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Title

Strategic Analysis of Continuity for Complex Energy and Environment Systems for Developing Regions

Abstract

It is possible that in the near future, energy engineering will be called upon to help society adapt to permanently constrained fuel supplies, constrained green house gas emissions, and electricity supply systems running with minimal capacity margins. The goal of this research is to develop an analytical method for adaptive energy systems engineering within the context of resource constraints. The method involves assessing available energy resources, environmental and social issues, and economic activities. A spectrum of development options is identified for a given region and a *Reference Energy Demand* is calculated for each representative level. A spectrum of conceptual *Reference Energy System Models* is generated for each development level with a range of renewable energy penetration. The outcome is a matrix of energy system investment and resource utilization for the range of energy service level defined by the development level. These models are then used for comparative risk assessment. The result is an easily understood visual based investment and risk assessment for both development and adaptation to constrained resource availability. The above approach is being applied to a relatively simple case study on Rotuma, an isolated Pacific Island society. The case study results will show a clear development space for Rotuma where needs and services are in balance with investment, local resource availability and environmental constraints.

1 Introduction

Most countries heavily rely on petroleum products as primary source of energy. However, global conventional oil production is expected to peak and then go into irreversible decline within the next two or three decades (Deffeyes, 2001), (Campbell, 2003), (Goodstein, 2004). Unless countries systematically prepare for declining oil supplies well ahead of time, there will be energy shortages of unprecedented scale (Hirsch, Bezdek, & Wendling, 2005). Energy shortages pose a severe risk to the continuity of society systems, herein referred to as *anthropogenic continuity*. But apart from imminent resource problems, energy extraction, conversion and use can also cause environmental problems; this poses an additional risk to anthropogenic continuity. These two risks are not well understood and are not or not adequately addressed in regional energy planning. Managing these risks is a daunting task because of the complexity of the problem and the uncertainties involved.

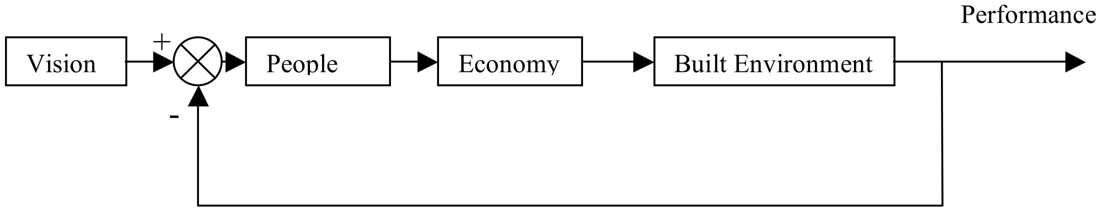

Figure 1: Anthropogenic Continuity Theory.

2 Materials and Methods

2.1 Introduction to the method

A theory has been proposed according to which people's cumulative behavior, and this particularly with regards to their energy consumption in a given region, is primarily a function of the built environment. The built environment includes all infrastructures and all man-made entities. Figure 1 depicts the basic functionality of activities in any society as a controls diagram. The diagram is useful for understanding fundamental principles and limitations for day-to-day-life decision making on all levels. Generally, decisions are made on the basis of a vision, or of any concrete objective. In control engineering terminology, the vision represents the reference input. The controller is human. Any activity is enacted through economies in a wider sense. The activity is enacted within, and thus limited by the built environment. It is important to note that any particular objective can be accomplished in various ways. The role of the economy is rationality, the desire to accomplish an objective with the optimum return of investment. The built environment determines the range of options. For example, Peter's objective may be to procure dinner. The vision is Peter's idea of where and how to get dinner. Peter's preferences and economic considerations determine the course of action. The built environment dictates which options are, or are not available.

