Fall 2012 Capstone Project

Comparative Life Cycle Assessment of a Thai Island's Diesel/PV/Wind Hybrid Microgrid

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Capstone Vision and Overview

The overarching goal of this project is to analyze and evaluate the sustainability of the Koh Jig diesel/PV/wind hybrid microgrid system installed by the Thai government and King Mongkut's University of Technology Thonburi in 2004 through a comprehensive sustainability assessment of all major environmental, social, and economic impacts of the system. Because the scope of this project is both multidisciplinary and data intensive in nature, we have decided to present our results in three separate stand-alone articles relating directly to the environmental, economic, and social implications of the Koh Jig microgrid that can act collectively to comment on the overall sustainability of the project. The potential for a fourth synthesis article has also been considered in order to comment on the feasibility of a microgrid as a sustainable electrification option.

Operating under the pretense that both the economic and social analyses will be continued into the spring semester at UNC, the environmental component of this project, "A Comparative Life Cycle Assessment of a Thai Island's Diesel/PV/Wind Hybrid Microgrid," represents the formal conclusion to our capstone research experience abroad.

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Acronyms
LCA = Life Cycle Assessment PV= photovoltaic AP = Acidification Potential GWP = Global Warming Potential HTP = Human Toxicity Potential ADP = Abiotic Resource Depletion Potential KMUTT = King Mongkut's University of Technology Thonburi

Abstract

Hybrid microgrid systems are an emerging response to the perceived need for rural electrification due to their purported environmental benefits. This study uses the method of Life Cycle Assessment (LCA) to compare the environmental burdens of the diesel/PV/wind hybrid microgrid designed for installation on the island of Koh Jig, Thailand with the electrification alternatives of grid extension and home diesel generators. The results show that the designed microgrid system had the lowest impact potentials in global warming and abiotic resource depletion potential, but not in acidification and human toxicity potential. As the performance of the microgrid differed from the design, the actual performance scenario is presented for consideration and shown to have little impact. Assumption analyses show that diesel combustion contributes significantly to the impacts of the system and that an increase in the renewable energy fraction of the system produces mixed results with regard to the four impact categories considered. The variation in final results across the chosen impact categories indicates that weighting is necessary to determine the environmental sustainability of the Koh Jig microgrid, and therefore it cannot simply be assumed environmentally sustainable. This reflects the inherent dilemma in determining any form of sustainability.

1. Introduction

Access to energy is considered one of the most important factors in improving the quality of life for disadvantaged communities worldwide and provides the potential for both economic and social benefit. Over 1 billion people, approximately 15% of the global population, do not have access to electricity. The majority of these people live in rural, isolated, and insular communities where connection to the regional electricity grid is difficult - and sometimes impossible - due to geographical obstructions, transmission losses, and low load densities [1,2].

While grid extensions and home diesel generators have functioned as the most common electrification methods in isolated regions, governments and policy makers have recently attempted to overcome the difficulties and insufficiencies of these methods by installing community-sized electrification systems. This infrastructure, known as a microgrid, provides electricity in a small local network that stabilizes power supply, voltage, frequency and avoids excessive power loss through transmission via long distribution lines [3]. A microgrid often contains a centralized diesel generator which works in conjunction with renewable energy sources such as solar, wind, and hydropower, to utilize a community's natural resources [4].

Although microgrid technology is still in its adolescence, the literature suggests that when applied in the right context, hybrid microgrids can provide significant environmental, economic, and social benefits to the communities in which they are installed. Despite these benefits, a number of problems with the technology and its integration exist, including the intermittency of renewable energy supply, difficulty with technology operation and maintenance, incongruity with community integration, and high initial capital costs [3]. These problems must be addressed before hybrid microgrid systems can become a more prevalently used electrification tool in regions where they were not previously available and in replacing traditional technologies, such as home diesel generators.

While problems associated with integration of the microgrid are well catalogued, little research has been published to verify the suggested benefits of specific hybrid microgrid systems. Of these, none broadens its scope beyond the life cycle assessment of individual energy technologies. The need exists to holistically assess the environmental impacts of a hybrid microgrid to better understand the environmental sustainability of such a system and how it compares to other electrification options.

1.1 Project Goal

The goal of this study is to compare the environmental sustainability of a diesel/PV/wind hybrid microgrid established in 2004 on Koh Jig, an island in Eastern Thailand, with two alternative electrification scenarios using LCA. This comparison is valuable, as both the technological design and implementation of the hybrid system on Koh Jig have been held up as models for other microgrid systems within Thailand and Southeast Asia by international research institutions and the International Energy Agency [5,6]. Due to Koh Jig's unique status as a "model system," the results of this study are intended to inform researchers and policymakers concerned with electrification scenarios in remote locations. Based on the rate of advancement of renewable energy technology, the results of this study are assumed to be relevant until the year 2020.

2. Materials and Methods

2.1 Study Site

Koh Jig is a small island (1.12 km^2) located 4 km off the eastern coast of Thailand in Chanthaburi Province (12^o N, 102^o E). The distance from the mainland and the low density of electricity usage by the island's estimated 437 residents makes grid extension an unattractive electrification option for Thailand's Provincial Electrical Authority [7,8]. Koh Jig is characterized by high levels of solar insolence of 4.73 kWh/m^2/day and an estimated average wind speed of 5.93 m/s [9].[1] Prior to the microgrid installation in late 2004, the electricity needs of the island were supplied through the use of an estimated 94 home diesel generators with capacities between 4 kW and 15 kW.[2] These generators were primarily used for four hours a day, between 18:00-22:00, to run small household appliances and charge batteries [7]. Under these conditions the daily load of the island before the microgrid was estimated from a survey of 98 households to be 115.87 kWh with a peak demand of 30 kW in 2001 [8]. [3]

2.2 Microgrid Installation Timeline

The Koh Jig diesel/PV/wind hybrid microgrid system was designed in 2003 by KMUTT and the Energy Policy and Planning Office of Thailand. Financial support for the project came in large part from the national government, with additional money raised from local funds. In 2004, this initial investment went to the purchase and installation of a 120 panel array of 75 W monocrystalline photovoltaic solar panels, a 65 kW diesel generator, and additional system components. However, funding constraints prevented the purchase of the original design's wind component. The installation was accompanied by the establishment of an energy committee to oversee the maintenance, management, and financing of the microgrid system. In 2006, funding became available to acquire 2 5 kW wind turbines whose installation was completed in early 2007 to complete the microgrid; a full schematic drawing of the optimal system can be found in Appendix A, Figure 1 [8].

2.3 Optimal Design and Current System

At the time of its implementation in 2004, the microgrid was designed to provide 265 kWh of electricity per day, an increase in demand from approximately 115 kWh in 2001 [8]. Using the manufacturing data provided for each system component and local climatological conditions, the designed renewable fraction was calculated to supply 53 kWh (30%) of the daily energy requirement, leaving the remaining 212 kWh (70%) to be supplied by the centralized 65 kW diesel generator[4]. While the system was designed to produce enough energy to exceed demand, a cycle of component failure has limited the production of Koh Jig's microgrid.

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[1] This monthly average comes from the KMUTT case study of Koh Jig that was submitted to the Energy Policy and Planning Office before the implementation of the microgrid system. Though we do not have access to the report, the citation has appeared in an available source [10].

[2] The exact number of pre-microgrid home diesel generators is disputed by several sources. The number of diesel generators was selected because it appeared in peer reviewed literature. Additionally, based on observations and interviews with local authorities on Koh Jig, a 5 kW capacity has been chosen to realistically model the home diesel generator electrification scenario.

[3] This energy demand is likely an underestimate of the true pre-grid conditions on the island. A detailed account of the 2001 energy survey for Koh Jig can be found in Appendix A, Table 1.

[4] References for calculations and manufacturing data can be found in Appendix D.

