# Understanding the Importance of an Energy Crisis

by

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# Dedication

Glory to God in the highest and on Earth peace goodwill towards all.

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# Overview and Guiding Questions

Human development and energy, in general, and electrical energy, specifically, co-exist seamlessly in high HDI countries[1] where reliability and availability is greater than 99%. In numerous low HDI countries[2], there is 2-50% electric grid *availability* with *reliability* at or below 50% due to load shedding and faults. In Africa, solar, wind, biomass and hydroelectric energy production are cited to meet growing demand and increase reliability and availability; however, the capital costs are greater than the ability-to-pay for wide scale implementation. Since the 1970s, the United States has continued to argue over the new sustainable energy infrastructure solution(s); thus resulting in no new infrastructure being built for wide scale implementation. Together the world is facing the daunting task of averting an energy crisis in developed countries and facing energy crises in developing countries. This thesis explores the importance of energy crises: from the past, current, and future. The first part entails arguing that the United States is not on a pathway to prevent an energy crisis based on an analysis of 1986 and 2004 niche and status-quo manufacturing of light-duty vehicles. The second part answers the question of what an energy crisis looks like by exploring and investigating current electrical energy crises in Fort Portal, Uganda. This part used both anthropological and physics education empowerment research to co-design and build for various energy crisis situations in hospitals, schools, and businesses all from locally available materials and expertise. Finally, looking into the US light-duty vehicle's future, I design a new hybrid vehicle powertrain (called transition mode hybrid). This third part describes my new patent as a way to avert an energy crisis in the light-duty transportation sector. Together these three projects investigate and address eight guiding questions.

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[1] The United Nations Development Programme defines the human development index (HDI) with education, health, and economic indicators.

[2] Low HDI countries are defined with human development indexes' at or below 0.50.

# Guiding Questions

In the United States, the term "energy crisis" is used loosely and is almost a common phrase. Was the 1970's an energy crisis? Are there current energy crises? What would it take to prevent another 1970's energy crisis in the future?

After the 1970s, did the United States' light-duty vehicle sector fundamentally change? Why or why not in terms of niche and status-quo manufacturing issues?

When there is an energy crisis, how will we, in the US, manage the energy we have in terms of diversification; sectors (Residential, Industrial, Transportation, Commercial); load shedding, prioritization, and rationing; etc?

What makes an energy event a crisis event? Is there any place in the world today where an energy crisis occurs regularly? Do reliability and/or availability determine whether an energy event is called an energy crisis? Should there be different levels of an energy crisis?

How do the images of the United States' energy crisis compare to the images of the Ugandan's energy crises?

What does a social benefit-to-cost analysis qualitatively look like in terms of either (1) purchasing an electricity producing device to avert an energy crisis versus (2) suffering the energy crisis costs? What does a micro-economic analysis qualitatively look like in terms of (1) grid $/kWh versus (2) off-grid $/kWh for specific services?

Bicycle Generator (Gen)
Hand-Crank Gen
Merry-Go-Round Gen
Micro-Hydroelectric Gen
Wind Turbine/Gen
Solar Panel (PV)
Gasoline Gen
Diesel Gen

On-grid Hospital
Off-grid School
On-grid University
On-grid Internet Café
Off-grid Village Business Entrepreneur

What sector in the United States is more susceptible to an energy crisis? How can the qualitative knowledge gained from Uganda be used to avert a crisis in the United States?

How would my vehicle hybrid powertrain design change using US cultural constraints of urban, suburban, and highway driving behaviors?

Does my new vehicle hybrid powertrain design do better to avert an impending energy crisis?