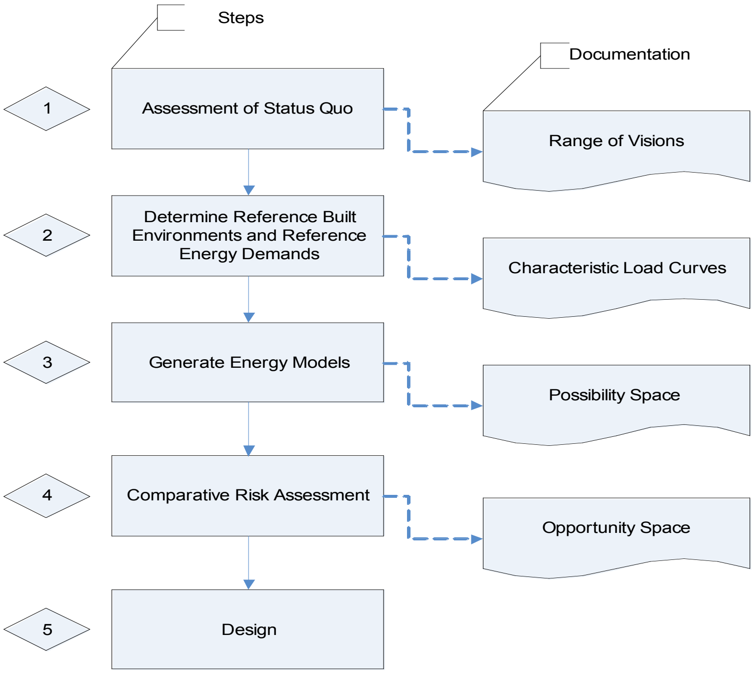

Figure 2: Methodology Overview.

The role of the built environment is therefore that of an enabler for and a limiter of any activities. Most research on sustainability takes the present built environment for granted, assuming that fully developed Western style built environments are both, irrevocable and most desirable. The herein presented method presumes that generally, a range of built environment levels can be equally desirable, and therefore a range of built environment levels is investigated. Thereby widening the scope of analysis opens the door for new solutions that have not previously been conceived.

2.2 General Description of the Method

An overview of the proposed method is given in Figure 2. The first step is the assessment of the status quo of the regional energy-environment-system. Produced data include energy flows, the economic situation, and people's subjective development objectives, herein referred to as their *development visions*. An every identified development vision is, in step 2, associated with a reference built environment which characterizes the particular development vision. And in turn, each type built environment requires a typical energy demand. Step 3 describes the development of a range of technically possible energy systems with different energy sources to supply the variety of energy demands. Combining a number of conceivable development levels with different types energy resources results in a matrix of options, describing the *possibility space* (Figure 3). Comparative Risk Analysis follows in step 4, to evaluate inherent risks to the society. Considered risks are given rise to by two factors: environmental damage and service supply reliability. The above four steps generate as an outcome an opportunity space; that is a set of actually feasible regional energy systems as a subset of the possibility space, which is the range of the many technically feasible regional energy systems. Step 5 brings about the design of the actual regional energy system, founded on the opportunity space.

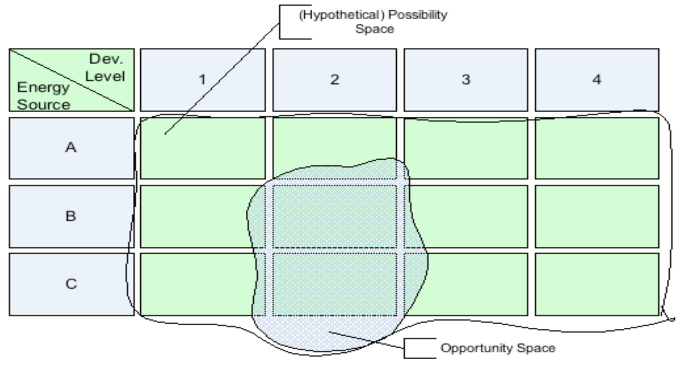

Figure 3: Possibility Space and its Subset, the Opportunity Space.

Having adumbrated the method above, the single steps are detailed in the subsequent sections.

