husk waste product through primary processing. It is estimated that grinding adds $20US/tonne to the husk.[x] Milling on site lowers the volume per kilogram of material, which is advantageous for transportation. Below various scenarios are given for powering the equipment. The authors suggest that all equipment be owned by an island cooperative, with farmers paying a fee for use based on quantity.

i. Mechanized grinder-mill with power options:
    1. “Grid” Electricity powers electric grinder (only Tahaa)
    2. Diesel electric generator
        a. diesel fuel
        b. coconut oil
    3. Diesel motorized grinder
        a. diesel fuel
        b. coconut oil

ii. Manually powered grinder-mill for smallest scale

For the smallest scale production, a hand or pedal cranked grinder may be sufficient. This system of husk milling would allow for the islanders to reduce their reliance on imported fuel. Currently, electricity in French Polynesia is provided mainly by diesel generators.[v] Assuming the hand-cranked grinder was insufficient for the necessary milling requirements, there are three options for fueling motorized husk grinders: imported diesel, biodiesel derived from coconut oil and straight coconut oil. It is conceivable that islanders could set up micro facilities to produce biodiesel, however small scale biodiesel production is not economical.[xxvi] Many simple diesel engines can run on vegetable oils without mechanical conversion, although long term wear is a concern[xxvii] and a pre-heating system is recommended. To use coconut oil the ambient temperature must be above 76°F (the gel point of coconut oil). Furthermore, unconverted engines are best started with conventional diesel and switched to coconut oil once the engine is hot.

At 42 MJ/kg coconut oil has a fuel value nearly equivalent to petroleum diesel (45MJ/kg).[xxviii] Coconut oil fuel could be a valuable, sustainable energy option for islanders and island production. Coconut oil could be pressed from copra on small-scale manual or mechanized presses currently available. A promotional video by the Thai government features a manual press.[xxix] The biggest obstacle for this plan is diverting copra from sales. The current subsidies raise the retail price of copra from $0.22 US per kilogram to $1.10/kg. In 2004, the average retail price of diesel fuel in French Polynesia was $1.10/L.[xxviii] Copra has an oil content of approximately 70% and coconut oil has a density of 0.925 kg/L. From this data the following calculations are done:

$$1\,kg\ copra \times \frac{0.7\ kg\ coconut\ oil}{1\,kg\ copra}\left(fractional\ oil\ content\right)\times\frac{1\,L}{0.925\,kg}\left(density\ of\ coconut\ oil\right)=0.76\ L\ of\ oil$$

$$\rightarrow 0.76\ L\ of\ oil \times \frac{45\,MJ/kg\ \left(energy\ content\ of\ diesel\right)}{42\,MJ/kg\ \left(energy\ content\ of\ oil\right)} = 0.82\ L\ diesel\ fuel$$

$$\Rightarrow 0.82\ L\ diesel\ fuel \times \frac{\$1.10}{1\,L\ diesel\ fuel}\left(price\ of\ diesel\right) = \$0.90/kg\ copra$$

$$\rightarrow \$0.90/\,kg\ copra \times \frac{1\,kg\ copra}{0.7\ kg\ coconut\ oil} = \$1.56/L\ coconut\ oil$$

Thus 1 kg copra converted for use as fuel is valued at \$0.90/ kg or the coconut oil fuel costs \$1.56/L. With the current copra subsidy (\$1.10/kg) coconut oil fuel (\$1.56/L) costs 42% more than diesel (\$1.10/L). Thus without a reduction in the current subsidy this scheme is not likely to be adopted.