# Chapter 1. Introduction

As an advocate of sustainable and secure energy systems, I explore three research projects about understanding the importance of energy crises. Using the questions just mentioned that have guided me throughout my thesis, I investigate an innovative sub-set of energy crises (1) from the past, (2) occurring today, and (3) for the future. In Section 1.1, I describe the results of my MINPAR light-duty vehicle simulation model (a) to describe what CAFE did as well as (b) yielding four policy implications. This past energy crisis occurred with the 1970's oil embargo and Iranian revolution. It was at this historical juncture that the United States developed the CAFE, but from that point on, CAFE's fuel economy (FE) hit a plateau. Using my MINPAR model, I compare the niche and status-quo manufactured vehicles to explain and yield four policy implications which go beyond the historical CAFE plateau. Two of the four policy implications were recently implemented after the 2008-2009 economic crisis and leadership under President Obama. However, this year's bold policy to implement an approximate 35 mile per gallon (mpg) FE regulation does little to avert a future US light-duty vehicle energy crisis. This leads to the second part of my thesis – Section 1.2: Are there any energy crises occurring in the world today? Yes, in developing countries there are energy crises occurring in hospitals, businesses, and schools on a regular basis. Consequently, my second project investigates energy and human development issues in Fort Portal, Uganda. Juxtaposing the definition of the energy crisis in the United States transportation sector (Chapter 3) with the abundant energy crises in the Ugandan commercial and institutional sectors (Chapter 4), unveils a telling case of global disparities. Using my expertise as a physics educator, I co-develop a Physics and Business of Energy curriculum with a business professor at Mountains of the Moon University, John Vianney Makanda. Together with local technicians we co-design and locally build five electrical energy devices to meet these critical needs using only available materials. After learning from the innovative strategies in Uganda, in Section 1.3, I apply a similar methodology to design a two-fuel plug-in hybrid electric vehicle with three driver-based options as well as an expert system algorithm for each driver option. Finally, I address how to avert or at least cushion the effects a US future energy crisis similar to that experienced in the 1970's using this new hybrid innovation (Chapter 5). Thus this introductory chapter highlights the original and interdisciplinary aspects of this thesis.

## 1.1 A Past Energy Crisis – US CAFE Regulation of Light-Duty Transportation

In the late 1970s, gasoline shortages associated with the Arab Oil Embargo (1973-74) and the Iranian Revolution (1979-80) created a crisis. In the US, the majority of people depend on their privately owned vehicles (cars and light trucks) for transportation. Gasoline stations had long lines, some stations closed, some of them limited sales, rationing was discussed. Many people were inconvenienced, and almost all felt threatened. The political motivation to do something, and fast, was strong.

The US responded fairly quickly with fuel-economy standards. The light-duty vehicle (LDV) manufacturers responded in turn to the proposed and actual regulations by changing the mix of new vehicles offered to the public in the late 1970s and early 1980s. They eliminated almost all light vehicles over 4000 lbs; and they also reduced the size (displacement) of engines offered. In the following quarter-century, fuel economy regulations changed but little and FE hit a plateau associated with the fixed FE standards. Gasoline consumption increased, largely with the increase of light-duty trucks as passenger vehicles (with their poorer fuel economy). And LDV technology was used to increase the power of the vehicles.

In Chapter 3, I analyze 886 and 813 vehicles offered by the manufacturers in 1986 and 2004, respectively. I show how the mix changed, reducing the number and variety of high fuel-economy niche vehicles offered in 1986 and increasing the number and variety of low fuel-economy niche vehicles offered in 2004, while the total FE distribution of status-quo vehicles stayed the same. I exhibit the data by separating the vehicles it three classes: 1) status quo, with fuel economies near the average as expected, 2) niche, with fuel economies better than 10% above the expected value, and 3) niche, with fuel economies worse than 10% below the expected value. The manufacturers, consumers, and government failed to build, to purchase, and to provide incentives for, respectively, the high FE improvements of 1986 to become the status-quo of 2004. If they would have, the status-quo FE distribution of 2004 would have been different than the status-quo FE distribution of 1986, but after 18 years of technological advances, the FE distributions look the same. Whether or not the new "hybrid vehicle" technologies will become the status-quo of 2020 or simply exploit a new loophole by offering the name "hybrid", but without substantial fuel economy improvement is discussed in Chapter 3. Furthermore, a cousin to the Japanese Kei (mini) car, van, and truck is revealed in this research as a possibility for US. If all the technological advancements [average power to displacement: <P/V>] of 1986 were put into 2004 FE instead of performance, then the US would have had a Kei-like vehicle option even given the customer preferences for acceleration [average power to mass: <P/M>]. Thus, this analysis ends Chapter 3 with the following four policy options from this section with a discussion about how the US might not do anything further until there is another crisis.