2.3 Assessment of Status Quo

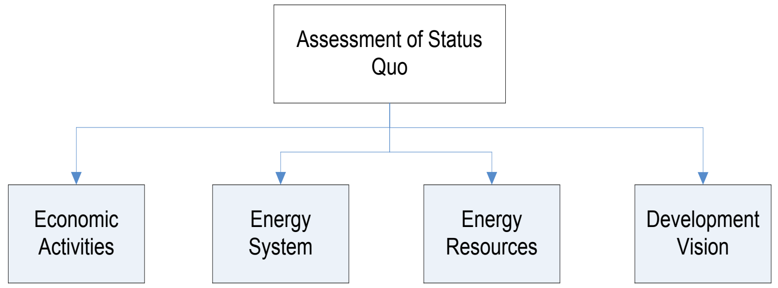

Figure 4: Assessment of Status Quo Overview.

Figure 4 shows the four different components of data collection required for subsequent analysis. Three of these components are part of standard regional energy planning procedure, and special only in detail and focus of the data collection.

Economic activities are assessed by how people spend their time, and also how much time is dedicated to economic activities. Essential outcomes are activity profiles and income distributions.

The **energy system** in place is analyzed on the supply side as well as on the demand side. Next to the main focus on surveying electricity, all other forms of energy use warrant a degree of attention; this is essential for an overall understanding of energy services and flows in the region. On the supply side, data is collected on the system layout, system condition, and system operation. Demand side analysis is done by means of an assessment of the energy services supplied, and the use and importance of these services to the people. Outcomes include appliance penetration data, energy expenditures, energy use distributions, and energy flow charts.

All significant local **energy resources** are assessed in terms of available quantities and accessibility. The data for all possible energy resources is plugged into subsequent energy models.

A novel part of an otherwise fairly standard 'status quo assessment' is a survey of **development visions**. This part adds a new dimension to traditional energy planning procedures. The rationale is twofold: people should have a say about where they would like to be in the future, but it is also recognized that finding feasible energy systems might require a larger range of options. A survey of development visions should identify a spectrum of visions of what different people would like their place to look like and be like in the future. The survey should pinpoint three or four representative visions, here referred to as development levels. These representative development levels are, in the next step, translated into characteristic build environments.

2.4 Determine Reference Built Environments and Energy Demands

A level of energy consumption is one of the decisive factors that characterize the level of development of a society. A level of development is unveiled by a particular lifestyle, and a particular lifestyle does occur because it is supported by the infrastructure, or in a wider sense, the built environment. This step of the method describes the transformation of people's visions to something tangible, something that can be analyzed with engineering methods.

It is assumed that the electricity aspect of a built environment is a function of the development level[1] and the local climate. If possible, appliance use profiles are created from empirical data; that is appliance use profiles from regions with similar climates and the target development level. Otherwise it is to be estimated. Appliance use profiles are used to model an energy demand in the form of an electricity load curve. Figure 4 shows the process as described. There is a built-in loop, which means that the process is to be repeated for each one of the identified development levels.

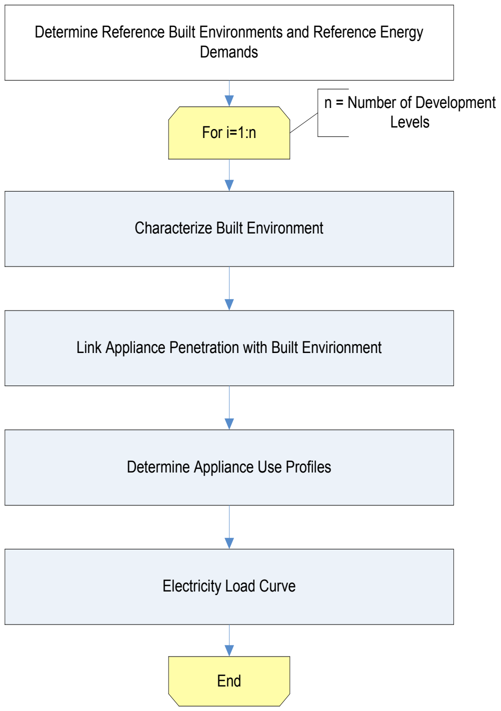

Figure 5: Determine the Built Environment.