Central Island Receives Un-milled Husks - May be Power Independent

Having a central island receive un-milled husks would allow for greater quality control. The downsides are increased transportation costs and reduced earnings of individual farmers since the un-milled husk is waste rather than a value-added byproduct. The prospect of utilizing coconut biofuel may be facilitated by centralization because oil (or biodiesel) could be produced in larger volumes and technicians from plant operations might be more capable of maintaining the equipment.

iii. Mechanized plant equipment: grinder-mill/former/press with power options:
    1. "Grid" Electricity powers electric grinder (only Tahaa, others?)
    2. Diesel electric generator
        a. diesel fuel
        b. coconut oil
    3. Diesel motorized grinder
        a. diesel fuel
        b. coconut oil

Referring to Figure 9, 1 kilogram of copra can be converted to 29.4 MJ or 8.17 KWh of energy. Therefore, coconut oil is worth about 10.75KWh/L. A small grinding machine has about 15 horse power (HP) and grinds about 225 kilograms of husks per hour – which translates to an energy demand of about 50 KWh/tonne of husk. Under this scenario, 163 kilograms of husk can be milled per kilogram of copra processed for fuel oil.

An annual production of 20,000 tonnes of board material requires 20,500 tonnes of husk.[viii,x] For 7,600 hours of annual manufacturing time, the processing equipment must have the capacity move 2.7 tonnes of husk per hour (demanding about 180 HP). Assuming that the other major two steps in the board manufacturing process (forming and pressing) have similar energy demands, the total processing energy required is on the order of 150KWh per tonne of husk. The

2.7 tonne/hr load could be fueled with 37.7 L of coconut oil/hr, equivalent to 49.6 kg of copra. The annual demand for the entire process is 3,078 MWh/yr corresponding to 1,800 barrels of oil (286 kiloliters).

One of the primary features of using coconut oil is the offset of green house gas emissions. As a carbon neutral bio-fuel (per IPCC[2]), significant carbon emissions could be avoided for every liter of diesel fuel replaced. The use of diesel has a direct emissions factor of 2.67 kg of CO_2/L of fuel – this translates into approximately 3 kg of CO_2/kg of diesel.[xxx] More relevant to the island use, according to the IPCC[xxxi] the commonly accepted figure for diesel generators is 0.75kg of CO_2/KWh produced with diesel. To produce 20,000 tonnes/yr uses 3,078 MWh/yr -- if all energy is sourced from coconut oil, about 2.3 Million tonnes of CO_2 emissions are averted.

The total offset of GHG emissions could eventually be sold on the emerging carbon markets. Currently values range from a low of US \$5/tonne to over \$25/tonne. This is definitely an area to watch as policy changes and other drivers of this market are poised for major changes.

Data (average values):

Density of coconut oil = 0.925 kg/L

Density of petroleum diesel = 0.885 kg/L

Fuel value of coconut oil = 42 MJ/kg

Fuel value of petroleum diesel = 45 MJ/kg

Standard 15 HP grinding equipment processes about 225kg of material per hour, scaling up, assume 180 HP capacity = 2,700 kg/hr

Density of coir board 1350 kg/m^3

Energy Conversions:

1 horse power = 0.746 KW

0.2778 KWh = 1 MJ

FIGURE 8
RELEVANT DATA USED IN FLOW DIAGRAMS

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[2] Intergovernmental Panel on Climate Change