Within 11 months of the wind turbines' installation, the turbines had stopped providing electrical power to Koh Jig due to converter malfunctions. Since their failure, the turbines have remained non-functional. In the first few years after installation, Koh Jig experienced failure of the solar converters as often as twice a year[5]. In response to these failures, the island residents, with assistance from KMUTT, shipped the broken converters back to the manufacturer in Germany, a process that takes 4-5 months round trip. In 2009 the generator was replaced with a comparable generator that is more easily serviced. These problems have caused the microgrid system installed on Koh Jig to operate differently in practice from the optimized design, with a much greater reliance on the diesel generator [11,12]. This study prioritizes the system as it was designed over the system as it performed in order to provide a steady comparison between the environmental impacts of the microgrid and its electrification alternatives. Furthermore, the difficulties inherent in data collection and source discrepancies limit the ability to accurately model the current system. A comparison to available data on the actual performance of the system will be included in the results section of this paper.

2.4 Functional Unit

This study assesses three alternative systems of electrification for the entire island of Koh Jig. These include the use of home diesel generators as the pre-grid electrification method, the installed microgrid system as it was ideally designed, and grid extension from the mainland as it might have been installed. The functional unit for comparison is defined as providing 265 kWh of electricity per day to the residents of Koh Jig for 20 years.[6]

2.5 System Boundaries

Unless explicitly stated otherwise, the processes considered relevant to the study include raw materials extraction, energy inputs from manufacturing, transportation of components and use phase inputs to Koh Jig Island for the 20 year duration of the functional unit , and their eventual disposal. Infrastructure requirements for the materials extraction and manufacturing phases were excluded from the scope of this project. All primary material impacts included processes traced back to nature, while secondary material processes were only included up to two steps back from the overall primary material production. Resource extraction and manufacturing of the grid extension transmission system's components were included, but manufacturing of the cables was excluded due to lack of available data[7]. The use phase considers the diesel fuel and lubrication oil needed for the diesel generators, and maintenance requirements for impact-producing processes.[8] In all electrification scenarios installation was excluded due to unavailability of data regarding installation processes. The ideal disposal of all materials has been subdivided into three separate processes including: landfilling, recycling, and incineration, with transportation included to disposal locations.

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[5] This consistent failure is suspected to have been caused by system overloading and poor battery bank design

[6] "Ideally designed" does not refer to the results of HOMER or other model simulations, rather it is assumed to be the ideal performance of all technologies that were installed as part of the microgrid system according to manufacturer's standards.

[7] Encountered studies excluded data on manufacturing of power transmission cables based on assumption that impacts were insignificant when compared to the impact of the cables' resource extraction [13]

[8] Information collected from onsite interviews found that maintenance beyond regular oil changes and diesel fuel was minimal for the microgrid. For this reason we only included it in impact-producing processes associated with the grid extension scenario.

In both the microgrid and grid extension scenarios the impacts of connection components and electrical meters installed in each user's house as part of the power distribution system were not included in the scope of this study since they are specific to individual households and not the overall microgrid system. The actual wiring between energy-producing components has been excluded due to the proximity of the system components to the grid control center.