(1) New Niche Technology: The US must be leery of policies which focus solely on new technologies for decreasing motor gasoline consumption. Moreover, high fuel efficient new technology vehicles must be supported to become status-quo quickly (e.g. with a hybrid credit). There must be a distinction between technology implementation which yields better-than status-quo FE versus same-as status-quo FE: e.g. mild versus partial/full hybrids. Furthermore, niche technologies which are worse-than status-quo FE should be the first to change to an alternative energy source.

(2) Status-quo Technology: The US should encourage the average status-quo vehicles to decrease mass and engine displacement by perhaps 30%. This could be done using status-quo technologies (P/V) without sacrificing performance standards (P/M) when all technological advances from 1986 went into fuel economy in a proposed 2004 scenario. No new technological advancements are needed to reach a 35 mpg target.

(3) Missing Key Offered Vehicle: The US could develop, support, and implement a cousin to the Kei car, van and/or truck with a policy-

based support mechanism equivalent to or stronger than what Japan implemented.

(4) Potential for a New Loophole: If the US wants to decrease greenhouse gas emissions and enhance security, then the US is obliged to watch carefully that the Reformed CAFE regulations do not create a new loophole: alternative fuels (e.g. Telsa's 244 mpg CAFE or the flex-fuel credit). In other words, upstream and downstream policy regulations must be implemented with or in conjunction with the Reformed CAFE regulations.

In the majority of Chapter 3, the discussion focused around manufactured designs of niche and status-quo light-duty vehicles. However, there are three additional pathways to reduce motor gasoline consumption which are briefly discussed as well: on-the-road fuel intensity, vehicle miles traveled, and changing energy source. In 2009, the United States' best-case scenario for 2020 will not reach 1990 fuel consumption levels much less the Kyoto Protocol target of 7% decrease from 1990 levels, given the current Reformed CAFE framework. Unlike Japan and the European Union, which have site-based constraints that are potentially forcing them to be more sustainable, it is the United States which must diversify its vehicle powertrain to avert another energy crisis. However, it will be difficult to do that without understanding what or how to define an energy crisis. The next section illustrates what current energy crises are.

### 1.2 Current Energy Crises – Uganda Electrical Energy and Human Development

To have electricity is to have vaccines and retro-viral medications safely stored in a refrigerator and to have lights during surgery (theatre). To have electricity is to have cell phones connect businesses which previously were not connected. To have electricity is to have lights at night for studying or to have computers and copy machines for curriculum development and enhancement. However, it is not enough to have availability; there must also be reliability. Uganda's total installed electricity capacity in 2005 was 309 MW (11 W/Capita) compared to the United States' capacity of 957 GM (3190 W/Capita). The inability to match the populations' demand with installed capacity creates load shedding (sharing electricity capacity) and at times faults (blackouts). These situations create energy crises in terms of unreliability of the electric grid for businesses, hospitals, and educational institutions. However, in Chapters 2 and 4, I discuss a definition of an energy crisis as an energy system failing to meet human development needs. With this definition, 90% of Ugandans constantly live within an energy crisis state because this is the number without access to grid electricity (the electrification rate in Uganda is approximately 10%).