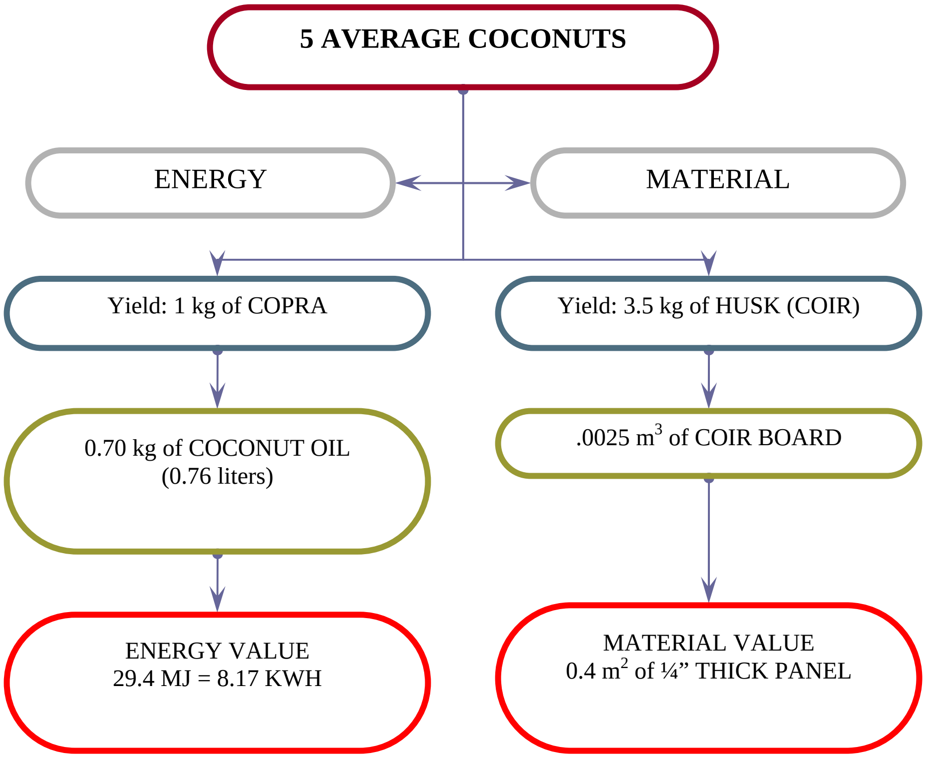

FIGURE 9

FLOW DIAGRAM: COCONUT TO ENERGY AND MATERIAL

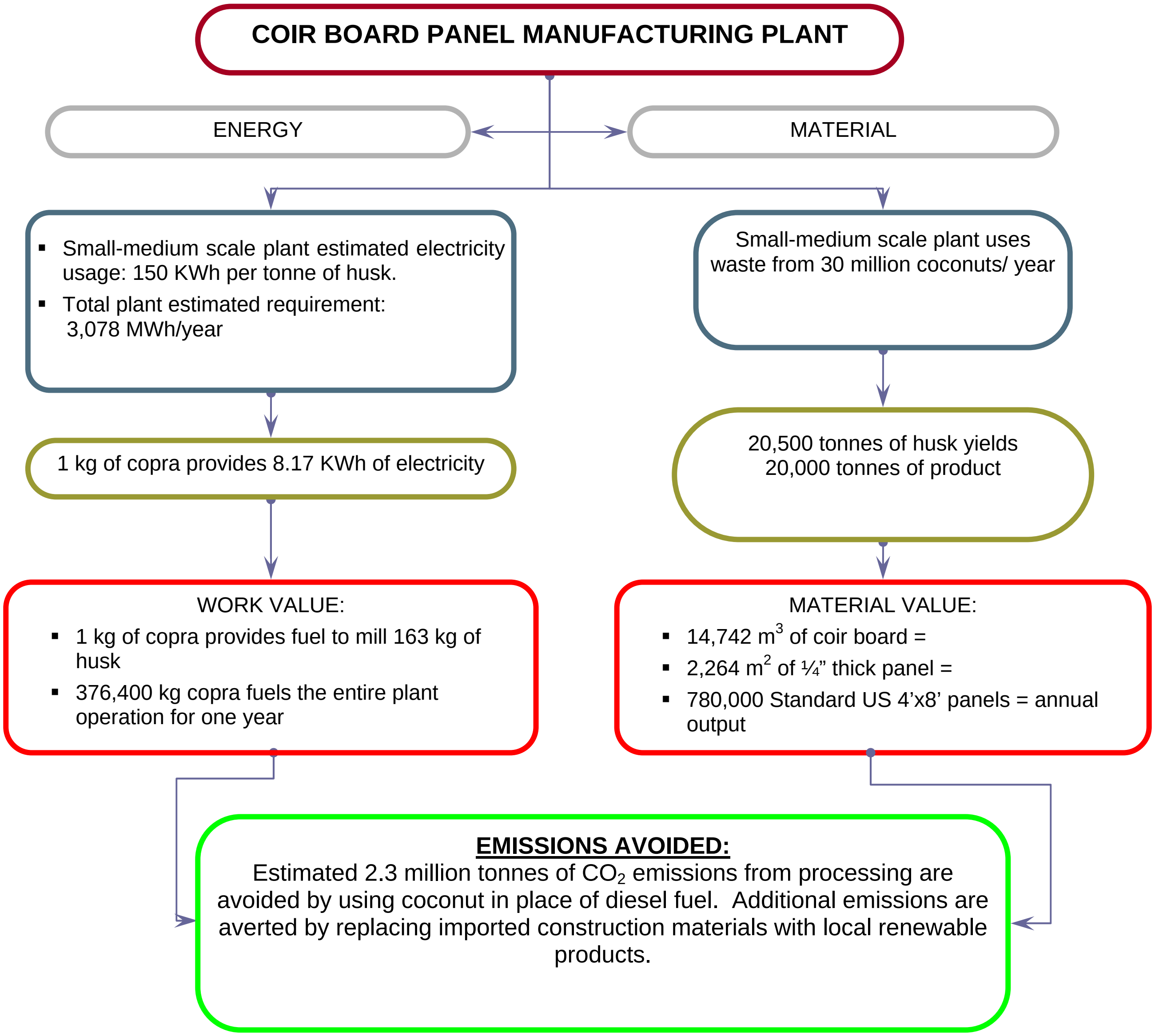

FIGURE 10

FLOW DIAGRAM: EMISSIONS AVOIDED

By using coconut oil fuel, 2.3 Million tonnes of averted CO_2 emissions is possible – this is equivalent to 60 million tree seedlings grown for ten years.[xxxii] These emissions savings translates into 115 tonnes of CO_2 averted per tonne of panels produced, and 155 tonnes of CO_2 averted per cubic meter of panels. To account for total emissions per panel one must consider additional emissions due to averted crop burning, transportation of goods and fuel and averted use of energy intensive materials. For a summary with integrated emissions data see section – Net Emissions.

TABLE X

COCONUT OIL FUEL PLAN TO AVERT EMISSIONS

Averted CO_2 Emissions - Coconut Oil Fuel Plan*		
	by mass	**by volume**
Coir Board energy Demand	**tonnes CO_2 per tonne of boards**	**tonnes CO2/m^3 of boards**
154 KWh/tonne	**115**	
208 KWh/m^3		**155**
*Diesel CO_2 emissions=0.75 kg/KWh; coconut oil is carbon nuetral		

For either scenario it is important to note that suitable equipment is available used on the world market. For grinders, prices range from below $170 for small and manual models to over $1,700 for large capacity equipment.[xxxiii] Some of the machinery is similar to or could be converted from copra production equipment. A quick web search brought up many sources of equipment, including a grinder up for auction in New Zealand (see Figure 11).[xxxiv]