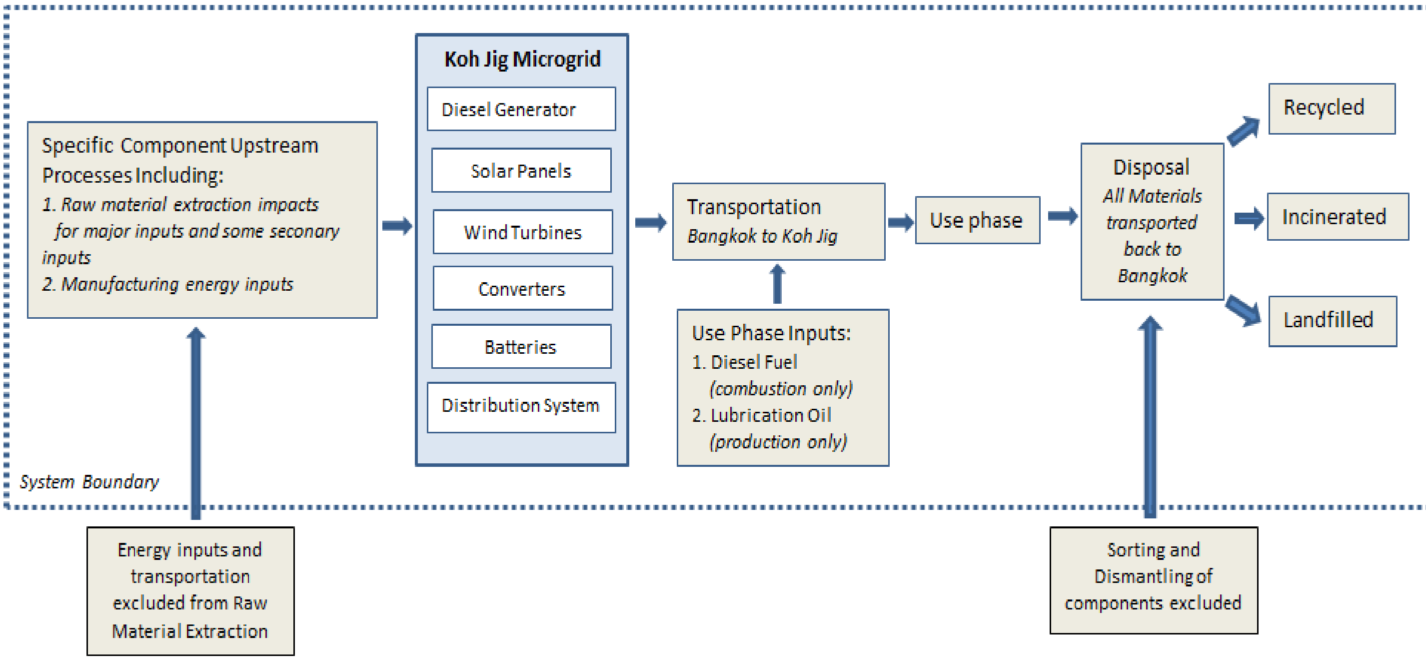

Figure 1: System boundaries of the Koh Jig microgrid

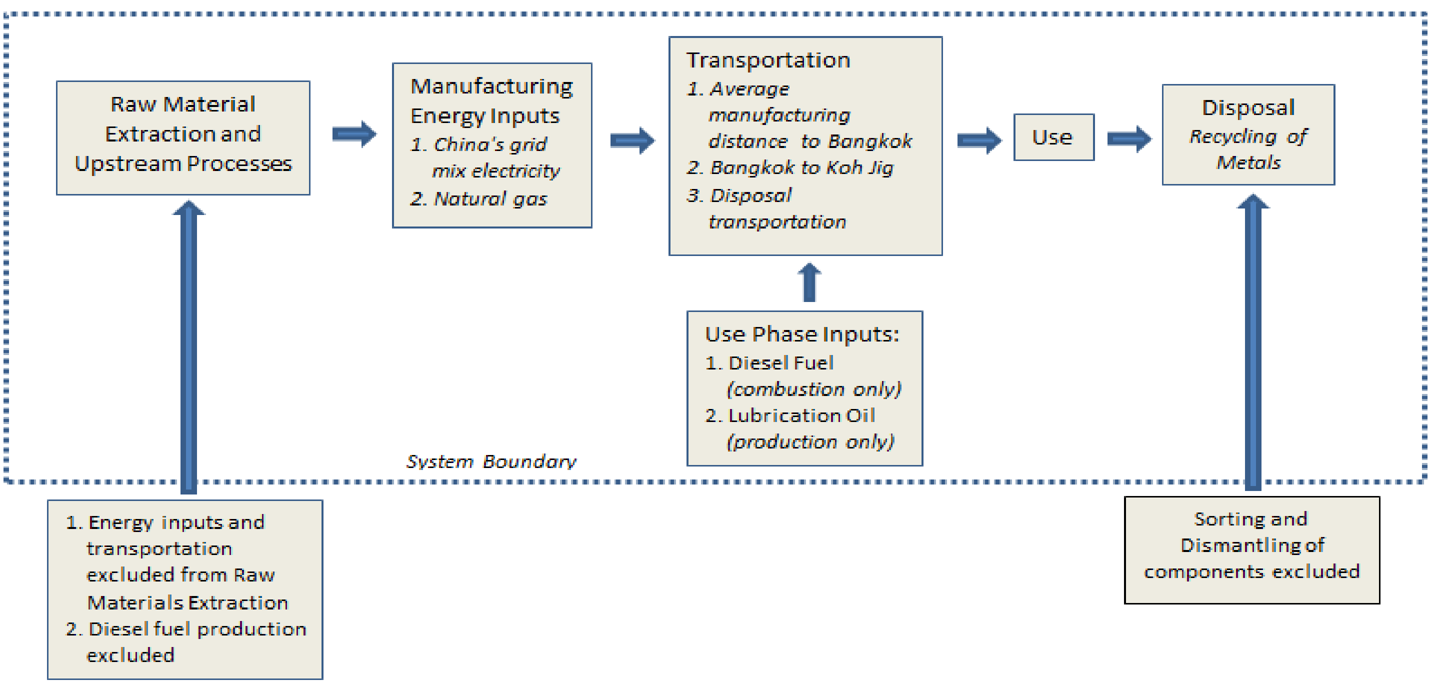

Figure 2: System boundaries of the home diesel generator scenario

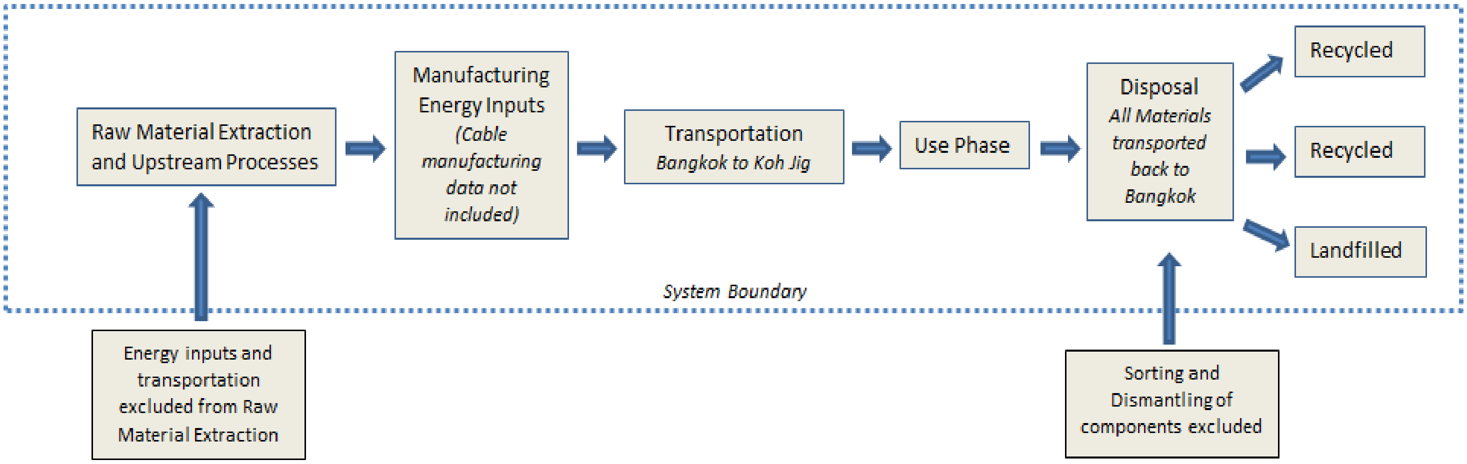

Figure 3: System boundaries of the grid extension scenario

2.6 Allocation and Crediting Procedures

Mass allocation was used to determine impact potentials. Credits were given for recycling based on the raw material extraction impacts and the efficiency of the recycling procedure, which is assumed to be 90%. Incineration credits were excluded because heat values from the applicable incineration processes were not available. As is typical, landfilled materials also received no disposal credits.

2.7 Inventory Building and Data Quality

General data was collected for raw materials extraction, product manufacturing, and transportation phases of this LCA using the ecoinvent database[9], National Renewable Energy Laboratory life cycle inventory database, and related LCA articles. Transportation distances were estimated using Google Earth software. Processes that contribute to resource extraction were often considered using aggregated data yielding impacts for one unit process for extraction. Product specific data (when available) or average product data was used to inform assumptions pertaining to each specific system component. Site specific data and system setup were taken from site visits, interviews with Koh Jig residents, interviews with system designers, and literature available on Koh Jig Island, with additional information supplied by the ecoinvent database.

2.8 General LCA Assumptions

The following table includes system-wide microgrid assumptions. Component-specific assumptions can be found in Appendix B.

[9] References for general database data can be found in Appendix D

General	Based on ISO guidelines, a 95% mass cut-off is applied to all components of the microgrid and the alternative electrification scenarios. Exceptions were made for rare and toxic materials [14].
Raw Material Extraction	Unless stated otherwise, only virgin materials were considered for all components.
Manufacturing	Only impacts from energy inputs are included in this phase.
Transportation	1. All components are transported from final manufacturing plant to Bangkok, via distributer if necessary. Return trips are included if the country of origin has a negative trade balance with Thailand. 2. Upon arriving in Bangkok, all components are transported 300 km to Koh Jig using a 3.5-20 ton truck. It is assumed that the truck will return to Bangkok empty. A notable exception to this is grid extension. 3. The 4 km ferry transport to the island has been excluded in all transportation calculations.
Use	1. Impacts from installation have been excluded for all scenarios. 2. No transmission losses or conversion losses take place on the island. 3. Only the combustion impacts are considered for diesel fuel. 4. Only the production impacts are considered for lubrication oil. 5. Maintenance is only included for impact-producing processes.
Disposal	1. All metals components are recycled with 90% efficiency. Credits were determined by crediting 90% of the impact from raw material extraction [15]. 2. Lubrication oil, mineral oil, fiberglass polyester, paper, and all plastics are incinerated with no credits given for heat recovery. 3. Concrete, glass, sulfuric acid (after dilution), asphalt, and the used solar cells are 100% landfilled. 4. Transport back to Bangkok for all disposal processes (truck returns empty).

Table 1: Overview of general assumptions for each life cycle phase

3. Inventory Analysis

3.1 The Microgrid System Components

The idealized microgrid system is composed of wind turbines, solar photovoltaic panels, a centralized diesel generator, lead acid batteries, wind/solar/bi-directional grid converters, and a local power distribution system. A complete description of material inputs and manufacturing energy inputs for each specific component can be found in Appendix B.

Component	Model	Mass (kg)	Origin	Transport	Distance	Lifetime (years)	Reference Flow
Diesel Generator	65kW P65E3 FG Wilson	930	Pondicherry, India [16}	Pondicherry, India to Bangkok, Thailand	4900 km (ship)	10	2
Wind Turbines	5 kW Fortis Montana	1,440	Hoogkerk, Netherlands [17]	*Leg 1* : Hoogkerk, Netherlands to Pune, India (Distributer) *Leg 2* : Pune, India to Bangkok, Thailand	*Leg 1* : 12,500 km (ship) *Leg 2* : 6,400 km (ship)	20	2
PV Solar Panels	75W Shell SQ75 Mono-Si	7.6	Camarillo, California [18]	Camarillo, California to Bangkok, Thailand	17,100 km (ship)	20	120
Lead Acid Batteries	2V Suncycle AS770	60	Fairfield, Australia [19]	*Leg 1* : Fairfield, Australia to Sydney, Australia *Leg 2* : Sydney to Bangkok	*Leg 1* : 20 km (truck) *Leg 2* : 7,500 km (ship)	10	300
Converters	Sunny Boy 2500 (SB) Windy Boy 2500 (WB) Sunny Island (SI)	(30) SB (30)WB (45) SI	Niestetal, Germany [20]	*Leg 1:* Niestetal, Germany to Bremen, Germany *Leg 2:* Bremen, Germany to Bangkok, Thailand	*Leg 1* : 280 km (truck) *Leg 2* : 19500 km (ship)	20	(3) SB (4) WB (3) SI
Dsistribution System	General Data	58,000	Bangkok, Thailand	---	300 km (truck)	40	1

Table 2: Microgrid component overview

3.2 Individual Home Diesel Generators

The electrification of Koh Jig using home diesel generators is modeled by summing the impacts of the 94 “generic” home diesel generators with a rated capacity of 5 kWh at 100% load to satisfy the functional unit. To develop a generic home diesel generator, the masses and transportation distances from 3 common generators were averaged in Table 3. Due to data limitations, the same raw material and manufacturing process assumptions as the centralized microgrid generator have been made and scaled to mass. The key difference between home and centralized generators is in their respective efficiencies, with the larger generator having a lower burn rate of 0.23 L/kWh according to manufacturer specifications. This burn rate is justified by the high quality of manufacturing, the assumption that the generator is run at full capacity, and the general trend of increased efficiency for larger generators. Conversely, the home diesel generators were given a burn rate of 0.39 L/kWh due to their low quality of manufacture, assumption that they are often run at less than full capacity, and the general trend of decreased efficiency for smaller generators.