In every developed country defined by the United Nations Development Program (UNDP), there is a national electric grid which hybridizes energy production from multiple power plants. In Uganda, the electric grid consists mainly of hydroelectric dams, plus the beginning of interest in thermal and nuclear plants. Breaking all the possible electrical power plants into energy conversion groupings, the following potential emerges:

| **Power plant type** | **Energy Conversion** | |
|---|---|---|
| Wind and Hydroelectric Dams | Mechanical to electrical | (ME) |
| Solar-Thermal, Geo-Thermal | Thermal to mechanical to electrical | (TME) |
| Fossil Fuel (i.e. coal-fired),<br>Sustainable Fuel (i.e. biogas-fired) | Chemical bonds to TME | (CTME) |
| Solar – Photovoltaic panels | Light to electrical | (LE) |
| Fuel Cell (i.e. hydrogen, methane) | Chemical bonds to electrical | (CE) |
| Nuclear (fission or fusion) | Nuclear bonds to TME | (NTME) |

**Copy of Table 14 from Chapter 4:**
**Breakdown of power plant types into energy conversion categories.**

With this organization, there are six categories of power plants. Based on local manufacturing capability currently available, and investigated in Fort Portal, Uganda, the last three categories were not considered in my Physics of Energy curriculum for Ugandan polytechnic/technical institutes. My goal was to break the three available categories into specific technologies which could be co-designed and implemented locally. These categories are then turned into a strategy to study a three-tier hybridized methodology for local manufacturing empowerment in Uganda. At the writing of this thesis, only the first category (mechanical to electrical energy) was taught, with the result of five co-designed and built electrical energy generating devices: bicycle generator (for tv/cell phone charging), hand-crank generator for a back-up surgical lighting system, vertical wind generator, micro-hydroelectric generator, and merry-go-round generator.

In developing this curriculum, it was confusing why the level of human power could be significant in Uganda (average 11 W/Capita or 62 kWh/Capita). Consequently, I developed a set of human activities based on electricity and without electricity. Both sets of activities were compared in terms of the chemical energy consumed during the activities (using well known kinesiology research). There were a set of activities which consumed less energy when (1) accomplished including electricity needed to run electrical device coming from a bicycle generator, than (2) accomplished without the electricity from a bicycle generator. For example, a group of ten men walking one hour to watch a football (i.e. soccer) game, sitting for three hours for the game, and then walking home consume more energy than the ten men taking turns on a bicycle generator/tv system while the others sit during the game. Although not intuitive, this comparison of human activity efficiency with electricity versus without electricity is compelling. Moving beyond understanding these issues, I create a set of economic discussions as well as a framework for prioritization of power loads (critical, desired, and ideal). Moving from meeting critical to ideal loads generates a policy mechanism for hospitals, businesses, and schools can use to project various trajectories in Chapter 4.

## 1.3 Future Energy Crisis – US Diversification of Light-Duty Transportation

Future Scenario: Imagine the 1970's happening this year. What happened then? There was an oil shortage. Roads were empty paths of concrete appearing as a relic from an ancient civilization. Long lines waited at gas stations, once perhaps 10 gallons were available/person. Speed limits went down to 55 mph to conserve fuel. An electric vehicle would have gotten people to and from work or the grocery store within a 30 mile range, but they did not exist. Now, what would happen? The same thing would happen. Have we learned anything? Yes. Have we done anything about it? No. Why? Because no one knows what the new locked-in energy source for vehicles will be. This is where my transition mode hybrid fits into the picture. It will transition the United States from gasoline to either an alternative fuel or to an all electric vehicle with its' adaptive and robust design.

I design the two fuel, three option, ten mode hybrid electric vehicle to diversify this sector – thus creating a design to avert a future energy crisis. The two fuel lines are designed with cylinder deactivation (either V3/6 or V4/8 vehicle)[3]. The three options include all electric, suburban 1, and suburban 2/highway options set up as a dashboard driver choice. The ten mode expert system power management strategy incorporates two battery charging/discharging cycles (50% HEV versus 20/80% EV/PHEV). Together this transition mode hybrid allows the United States light-duty sector to diverse the powertrain in terms of the potential for plug-in electricity, traditional fossil fuel and three upcoming sustainable fuel possibilities (which could run methane, ethanol, and hydrogen).