FIGURE 11
GRINDER FOR AUCTION.[xxxiv]

NET EMISSIONS

The culmination of the research on emissions is summarized through a comparison of lifecycle emissions of OSB/plywood to Coir Board (produced with either diesel or coconut oil). The resulting emissions are shown in Table XI below.

TABLE XI
NET EMISSIONS FOR LIFECYCLE OF BUILDING PRODUCT

Material	Production CO_2 (MT)	Import CO_2 (MT)	Local Distribution CO_2 (MT)	Husk Burning CO_2 (MT)	Total CO_2 (MT)
OSB/Plywood	18,400	2,625	0	27	21,052
Coir Board, diesel	2,400	0	1,640	0	4,040
Coir Board, coconut oil	0	0	1,640	0	**1,640**

The following assumptions were made: the production value is for 1 plant with a 20,000 MT capacity, 20,000 MT of imported plywood is used as a comparison, there is a 1:1 conversion of husk to coir board, import distance is 7,500 km (from Northwest US to French Polynesia), and lastly, local distribution uses existing route 6E and 12E for coir board only.

COST COMPARISON

Cost comparisons are crucial to validate the financial sustainability of such a product. Cost analysis for coir versus plywood, oriented strand board (OSB), and fiber cement boards should be undertaken. The cost comparison looks at standard sheets of plywood (4'x8'x0.25" and 0.5" or 1.2m x 2.4m x 8cm and 15cm) and fiber cement boards (4'x8'x0.25" and 0.5" or 1.2m x 2.4m x 4cm and 15cm). Costs for plywood and OSB were estimated according to current global world market values and a 20% shipping markup, yielding a $300/m^3$ cost or $6.00 per panel.