Company	Model	Mass (kg)	Origin	Transport	Distance	Lifetime (years)	Reference Flow
Hi-earns Mech., Electrical Co. Ltd. [21]	5 kW DG6000E	104	Changzhou, China	*Leg 1* : Changzhou, China to Shanghai, China *Leg 2* : Shanghai, China to Bangkok Thailand	*Leg 1* : 180 km (truck) *Leg 2* : 4200 km (ship)	---	---
Chongqing Shineray Agr. and Machinery Co., Ltd. [22]	5 kW SRDE6500	95	Chongqing, China	*Leg 1* : Chongqing, China to Guangzhou, China *Leg 2* : Guangzhou, China to Bangkok, Thailand	*Leg 1* : 950 km (truck) *Leg 2* : 2660 km (ship)	---	---
Guangzhou Dingfeng Machinery Co., Ltd. [23]	5 kW PGO DF500D	90	Guangzhou, China	Guangzhou Port, China to Bangkok, Thailand	2660 km (ship)	---	---
Averaged Data	Generic 5 kW Diesel Generator	96	---	---	570 km (truck) 3170 km (ship)	8.7	216

Table 3: Generic home diesel generator overview

3.3 Extension of Thai National Grid

The extension of the existing Thai grid consists of the submarine power distribution cable required to connect Koh Jig to the existing power distribution grid on the mainland's coast, a transformer to convert the power to a safe voltage, and the same local power distribution center on Koh Jig modeled in the microgrid system. The following table provides all assumptions made for the life cycle grid extension analysis. Specific materials used for grid extension can be found Appendix B.

Component Category	Component	Component Model/Type	Design Considerations	Maintenance	Lifetime (years)
Cable	Submarine Power Transmission Cable	3 Phase 150 kV Sea Cable	**Shipping Distance**: 300km (Bangkok to Koh Jig) **Cable Length**: 4 km (Connect aerial power cable at coast to Koh Jig)	**Equipment**: Small diesel powered ship	40
Transformer	Power Distribution Transformer	315 kVA Distribution Transformer	**Shipping Distance**: 300km (Bangkok to Koh Jig) **Installation Location:** Koh Jig **Number**: 1	---	30
Infrastructure	Island Power Distribution Infrastructure	Generalized	**Shipping Distance**: 300km (Bangkok to Koh Jig) **Grid Length**: 1.8 km loop	---	40
Total System	---	---	**Power Loss in Transmission**: 5.9%	Maintenance occurs once over 20 year duration of functional unit	---

Table 4: Extension of Thai national grid [24,25]

4. Impact Assessment Results

For the purposes of this study, four impact criteria - global warming potential (GWP), acidification potential (AP), human toxicity potential (HTP), and abiotic resource depletion potential (ADP) – have been considered using the CML method, with a 100-year outlook for global warming potential and an infinite outlook for human toxicity potential in interpreting the life cycle emissions. We have chosen to omit any additional normalization or weighting methods which would further simplify, but add greater uncertainty to, our results. Percentages calculated from total impact potential values do not consider end of life credits. Values are rounded to the nearest whole number due to uncertainty in data and for simplicity of presentation.

4.1 Compared Systems and Technologies

Total by Component	Acidification Potential (kg SO_2 eq)	Global Warming Potential (kg CO_2 eq)	Human Toxicity Potential (kg 1,4 DCB eq)	Abiotic Resource Depletion Potential (kg Sb eq)
Solar Panels	10400	8532	15951	3193
Wind Turbines	133	54443	41081	354
Diesel Generator	13573	1056322	19726	6751
Batteries	505	63416	61948	494
Converters	12	1121	12922	7
Transmission System	281	40326	151822	251
Total	24903	1224161	303451	11050

Table 5: Reference flow impacts from each component of the optimized microgrid system

Table 5 shows the total impact potentials of the microgrid for the four impact categories and the contributions made by each component. Of the total acidification potential of the microgrid (24,900 kg SO_2 eq), the solar panels and the diesel generator contribute a combined 96% of the total, at 10,400 kg SO_2 eq (42%) and 13,600 kg SO_2 eq (55%) respectively. The diesel generator accounts for 86% of the total global warming potential of the microgrid (1,220,000 kg CO_2 eq) with 1,060,000 kg CO_2 eq. The distribution system accounts for 50% of the total human toxicity potential (303,000 kg 1, 4 DCB eq) with a contribution of 152,000 kg 1,4 DCB eq. Of the total abiotic resource depletion potential incurred by the microgrid (11,000 kg Sb eq), 61% arises from the diesel generator, which contributes 6,750 kg Sb eq.

Total by Life Cycle Phase	Acidification Potential (kg SO_2 eq)	Global Warming Potential (kg CO_2 eq)	Human Toxicity Potential (kg 1,4 DCB eq)	Abiotic Resource Depletion Potential (kg Sb eq)
Resource Extraction	2133	144879	1989227	1227
Manufacture	10896	108915	35717	3955
Transport	401	54229	26476	360
Use	13275	1010683	4678	6468
End of Life	-1802	-94546	-1752648	-960
Total	24903	1224161	303451	11050

Table 6: Reference flow impacts from each life cycle phase for the optimized microgrid system

Table 6 shows the breakdown of the microgrid's impacts based on life cycle phase. For the microgrid's acidification potential, 91% of the total 26,700 kg SO_2 eq is comprised of the manufacturing and use phases, at

10,900 kg SO_2 eq (41%) and 13,300 kg SO_2 eq (50%) respectively. The use phase is also responsible for 77% of the microgrid's global warming potential -- a contribution of 1,010,000 kg CO_2 eq to the total value of 1,320,000 kg CO_2 eq. In human toxicity potential, the resource extraction phase contributes 1,990,000 kg 1,4 DCB eq, or 87%, of the total value of 2,290,000 kg 1,4 DCB eq. The use phase is most significant in abiotic resource depletion potential, adding 6,470 kg Sb eq (54%) to the final 12,000 kg SB eq. The end of life phase credits back 7% of the acidification potential (1,800 kg SO_2 eq), 7% of global warming potential (94,500 kg CO_2 eq), 77% of the human toxicity potential (1,752,648 kg 1,4 DCB eq), and 8% of the abiotic resource depletion potential (960 kg Sb eq).

4.2 Actual Performance Scenario for Consideration:

While we primarily consider the impacts of the microgrid as it was designed to work, events such as the malfunctioning of the wind turbines and solar converters have given rise to an "actual performance scenario" that we have included for consideration. Notable differences between this and the designed case include an increase in electricity generation from diesel to cover the malfunctioning wind turbines and the inclusion of 8 maintenance trips to and from Germany for the solar converters.

Total by Component	Acidification Potential (kg SO_2 eq)	Global Warming Potential (kg CO_2 eq)	Human Toxicity Potential (kg 1, 4 DCB eq)	Abiotic Resource Depletion Potential (kg Sb eq)
Solar Panels	10400	8532	15951	3193
Wind Turbines	133	54443	41081	354
Diesel Generator	17409	1351210	22197	8634
Batteries	505	63416	61948	494
Converters	15	1287	13001	9
Distribution System	281	40326	151822	251
Total	28743	1519214	306001	12935

Table 7: Reference flow impacts from each component of the microgrid system actual performance scenario

Table 7 demonstrates that the greatest change resulting from consideration of the actual performance scenario, versus optimal performance, comes from the diesel generator impact potentials. The diesel generator experiences increases of 31% in acidification potential (from 13600 to 17408 kg SO_2 eq), 28% in global warming potential (from 1,060,000 to 1,350,000 kg CO_2 eq), 13% in human toxicity potential (from 19,700 to 22,197 kg 1,4 DCB eq), and 19% in abiotic resource depletion potential (from 6,750 to 8,630 kg Sb eq).