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[1] I have to define development level somewhere: it can be anything, really, but in the case of developing countries it is probably the degree of Westernization.

2.5 Energy Models

Once reference load curves have been determined for each of the identified development levels, energy models are developed with different energy supply options. What the energy supply options are is determined by the available energy resources. Only commercially proven technologies are herein considered. Combining m development options with n energy resource options results in a total number of n*m basic energy system options. All n*m option models are developed using standard energy modeling software. System sizing and requirements, investment, life cycle costs, and cost of energy are computed separately for each option.

2.6 Comparative Risk Assessment

Risk assessments always begin with setting out the context of the risk management problem at hand. In this case, the overall strategic goal is anthropogenic continuity. The unwanted opponent of anthropogenic continuity is *collapse* of a society. A tangible concept explaining the collapse of previous societies has been published by (Diamond, 2005). According to Diamond, there are five fundamental factors which are essential to the study of collapse: 1) environmental damage, 2) climate change, 3) hostile neighbors, 4) friendly trade partners, and 5) society's response to environmental problems. Two of these factors, 'climate change', and 'hostile neighbors' are beyond the scope of this engineering analysis. Although engineering solutions may contribute to climate change, it needs be appreciated that climate change policies within one region cannot do anything to avert climate change in this particular region. Local engineering does, however, significantly affect possible 'environmental damage' in a region. Petroleum supplies and shortages to and in a region are covered under the 'friendly trade partners' factor. (Diamond, 2005) found that his fifth factor, 'society's response to environmental damage' was the single one factor which played a role in the failure of all societies that failed. In an effort to learn from others' mistakes, this research is dedicated to contribute to improving our own 'society's response to environmental problems.

Two out of the five factors Diamond introduced are suitable and appropriate for risk analysis to anthropogenic continuity in the regional energy planning context: 1) Resource availability to supply candidate energy systems ('friendly trade partners') and 2) Environmental problems.

The Risk of Energy Shortages

Figure 6 overviews the evaluation of the risk to us caused by declining conventional oil production. This probability for this risk is determined on the basis of petroleum production forecasts. This is difficult to analyze, because of the inherent uncertainties in assessing petroleum availability. At the current standard of knowledge in petroleum geology, it can be taken for a fact that global petroleum production will peak. Due to unreliable reserve estimates and production data it is, however, unclear when the peak will occur. Also unclear is, what the supply situation in a specific country will be, relative to global fuel availability. For member countries of the International Energy Agency (IEA), the

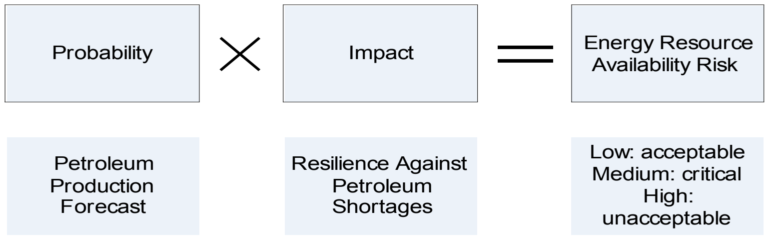

Figure 6: Determining the risk of fuel shortages.

IEA will ration energy supplies in a shortage situation, for non-members the supply situation is less predictable.

We propose to keep analysis independent of the exact year of peak oil occurrence. In order to facilitate meaningful analysis, it is assumed that the development options derived in the previous sections are fully developed and fully functional at the year of peak oil, whatever the exact year may be. At the lack of more detailed data, it is assumed that fuel supply to a specific country will follow the same trend as global fuel supply. Post-peak global fuel supply is here modeled according to (Hirsch, Bezdek, & Wendling, 2005). Hirsch modeled three different scenarios of mitigation to the petroleum supply risk, assuming 20 years, 10 years, and 0 years of preparation time for strategic risk management program. It is here assumed that there will be no preparation time, and that mitigation of the petroleum shortage problem will commence only after peak oil happens. This is a valid assumption in case peak oil happens soon, i.e. in less than ten years from now. (Dantas, Krumdieck, & Page, 2006) proposed two methods for calculating the probability of peak oil occurrence in any given year. A conservative approach yielded a likelihood for peak oil occurrence before 10 years from now, i.e. before 2016, of 40%. But what is believed to be a more realistic approach suggests that the likelihood of oil peaking within 10 years from now is closer to 80%. The global energy supply scenario after (Hirsch, Bezdek, & Wendling, 2005) is shown in Figure 7. Year X refers to the unknown years of peak oil. The supply for the 20 years time span considered is approximated by an annual 2% rise in petroleum production up to year X, and a production decline of an equal 2% per annum thereafter. The mitigation wedge in the figure results from a mix of energy savings through efficiency, and substitute fuels to replace petroleum products.