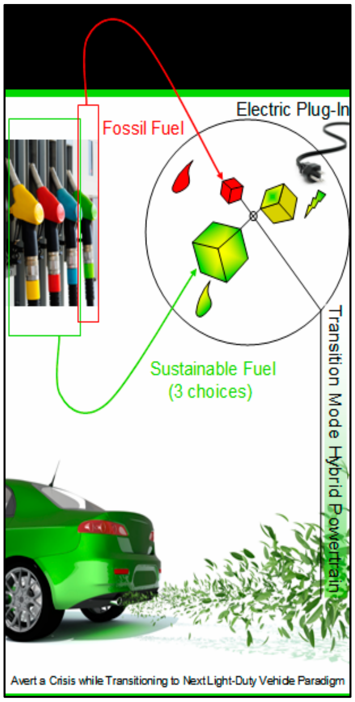

**Figure 1: Transition mode hybrid powertrain concept.**

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[3] The TetraFuel Fiat vehicle currently selling in Brazil is a comparable design, which illustrates the manufacturability and high demand for this design.

Unlike most new concept cars, this design is not based on new technology. Rather it is based on organizing currently manufactured technology in a new way.

- Cylinder Deactivation
  - First set on Fossil Fuel
  - Second set on Sustainable Fuel
- Continuous Variable Transmission
  - Sun, Ring, Planet Gears
  - Two Motors – GM Two-Mode
- Two Battery Banks
  - 50% - Prius charging/discharging cycle
  - 20/80% - Insight charging/discharging cycle
- Split tank with two fuel lines
- Dual fuel (sensors)
  - Tetra fuel vehicle in Brazil

**Table 1: Understanding the foundation of this transition mode hybrid powertrain.**

Moreover, this design uses the drivers' knowledge to choose, when desired, an all electric option (called urban option). This means that only part of the powertrain will be considered in the power management algorithm. Also, it means that the driver has to know that the vehicle range is only about 30 miles and therefore must be prepared to plug-in to an electrical outlet to recharge the batteries (or switch to another driving option). Furthermore, Chapter 5 goes into detail of the three level sequential optimization vehicle designs (including the three driver options).

For an SUV, the simulations comparing fuel economy gains were similar to those reported in the literature - V6 gasoline ICE (22.7 mpg), V3/V6 cylinder deactivation gasoline ICE (24.5 mpg), V3/V6 cylinder deactivation electric motor hybrid (28.2 mpg) – and greater for the transition mode (32 mpg) design in the urban driving cycle. The all electric option was completed with a 30 mile range and at least tripling the fuel economy. The suburban plug-in option was completed at least doubling the fuel economy (depending on driving cycle chosen). The suburban 2/highway option yielded the 300 mile range with 32 mpg expected HEV result (no plug-in capability – i.e. driver is not near plug or driver does not have time to recharge).

# Chapter 2. Background Concepts and Literature

Whether societies are motivated by energy security, wealth, health, education, and/or climate change issues, I believe that ultimately an analysis which separates energy sectors will be an image of the past. As societies change the energy options for vehicles and as societies potentially include agricultural products which can be for food or energy, the old paradigm will shift. The new paradigm will merge the previously separated energy sectors and shift into an interconnected multidimensional paradigm. However the world chooses to embrace the shift, the hope is that energy, inequality, and human development will not be considered solely a science and engineering/technology policy debate, but weave the contentious societal dimensions as well. It is in merging these three thesis chapters into a continuous story of how an energy crisis can change public policy and what an energy crisis looks and feels like that hopefully the reader develops (1) a deeper since of how much further the world has to go and (2) how society plays a vital role in science and engineering design solutions for various human development energy systems. Energy is how we live and act; it is not simply how nature behaves.