4.3 Home Diesel Generation Scenario

Home Diesel Generator	Acidification Potential (kg SO_2 eq)	Global Warming Potential (kg CO_2 eq)	Human Toxicity Potential (kg 1,4 DCB eq)	Abiotic Resource Depletion Potential (kg Sb eq)
Resource Extraction	1389	258545	1398383	1658
Manufacture	1057	182400	117195	1279
Transport	146	12371	2973	86
Use	31819	2428946	26116	16007
End of Life	-1246	-178614	-1257168	-1487
Total	33165	2703648	287498	17543

Table 8: Reference flow impacts from each life cycle phase for electrification via home diesel generators

Table 8 demonstrates that the use phase of the home diesel generator electrification scenario contributes 91% (31,800 kg SO_2 eq) of the total acidification potential of 34,800 kg SO_2 eq. The use phase also contributes 83% of the global warming potential -- 2,430,000 kg CO_2 of the total 2,930,000 kg CO_2 eq. The resource extraction phase contributes 1,400,000 kg 1,4 DCB eq, approximately 90%, of the total human toxicity potential of 1,555,867 kg 1,4 DCB eq. The use phase comprises 83% of the abiotic resource depletion potential of 19,400 kg Sb eq, with a contribution of 16,000 kg Sb eq. The end of life phase credits back 4% (1,250 kg SO_2 eq) to the acidification potential, 6% (179,000 kg CO_2 eq) to the global warming potential, 81% (1,260,000 kg 1,4 DCB eq) to the human toxicity potential, and 8% (1,490 kg Sb eq) to the abiotic resource depletion.

4.4 Grid Extension to the Thai National Grid Scenario

Grid Extension	Acidification Potential (kg SO_2 eq)	Global Warming Potential (kg CO_2 eq)	Human Toxicity Potential (kg 1,4 DCB eq)	Abiotic Resource Depletion Potential (kg Sb eq)
Resource Extraction	15956	1022506	18600019	6766
Manufacture	366	78827	10009	603
Transport	271	38036	5359	267
Use	8995	1782584	300978	13490
End of Life	-14380	-559709	-18533400	-3887
Total	11207	2362243	382965	17239

Table 9: Reference flow impacts from each life cycle phase for electrification via grid extension

Table 9 shows that the resource extraction phase contributes 62%, or 16,000 kg SO_2 eq, to the total acidification potential of 25,600 kg SO_2 eq. The use phase contributes 61% to the global warming potential -- 1,780,000 kg CO_2 eq of the total 2,920,000 kg CO_2 eq. The resource extraction phase contributes 98% - 18,600,000 kg 1,4 DCB eq - to the human toxicity potential value of 18,900,000 kg 1,4 DCB eq. The use phase contributes 64% of the abiotic resource depletion, 13,500 kg Sb eq of the final 21,100 kg Sb eq. The end of life phase credits back 56% (14,400 kg SO_2 eq) to acidification potential, 19% (560,000 kg CO_2 eq) to global warming potential, 98% (18,500,000 kg 1,4 DCB eq) to human toxicity potential, and 18% (3,890 kg Sb eq) to abiotic resource depletion.

4.5 Overall Environmental Impact of Compared Systems

System	Acidification Potential (kg SO2 eq)	Global Warming Potential (kg CO2 eq)	Human Toxicity Potential (kg 1,4 DCB eq)	Abiotic Resource Depletion Potential (kg Sb eq)
Optimal Microgrid	24,903	1,224,161	303,451	11,050
Actual Microgrid	28,743	1,519,214	306,001	12,935
Home Diesel Generators	33,165	2,703,648	287,498	17,543
Grid Extension	11,207	2,362,243	382,965	17,239

Table 10: Impacts of different electrification methods for Koh Jig

Table 10 shows that home diesel generators have the highest impact potential potentials in acidification potential, global warming potential, and abiotic resource depletion potential, with values of 33,400 kg SO_2 eq, 2,760,000 kg CO_2 eq, and 17,900 kg Sb eq, respectively. However, they also had the lowest human toxicity potential of all scenarios considered at 287,000 kg 1,4 DCB eq. For human toxicity potential, the grid extension has the highest impact at 383,000 kg 1,4 DCB eq.

5. Discussion

5.1 Comparative Electrification Scenarios[10]

The results indicate that the designed microgrid scenario has the lowest impact in global warming potential and abiotic resource depletion potential. The designed microgrid has a global warming potential that is 48% lower than next lowest scenario - grid extension - and abiotic resource depletion potential that is 36% lower than the next lowest scenario -- grid extension. The LCIA results indicate that 77% of the global warming potential of the microgrid comes from the use phase, which results entirely from the fuel combusted by the diesel generator. In the case of the home diesel generators, the use phase contributes 82% of the global warming potential for the same reason. In the grid extension scenario grid, 56% of the global warming potential results from the combustion of fossil fuels in the Thai electricity grid mix. These results show that the majority of global warming potential from all scenarios results from the combustion of fossil fuels. However, the microgrid has the lowest global warming potential because 30% of its energy is supplied by renewables, as opposed to the Thai grid mix which derives 91.1% of electricity from fossil fuels, and due to the relatively high efficiency of the centralized diesel generator [26].

[10] Calculations of percent contributions in this section are calculated from data which is not included due to restrictions in the use of the ecoinvent database .

Mirroring the trend of global warming potential, the combustion of fossil fuels contributes the majority of abiotic resource depletion potential in all scenarios. Fossil fuel combustion contributes 60%, 80%, 59% of the abiotic resource depletion potential for the microgrid, home diesel generator, and grid extension respectively. The reduction of the fossil fuel consumption by the microgrid's renewable energy components explains the microgrid's relatively low abiotic resource depletion potential.

The human toxicity potential of the microgrid and the grid extension, the scenarios with the largest human toxicity potentials, result in large part from the use of copper wire. The extraction and refinement of copper accounts for 85% of the microgrid's human toxicity potential and 93% of grid extension's toxicity potential. While the copper contributes a large portion of the microgrid's human toxicity potential, the hybrid system is only 1% higher than the home diesel generators in this impact category. This results from the home diesel generators' relatively low efficiency and consequently high emissions.

The microgrid's acidification potential is 122% larger than the lowest scenario, grid extension. This results primarily from the energy consumed in manufacturing the solar panel's monocrystalline wafers (32% of system total) and the combustion of diesel fuel in the diesel generator (53 % of system total). Diesel combustion accounts for 91% of the home diesel generators' acidification potential. The extraction and refinement of copper causes 71% of the grid extension's acidification potential. The microgrid's relatively high acidification potential values can thus be attributed to a combination of wafer manufacturing and diesel combustion.

The optimal microgrid is lower than the actual microgrid performance scenario in every impact category. The actual performance scenario ranges from 1-25% (14.5% mean) higher calculated impacts across all categories. This difference results from the increased combustion of diesel fuel due to the failure of renewable energy technology and the subsequent increase in diesel generator use.

5.2 Sensitivity Analysis[11]

To investigate assumptions and system parameters involved in this study, sensitivity analyses were conducted by changing the following variables: large diesel generator burn rate (Appendix C, Table 8), renewable energy fraction (Appendix C, Table 3), specific contribution from wind and solar components (Appendix C, Tables 4 and 5), methods to meet variable electricity demand (Appendix C, Tables 6 and 7), and possible scenarios for grid extension (Appendix C, Tables 1 and 2).