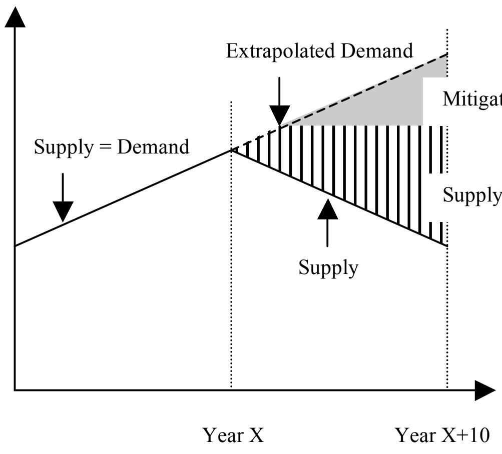

Figure 7: Modeling Fuel Supplies, after (Hirsch, Bezdek, & Wendling, 2005)

Environmental Damage

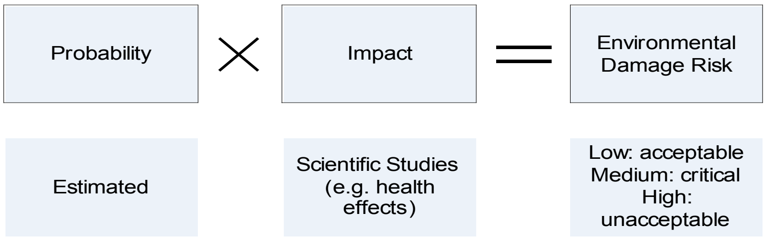

Figure 8: Risk through Environmental Damage.

Risk analysis for environmental damage is assessed as indicated in Figure 8. Impacts are on the basis of direct as well as indirect damage. Direct damage shall be referred to as damage or degradation to be nominally expected during the lifetime of an energy plant. Indirect damage shall be damage caused not by the energy system but by various other consequences from a strategic development level. The issues involved in assessing the risk to environmental damage are highly complex. In order to preserve transparency and comparability, the analysis is, in this research, held at relatively high level. Where reasonable, risks are assessed quantitatively. Otherwise qualitative analysis is used.

3 Case Study

3.1 General and results

The method above is being applied to Rotuma Island, a small Pacific Island within Fijian territory. Rotuma has been chosen for several reasons: with a land area of $40km^2$ and a 2500 permanent population it is small and relatively easy to overview. The closest neighboring island is more than 500km away; Rotuma can therefore be analyzed as a closed system. Rotuma has 32 main villages located around the perimeter of the island. The island is approximately 15km long and 4km wide. The climate is tropical with high rainfall and the soil is unusually fertile. Parts of the island are too rocky or too steep for cultivation; thus about 30% of the island is covered in native bush (Clarke & Thaman, 1993). Despite of relatively strong Western influence, most people are fully ingrained in their traditional way of live of subsistence farming. Traditional transportation by canoes has been replaced by bus, trucks and motorbikes on the main road around the perimeter of the island. The link to the closest neighbor, Fiji, is by a monthly boat service and almost weekly flights by small aircraft. The majority of people live in simple concrete structures with corrugated iron roofs (Fiji-Bureau-of-Statistics, 1996).