Cost analysis for coir versus plywood, oriented strand board (OSB), and fiber cement boards should be undertaken. The cross analysis looks at standard sheets of plywood (4'x8'x0.25" and 0.5" or 1.2m x 2.4m x 8cm and 15cm) and fiber cement boards (4'x8'x0.25" and 0.5" or 1.2m x 2.4m x 4cm and 15cm). Unfortunately, local prices for plywood and OSB could not be obtained, so the costs were estimated according to current global world market values and a 20% shipping markup, yielding a $300/m^3$ cost or $6.00 per panel.

Initial Investment

According to an economic study and financial data provided by Agrotechnology, the initial capital investment for a medium sized coir board production plant with a production capacity of 15,000 m^3/yr is $2.0 million US. This production capacity is equivalent to producing 750,000 panels/yr of similar size to the compared case of OSB & plywood panels.

Operating Costs

Four major expenses must be considered when calculating the operating cost of the coir board production plant. These expenses are overhead, labor, materials, and cost of running equipment. An overhead (insurance, office expenses, etc.) of $50,000 is assumed at 10% of the total annual revenue of $500,000/yr. Labor expense for 8 workers is $160,000/yr. Lastly energy costs are determined to be $1.23 million/yr for an electricity grid connection or $307,800/yr for a diesel or coconut oil generator.

Breakeven Cost

To breakeven in year 1 of operation, the cost per panel is calculated in the Table XII below (assuming production capacity of 750,000 panels/yr):

TABLE XII

COST PER COIR BOARD PANEL FOR BREAKEVEN SCENARIO

Power Supply	Initial Investment ($)	Operating Cost (OH, Labor, Materials) ($)	Energy Cost ($)	Cost per Panel ($)
Grid Connection	2,000,000	210,000	1,230,000	4.60
Generator	2,000,000	210,000	307,800	3.36

Twenty-five Percent Return Cost

To earn a 25% return on the initial investment in year 1 of operation, the cost per panel is calculated in Table XIII below:

TABLE XIII

COST PER COIR BOARD PANEL FOR 25% RETURN SCENARIO

Power Supply	Initial Investment ($)	Operating Cost (all) ($)	Revenue ($)	Cost per Panel ($)
Grid Connection	2,000,000	1,440,000	500,000	5.25
Generator	2,000,000	517,800	500,000	4.02

According to estimates by Agrotechnology, export quality boards can be produced for $5/board (4’x8’x1/4”) assuming a 25% rate of return, which corroborates the authors estimates to be on-target.

Overall Cost Comparison

An overall cost comparison between the two scenarios (breakeven and 25% return) for coir board and the current market cost for its alternative of plywood or OSB is contained within Table XIV.

TABLE XIV
OVERALL COST COMPARISON

Scenario	Plywood/OSB	Coir Board, grid connected	Coir Board, generator
Breakeven	$6.00/panel	$4.60/panel	$3.36/panel
25% Return	$6.00/panel	$5.25/panel	$4.02/panel

CONCLUSIONS

Various alternative schemes for implementation were evaluated. It is suggested that manufacturing plants be located on an outer island, along both an existing and proposed ferry route. The results show that the embodied energy content of coir board is equal to 5% of the total embodied energy content of plywood/OSB, assuming that energy consumed during shipment of plywood/OSB is neglected. Therefore, it reduces the embodied energy content of coir board to less than 5% because it does not utilize transport energy. As far as savings in CO_2 emissions, the results show that an 80% reduction can be achieved using coir from diesel rather than OSB/plywood. Concurrently, a reduction of 92% can be obtained by switching to coconut oil for manufacture of coir board. Lastly, cost per panel for both a breakeven and a 25% return on initial investment within the first year of operation is competitive with current market prices for comparable building materials such as plywood and OSB.

Finally, implementation remains a critical stage yet to be undertaken. A testing program would be necessary to win the support of the local builders and ensure the material is appropriate. A pilot scale plant would facilitate technology transfer among communities and ensure all technical, economic, and social concerns had been sufficiently addressed.

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