While the large centralized generator has an estimated burn rate of 0.23 L/kWh, the generic home diesel generators have an estimated burn rate of 0.39 L/kWh. If the large diesel generator's burn rate was to change from 0.23 to 0.5 L/kWh, substantial differences ranging from 60-90% in all impact categories except for human toxicity potential can be expected. As burn rate represents the amount of fuel consumed, these results highlight the importance of any factors that affect diesel consumption, such as temperature, altitude, operation and maintenance, and fuel quality.

[11] The accompanying tables for this section can be found in Appendix C

The renewable energy fraction of the designed system is 30% (11% solar, 19% wind). When the renewable energy fraction of the system is increased from 0% to 100%, maintaining the designed proportion of solar to wind, the impacts in all categories except for global warming potential increase by an average of 5% for every 10% increase in the renewable fraction. When only the solar fraction is increased from 0% to 100%, this average increase is 12%. In both of these scenarios, global warming potential decreases linearly as the renewable energy percentage increases. However, when the increased renewable energy capacity comes from an increase solely in wind fraction from 0% to 100%, impacts in all categories decrease linearly except for human toxicity potential, which increases linearly.

The designed microgrid supplies 265 kWh/day. When supply increases from 0 kWh/day to 600 kWh/day, impacts increase linearly in all categories due to higher diesel generator use. If renewable technologies and diesel generator usage are changed to maintain the designed proportion of 11% solar, 19% wind, and 70% diesel when the load increases from 0 kWh/day to 600 kWh/day, impacts increase linearly in all categories. When renewable technology and diesel, rather than diesel alone, are scaled to meet demand, the impacts are higher in all categories except global warming potential.

While it is assumed that Koh Jig can be directly connected to the mainland electricity grid, the possibility remains that extending the Thai electricity grid would require the connection of Koh Jig to a power distribution substation. In considering this possibility, it is assumed that Koh Jig would connect with the nearest substation in the surrounding provinces (Chanthaburi or Trat). This sensitivity analysis explored the impacts of connecting Koh Jig to the Chanthaburi substation (65 km) and the Trat province substation (30 km) via an aerial power distribution cable system. These scenarios consider the impacts incurred by the infrastructure (aerial cable masts, mast foundations, and cable isolators). The Trat province scenario results in acidification, global warming, human toxicity, and abiotic resource depletion potentials of 26,500 kg SO_2 eq, 4,720,000 kg CO_2 eq, 3,290,000 kg 1,4 DCB eq, and 30,400 kg Sb eq respectively. The Chanthaburi scenario resulted in acidification, global warming, human toxicity, and abiotic resource depletion potentials of 42,300 kg SO_2 eq, 4,270,000 kg CO_2 eq, 6,930,000 kg 1,4 DCB eq, and 43,900 kg Sb eq respectively. These results show that the addition of the aerial cable contributes greatly to the overall impact of the grid extension scenario. These consistently higher impacts result from the use of more cable and its required infrastructure. This 65 km connection has the largest impacts when compared to the home diesel generator and microgrid systems considered on Koh Jig. This scenario illustrates a case in which the electrification site is far more isolated than the location of Koh Jig, a common characteristic of sites in which microgrids are considered.

5.3 Limitations and Improvement Potential

Although consideration of the actual performance of the system is important to this research, the data concerning performance is quite poor due to a lack of research after 2007. Beyond this, specific data on the pre-microgrid electrification conditions have been collected through surveys of the local population, which inevitably introduce inconsistencies between different studies and reports. Additionally, this study’s reliance on interlingual interviews introduces the possibility of error.

The uncertainty regarding the disposal phase reflects both the lack of general knowledge of disposal processes within rural communities (for example, the percentage of parts reused, landfilled, and burned locally) and the limited availability of information pertaining to the impacts of disposal processes. For this study the disposal assumptions predicted in the optimal design were used again to model the actual disposal impact, thus the actual disposal of microgrid components will likely be more impactful.

Impact potentials for the installation of both the grid extension and microgrid as well, as manufacturing of grid extension cables and infrastructure, could not be included in the scope because data was unavailable to make appropriate assumptions. The electrical meters installed with the microgrid were also not included in the scope because related data was not found.

Finally, it is understood that most of the ecoinvent processes and conversion factors used in this study model European processes. When available, CML global or generic averages were used to approximate impact potentials for Asian processes.

6. Conclusions

This study assesses the environmental impacts of the hybrid microgrid on Koh Jig in order to better understand the environmental sustainability of such a system in comparison to home diesel generation and grid extension. The hybrid microgrid results in the lowest impact for both global warming and abiotic resource depletion potential. Sensitivity analysis shows that the system can support a significant increase in the load before it becomes the most environmentally impactful option. The relatively low overall impacts of the microgrid system can be attributed to the renewable component and the high efficiency of the diesel generator. The versatility results from ability to scale power production with the diesel generator to meet demand, implying that the diesel generator is a critical factor in the system's relatively favorable environmental impacts. This contradicts the common perception that a complete reliance on renewable energy technology will always provide the least impactful electrification scenario.

Although increasing the number of solar panels and wind turbines - scaling the renewable energy - to meet demand reduces global warming potential, scaling diesel generation to meet demand results in lower impacts in all categories except global warming potential. This incongruity demonstrates that while the diesel generator serves a valuable purpose in the hybrid system, in some categories it is also the primary impact contributor. Although this dilemma can be solved by assigning relative importance to each impact category, the advent of a scalable, low impact power source presents the best solution for the environmental sustainability of microgrid systems. In the absence of such technology, a framework that utilizes project specific considerations to prioritize impact categories is needed before any judgment of environmental sustainability can be made.

6.1 Research Applications and Opportunities for Future Research

Although a Life Cycle Assessment of the potential impacts of a microgrid system can provide the relative environmental impacts of the system in comparison to alternative electrification scenarios, it cannot comment on the overall sustainability of the system without consideration of the economic and social aspects. These aspects are highly important in informing questions such as whether increased electrification is even a suitable goal for development or how feasible these systems are to implement in the first place. Such questions are beyond the scope of this study, but this study can contribute to a comprehensive assessment of the environmental, economic, and social life cycles of this and other microgrid systems.

7. Acknowledgements

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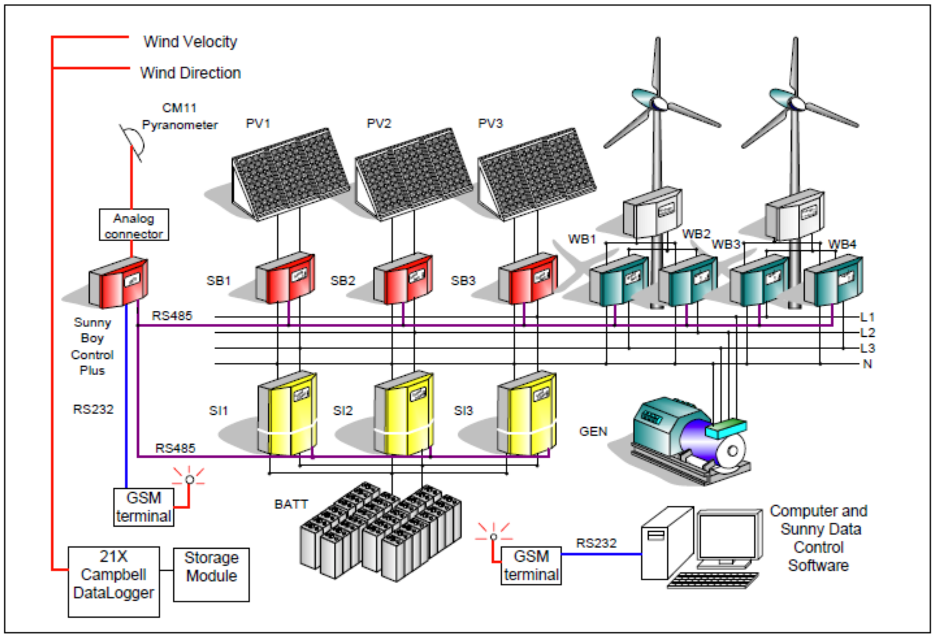
9. Appendices

Appendix A:

General Koh Jig Information



Appendix A, Figure 1: Schematic diagram of optimized microgrid system [8]

Table 5.1: Energy demand in Ko Jig village (July 2001)