Field research has been conducted on the island in 2006; activities on the island included detailed energy supply system, energy needs, and energy resources surveys, as well as a survey of people’s personal development objectives. Figure 9 gives an overview of appliance ownership on the island. The energy system is based on village level Diesel generation. Electricity is typically available for about 4 hours every evening. The Diesel supply to the island is unreliable and expensive. Indigenous energy resources have been surveyed in some detail. Three options are technically possible: Coconut oil, wind, and solar power. Coconuts are the main export from the island. More than enough copra is available to replace the present Diesel demand with bio-diesel from coconut oil. Average daily insolation varies from 3.5kWh/day in winter, to 4.5kWh/day in summer. Figure 10 gives an overview of the wind power potential. The wind map has been modeled using topographical data and wind data from global weather models as well as data recorded on the island. While annual mean wind speeds suggest that wind power might be feasible, the wind is relatively unreliable. Significant power winds are the Southeast trades. The trade winds can stop for several weeks during periods of intertropical convergence.

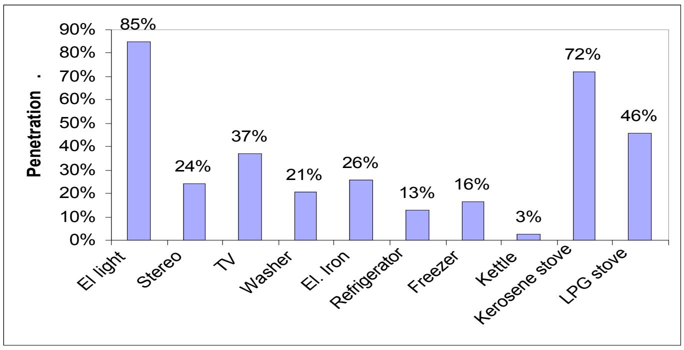

Figure 9: Appliance Penetration on Rotuma Island, 2006 Survey.

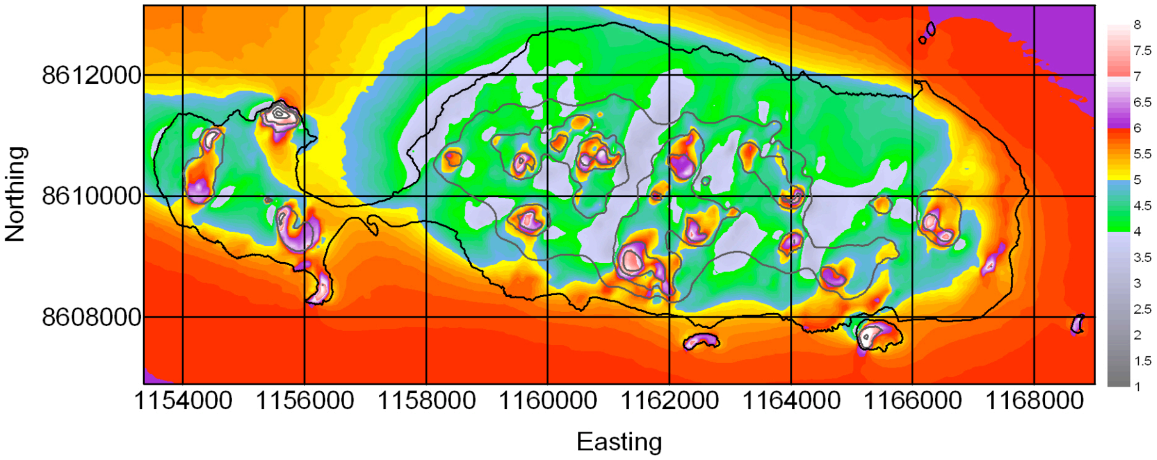

Figure 10: Annual Mean Wind Speeds [m/s] on Rotuma Island for a 25m elevation from the ground.

As mentioned above, apart from the more technical surveys above, an attempt was made at surveying the development objectives of the people in Rotuma. Individual preferences vary widely. Some people explained how the modernized way of life, e.g., especially paying the monthly electricity bills did actually make their lives harder; these people expressed their interest in reverting back to the traditional life without electricity and so forth. The other extreme were people who enjoy Western amenities, and would like to get as much of it as possible. But there were also people who were content with the present level of development, not wanting any change, or only very selected change. In order to cover the spectrum of differing objectives, people's visions for the future were categorized into four levels: (1) Back to Traditional Life, (2) Some improvements, but no considerable change, (3) Moderate development, and (4) full development to a level comparable to Suva (this is the capital of Fiji).