Appliances	Power (Watt)	Quantity (Unit)	Duration (hr)	Energy demand (kWh)
Fluorescent lamp	13	686	18.30-22.30	35.672
Television 29"	200	1	18.30-22.30	0.80
Television 25"	150	2	18.30-22.30	1.2
Television 21"	100	6	18.30-22.30	2.4
Television 20"	70	41	18.30-22.30	11.48
Television 14"	50	53	18.30-22.30	10.6
Television 14"B/W	20	6	18.30-22.30	0.48
Stereo	30	63	18.30-22.30	7.56
VCD player	35	58	18.30-22.30	8.12
Fan	35	180	18.30-22.30	25.2
Motor/pump	2,500	1	18.30-22.30	10
Washing machine	500	2	18.30-22.30	2
Mosque's sound broadcast	90	1	6.00-8.00 16.00-18.00	0.36
Total				115.87
Power maximum				30 kW

Appendix A, Table 1: Energy demand in Koh Jig village [8]

Appendix B:

Life Cycle Calculations

Diesel Generator	1. The two diesel Generators (Hino W04D and FG-Wilson P75P1), have the same weight, and fuel usage statistics. 2. Generator components percentages 30% Steel, 30% Casted Steel, 35% Aluminum, 3% Copper, 2% Plastic. [A]. 3. It takes 54GJ Natural Gas and 16 GJ Electricity per ton engine for all factory processes [B]. 4.The production process for both the home and centralized diesel generators are assumed to be comparable to the production of a gas engine. 5. Diesel fuel has a specific gravity of 0.85 [C]. 6. Home diesel generators and system generator diesel burn rates were assumed to be different. 7. The FG Wilson generator was assumed to be manufactured at the FG Wilson facilities in India.
Wind Turbines	1. No emissions during the use phase. 2. Manufacturing was assumed to take place at the Fortis Wind Energy company headquarters in Hoogkerk, Netherlands. The turbines were assumed to be shipped to a Fortis distributor in Pune, India before being shipped to Thailand. 3. Foundation components are assumed to be from Bangkok, Thailand and shipped separately to Koh Jig by truck. 4. Material components and manufacturing energy of the turbines were taken from an inventory of a 5 kW S-343 Endurance Wind power turbine, and were adjusted by size proportions for the Fortis turbine [D,E,F]. 5. The guy wire for the stabilization of the mast is assumed to be made of stainless steel.
PV Solar Panels	1. The panels produced no emissions during the use phase. 2. The panels were assumed to have been manufactured in the Shell monocrystalline silicon PV production plant in Camarillo, California before being shipped by freighter ship to Bangkok. The emissions data from the average U.S. electricity grid mix were used for the manufacturing emissions from electricity usage [G]. 3. "Manufacturing" was assumed to include the production of the mono-Si wafers, solar cells, and actual module lamination and assembly, as these were all presumed to have occurred in the same building in quick succession. Impacts from energy from manufacturing the mono-Si wafers were also thought to be too large to be excluded. 4. Production of the poly-Si was assumed to be by the Czochralski crystal pulling method. 5. The panels were assumed to have 3.2 mm thick glass. 6. The weight of the solar cells were estimated from volume and density data [H]. 7. Exceptions to the material mass cut-off limit of 95% were made for the copper and lead panel components [I].
Lead Acid Batteries	1. The batteries produced no emissions during the use phase. 2. There is no need to replace the water/sulfuric acid during the use phase due to the addition of antimony to prevent the water from hydrolyzing. 3. The batteries were assumed to have been produced at the manufacturer of Suncycle batteries (Battery Energy Power Solutions Pty Ltd) headquarters in Fairfield, Australia. They were then assumed to have been sent by truck to Sydney before travelling to Bangkok via ocean freighter. 4. Based on industry findings that most lead acid batteries contain 60-80% recycled lead, this study uses a 70% recycled lead and 30% virgin lead mix [19]. 5. Exceptions to the material mass cut-off limit of 95% were made for the copper and tin components of the battery. 6. The manufacturing energy value was taken from the Sullivan and Gaines paper, while the breakdown by energy type of that value was estimated from the Rantik paper. [J,K]
Converters	1. The material breakdown of a solar inverter was taken from an ecoinvent process for a 2500 kW solar inverter and was scaled by mass to represent the solar inverters, wind inverters, and bi-lateral grid managers [L]. 2. Manufacutring was assumed to take place at the SMA Solar Technology Germany company headquarters in Niestetal, Germany. 3. In the scenario representing the actual timeline of events at Koh Jig, one solar inverter was assumed to be shipped back and forth to Germany 8 times, representing twice a year for four years. The three solar converters were also replaced in 2012. 4. Exceptions to the 95% mass allocation rule were made for lead, gold, and silver components of the inverter because of the high toxic and hazardous impacts.
Island Transmission	1. Grid infrastructure is represented by an ecoinvent process for a low-voltage distribution system, though selectively only the processes involving metal production and PVC production were included. The materials extraction and manufacturing phases were assumed to take place in Bangkok, Thailand. 2. Manufacturing energy is represented by electricity use from concrete block formation and the electricity needed to produce light fuel oil used in distribution system production. 3. Wood was excluded and replaced by concrete based on the schematic drawings of the Koh Jog system, which suggested 60 concrete poles that were 8.5 meters high and had an assumed cross-sectional area of 0.4 m2 [8]. 4. The transmission system for the microgrid was assumed to cover a distance of 1.8 km from the microgrid center through a network of wiring and concrete poles [8].

Appendix B, Table 3: Microgrid system component specific assumptions (comments marked in blue refer to the actual performance scenario)

Senario	System Component	Reference Flow	Total Mass (kg)	Materials	Material Mass (kg)	Manufacturing Energy Inputs [heat / electrical] MJ	Disposal Recycled [R] Incinerated [I] Landfilled [L]
Microgrid		**1**					
	Diesel Generator	2	930	Steel	558	50220 / 14880	90% R
				Aluminium	325.5		90%R
				Copper	18.6		90% R
	Diesel Fuel	---			343790.4115		---
	Lubrication Oil	---			872.496		---
	Wind Turbines	2	12146.77	Concrete	10,662.55	0 / 71734	100% L
				Galvinized Steel	1070.2		90% R
				Steel	233.5		90% R
				Stainless Steel	72.13		90% R
				Steel Rebar	45.7		90% R
				Fiberglass	13.6		40% I / 60% L
				Copper	29.5		90% R
	PV Solar Panels	120	9.24	Glass	5.2	5997 / 49054	100% L
				Aluminium	2.8		90% R
				Ethyl Vinyl Acetate	0.7		100% I
				Solar Cells	0.466		100% I
				Copper	0.07		90% R
				Lead	0.004		90% R
	Lead Acid Batteries	300	60	Lead	43.44	0 / 1860	90% R
				Sulfuric Acid	13.2		100% L
				ABS Plastic	3.06		100% I
				Tin	0.12		90% R
				Copper	0.06		90% R
	Converters	10	360	Steel	190.72	0 / 2153	90% R
				Copper	123.67		90% R
				Aluminium	35.37		90% R
				PE	1.17		100% I
				Lead	0.88		90% R
				SAN	0.19		100% I
				PVC	0.19		100% I
				Silver	0.086		90% R
				Gold	0.0001589		90% R
	Transmisson	1	57997.8	Concrete	48960	176619 / 1058	100% L
				Steel	4140		90% R
				Copper	3384		90% R
				PVC	1110.6		100% L
				Lead	403.2		90% R
Home Diesel Generators		**216**					
	Generator Engine		96	Steel	57.6	5184 / 1536	90% R
				Aluminum	33.6		90% R
				Copper	1.92		90% R
	Diesel Fuel	---			637998.1		---
	Lubrication Oil	---			17029.44		---
Grid Extension		**1**					
	Cable			Steel	151875.5	---	90% R
				Lead	27800		90% R
				Copper	17200		90% R
				Aluminum	237250		90% R
				Glass	18336.5		100% L
				Cement	1566.5		100% L
				Insulation oil	8080		100% I
				Paper	7600		100% I
				Bronze	6400		90% L
				Polypropylene	3800		100% R
				Asphalt	1400		100% L
	Transformer		984.67	Steel	571.33	2254 / 529	90% R
				Mineral oil	226.67		100% I
				Aluminum	133.2		90% R
	Infrastructure			Concrete	4212000	---	100% L
				Steel	585000		90%R
				Iron	195000		90%R
				Zinc	9100		90% R

Appendix B, Table 4: Inventory of materials for microgrid system components and grid extension

Total by Life Cycle Phase	Acidification Potential (kg SO_2 eq)	Global Warming Potential (kg CO_2 eq)	Human Toxicity Potential (kg 1,4 DCB eq)	Abiotic Resource Depletion Potential (kg Sb eq)
Resource Extraction	2133.35	144878.7	1989227	1226.882
Manufacture	10895.78	108914.9	35717.07	3954.738
Transport	449.6317	60807.18	27939.4	406.6971
Use	17065.69	1299159	5765.577	8305.894
End of Life	-1801.78	-94545.8	-1752648	-959.667
Total	28742.67	1519214	306001.3	12934.54

Appendix B, Table 5: Impact assessment results for actual microgrid performance scenario

Appendix C:

Sensitivity Analyses

Scenario One: Grid Extension

Grid Connection Distance (km)	Grid Connection Location	Acidification Potential (kg SO_2 eq)	Global Warming Potential (kg CO_2 eq)	Human Toxicity Potential (kg 1,4 DCB eq)	Abiotic Resource Depletion Potential (kg Sb eq)
65	Chonburi Province Power Distribution Substation	42,347.96	7,272,081.65	6,925,281.75	43,926.83
30	Trat Province Substation	26,453.97	4,723,596.41	3,388,150.51	30,409.47
0	Coastal Grid (No Substation)	11,207.25	2,362,243.21	382,965.00	17,239.21

Appendix C, Table 1: Sensitivity analysis of grid connection location

Power Demand (kWh/day)	Acidification Potential (kg SO_2 eq)	Global Warming Potential (kg CO_2 eq)	Human Toxicity Potential (kg 1,4 DCB eq)	Abiotic Resource Depletion Potential (kg Sb eq)
100	37,637.91	6,253,964.50	6,798,043.05	36,133.10
200	40,492.48	6,871,005.20	6,875,157.41	40,856.57
300	43,347.06	7,488,045.89	6,952,271.78	45,580.04
400	46,201.64	8,105,086.59	7,029,386.15	50,303.51
500	49,056.22	8,722,127.28	7,106,500.52	55,026.98
600	51,910.80	9,339,167.98	7,183,614.88	59,750.45

Appendix C, Table 2: Sensitivity analysis of functional unit power demand

Scenario Two: Microgrid

Renewable Energy Fraction (%)	Acidification Potential (kg SO_2 eq)	Global Warming Potential (kg CO_2 eq)	Human Toxicity Potential (kg 1,4 DCB eq)	Abiotic Resource Depletion Potential (kg Sb eq)
0	20124.23	1603517	250125.6	10327.5
10	21653.17	1486068	274614.9	10601.03
20	23267.98	1368689	299236.4	10900.37
30 (baseline)	24903.38	1224161	303450.5	11049.79
40	26345.25	1106640	327806.5	11296.32
50	28220.47	989474.8	352827.2	11675.89
60	29682.53	844803.8	356775.5	11772.09
70	31384.41	727496.4	381530.2	12098.44
80	32826.29	609975.8	405886.2	12344.97
90	34375.01	465375.8	409967.5	12467.78
100	35903.55	347926.3	434456.4	12740.91

Appendix C, Table 3: Sensitivity analysis of microgrid renewable energy fraction

Solar fraction (%)	Acidification Potential (kg SO_2 eq)	Global Warming Potential (kg CO_2 eq)	Human Toxicity Potential (kg 1,4 DCB eq)	Abiotic Resource Depletion Potential (kg Sb eq)
0	16613.25	1377817	288859	8892.697
10	24557.1	1223877	302919.2	10943.75
20	31931.19	1098643	315764.4	12890.41
30	39546.82	959019.6	329150.6	14875.97
40	47249.13	819467.8	342669.7	16888.13
50	54951.43	679916	356188.8	18900.3
60	62567.07	540293	369575	20885.85
70	70269.37	400741.2	383094.2	22898.01
80	78058.34	261260.5	396746.2	24936.79
90	85847.32	121779.7	410398.3	26975.56
100	93549.62	-17772.1	423917.4	28987.73

Appendix C, Table 4: Sensitivity analysis of microgrid solar fraction

Wind Fraction (%)	Acidification Potential (kg SO_2 eq)	Global Warming Potential (kg CO_2 eq)	Human Toxicity Potential (kg 1,4 DCB eq)	Abiotic Resource Depletion Potential (kg Sb eq)
0	28415.15	1449862	264717.9	12485.4
10	26630.05	1356861	304563.2	11897.65
20	24778.46	1236638	323868	11132.97
30	22926.87	1116416	343172.7	10368.29
40	21075.28	996193.2	362477.4	9603.606
50	19223.68	875970.7	381782.1	8838.924
60	17372.09	755748.3	401086.9	8074.242
70	15520.5	635525.8	420391.6	7309.56
80	13668.91	515303.4	439696.3	6544.879
90	11817.32	395080.9	459001	5780.197
100	9965.724	274858.5	478305.8	5015.515

Appendix C, Table 5: Sensitivity analysis of microgrid wind fraction

Power Demand - Met Using Already Installed Technology (kWh/day)	Acidification Potential (kg SO_2 eq)	Global Warming Potential (kg CO_2 eq)	Human Toxicity Potential (kg 1,4 DCB eq)	Abiotic Resource Depletion Potential (kg Sb eq)
100	12924.81	303332.1	295732.3	5169.521
200	20162.86	859724.2	300396.1	8722.798
300	27328.52	1410552	305013.3	12240.54
400	34638.95	1972508	309723.7	15829.35
500	41876.99	2528900	314387.5	19382.63
600	49259.8	3096420	319144.6	23006.97

Appendix C, Table 6: Sensitivity analysis of power demand -- installed technology

Power Demand - Met By Scaling Technology (kWh/day)	Acidification Potential (kg SO_2 eq)	Global Warming Potential (kg CO_2 eq)	Human Toxicity Potential (kg 1,4 DCB eq)	Abiotic Resource Depletion Potential (kg Sb eq)
100	10063.76	549045.3	267686.9	4800.035
200	19010.36	968869.6	297341	8635.134
300	28043.64	1388765	327128.1	12496.84
400	37336.93	1808874	357313.9	16438.39
500	46043.71	2201334	366161.6	20043.33
600	54990.32	2621159	395815.7	23878.43

Appendix C, Table 7: Sensitivity analysis of power demand -- scaled technology

Large Diesel Generator Burn Rate (L/kWh)	Acidification Potential (kg SO_2 eq)	Global Warming Potential (kg CO_2 eq)	Human Toxicity Potential (kg 1,4 DCB eq)	Abiotic Resource Depletion Potential (kg Sb eq)
0.25	25926.33	1302765	304109.8	11552.18
0.3	28816.16	1524908	305971.8	12970.85
0.35	31705.98	1747050	307833.9	14389.51
0.4	34595.81	1969192	309695.9	15808.17
.412 (home generator efficiency)	35289.37	2022506	310142.8	16148.65
0.45	37485.63	2191334	311558	17226.84
0.5	40375.46	2413477	313420	18645.5

Appendix C, Table 8: Sensitivity analysis of diesel burn rate efficiency

Scenario Three: Home Diesel Generators

Number of Home Diesel Generators	Acidification Potential (kg SO_2 eq)	Global Warming Potential (kg CO_2 eq)	Human Toxicity Potential (kg 1,4 DCB eq)	Abiotic Resource Depletion Potential (kg Sb eq)
50	32460.56	2566089	157247.2	16519.5
94 (baseline scenario)	33165.43	2703648	287498.1	17542.86

Appendix C, Table 9: Sensitivity analysis of the number of home diesel generators

Appendix D:

Appendix-Specific References

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