Dev. Level / Energy Source	Back to Traditional Life	No Considerable Change	Moderate Development	Full Development
Fossil Fuel	N/A	Village Diesel Generators	Central Diesel Generators	Central Diesel Generators
Copra Biodiesel	N/A	Village Diesel Generators	Central Diesel Generators	Central Diesel Generators
Solar PV	N/A	Village PV Plant, Battery Storage	Central PV Plant, Battery Storage	Central PV Plant, Battery Storage
Hybrid Solar PV & Fossil	N/A	Village Diesel - PV-Battery Plant	Central PV-Diesel-Battery Plant	Central Diesel-PV-Battery Plant
Wind	N/A	Village Wind Turbines & Battery Storage	Central Wind Plant & Pumped Storage	Central Wind Plant and Pumped Storage
Hybrid Wind & Fossil	N/A	Village Wind Plants & Diesel Generators	Central Wind Plant & Diesel Generators	Central Wind Plant & Diesel Generators

Figure 11: Rotuma Energy System Possibility Space.

3.2 Rotuma Potential

Following the method above, several energy models were created for different combinations of development levels with energy systems based on different resource inputs. The resource options are derived from the resource survey. The following energy supply options are considered: (1) Fossil fuel (Diesel), (2) Copra (bio diesel), (3) Solar (PV), (4) Mix Solar&Fossil, (5) Wind, (6) Mix Wind&Fossil. Combining the four development options of the previous section with the six supply options above, results in a total of 24 energy system options; or in reality 18 options, because the 'Back to Traditional Life' option implies no electricity usage. The range of options, which we refer to as possibility space, is shown in matrix form in Figure 11. Every element in the possibility space stands for an energy model. Each energy system is modeled using real data collected on the island. The modeling platform is Homer with auxiliary modeling in Matlab. The demand is modeled through load curves, one for each development level. The load curve for the 'No Considerable Change' option is based on real load curves recorded on the island. Load curves for the other development levels are modeled on the basis of hypothetical appliance penetration and use data. Modeling the energy systems has not yet been completed at the time of writing. Comparative risk assessment following the method described is in progress, but results are not yet available.

4 Discussion

The work treated in this paper reflects an attempt to define sustainability in very tangible terms. Sustainability is treated in the light of two significant risks faced by all peoples around the world: The risk of resource supply shortages caused by the imminent peaking of conventional oil production and another risk given rise to by environmental problems. The term sustainability is used in very different ways by different researchers. In this research, sustainability is defined as Anthropogenic Continuity. Anthropogenic Continuity does not refer to a static state of a society. Anthropogenic systems are never static and are generally in a continuous process of change and adaptation. But it is also possible that this continuity of regional anthropogenic systems is, often painfully, interrupted by various forms of crises. It is therefore the utmost concern behind this research, to mitigate the risks to the Continuity of our Anthropogenic Systems. It is fully recognized that the mitigation of this risk is likely to involve much more than replacing fossil fuels with renewable energies; hence the approach to expand the scope of analysis to include various levels of development. The employment of risk analysis ultimately allows for articulate communication of analysis results. Risk is a language spoken throughout professional disciplines. Communication of the results leads the audience from the easily understood possibility space, through risk analysis, to the opportunity space. The opportunity space includes only those energy system options which inherently pose manageable levels of risk to the Continuity of the Regional Anthropogenic System.

5 Conclusions

This paper presented a workable method to manage the new energy resource and environmental constraints facing our societies. This method has been tailored to suit developing countries, but the general approach is applicable to any society. The issues involved are complex, and this method is only one of many conceivable ways of addressing the risks to Anthropogenic Continuity. Much more work is required, and the authors hope that this paper encourages more research into risk management for the risks to Anthropogenic Continuity.

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