## 2.1 Using Energy Systems and Human Development to Define an Energy Crisis

The foundation for this thesis and my future work is the research literature on storage device technologies, vehicle and building hybridization optimization studies, as well as energy policy analysis that includes energy and equity issues (previous section). Background literature on Ragone maps and computer simulations for various storage devices is discussed in section 2.1A. Section 2.1B illustrates the benefits of using two storage devices by examining the power management controls of hybrid vehicles. With buildings, the discussion in section 2.1C illustrates the benefits of using two storage devices by examining a study of energy storage for a PV array. Unfortunately, in this thesis there wasn't time to delve into designing hybrid building options. However, this thesis does analyze an innovative vehicle hybrid powertrain.

### 2.1A Energy Systems Concepts

Energy systems are complicated; they encompass fundamental physics, engineering optimizations (choosing between trade-offs), environmental technology design, and policy and economic debates. The world's energy system is not in equilibrium between production and consumption growth rate (barrels of oil/year, electrical consumption/year, etc.). An impeding crisis is debated (1) based on future fossil fuel shortages or price fluctuations, (2) based on developing countries' human development, and (2) based on ecological impacts. The successful use of alternative fuels in countries like Brazil suggests that there is hope for reaching long-term equilibrium. However, studying how to reach a stable energy and resource flow (i.e. matching demand and production) is still in the process and currently does not involve the energy crises facing developing countries hospitals, schools, and businesses.

The design of a stable energy system focuses on three energy mechanisms as well as the infrastructure needed.

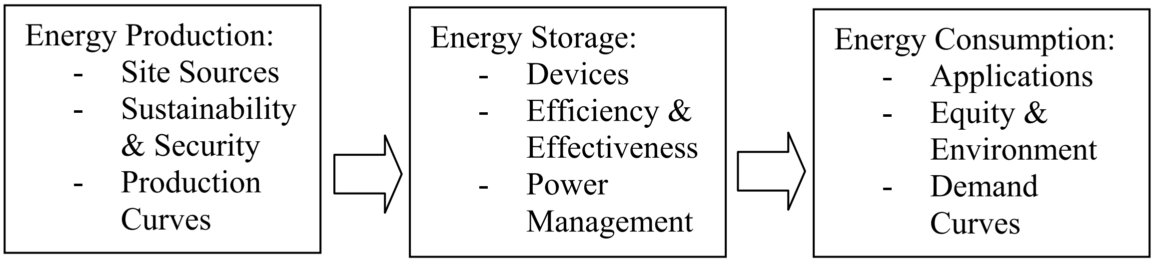


**Figure 2: Energy systems flow of terms and organization.**

The first mechanism is energy production. Currently, research on sustainable sources is focused on renewable and clean energy sources instead of fossil fuels. Renewable energy sources are defined as a natural energy flows which use stable resources: input equals output usually over a year or a few years. All truly renewable sources, except geothermal, are derived from solar radiation. Clean energy concentrates on eliminating greenhouse gas (GHG) emissions which affect climate change (as well as other pollutants). These energy sources are not necessarily renewable. Nuclear energy, for example, is not renewable, yet it produces no GHG emissions and is one reason why it is heavily researched as an alternative to fossil fuel.

The second mechanism is storage devices and the potential for hybridization. Hybridization here is defined as using more than one energy storage device (ESD) and/or generation device (EGD). One storage device may have high power capability which effectively meets demand whereas another device may efficiently use the energy source, but not meet all power demands. A good illustration of this is an electric vehicle which cannot exceed 45 mph versus a plug-in hybrid with an all electric option. The second vehicle is less efficient compare to the electric vehicle for city driving, but it meets highway driving power demands; whereas, the electric vehicle cannot meet the power demand at all.

At this time, two areas of research which consider storage management potentials are hybrid vehicles and residential buildings. In vehicles, the internal combustion engine with a tank of fuel has been well-matched with the electric battery or hydraulic accumulators in effectively meeting power demand and increasing energy efficiencies. In understanding and developing my energy system vehicle model for driving cycles, I wrote a MatLab-based three-level sequential-optimization algorithm to design a two fuel plug-in hybrid electric vehicle. In buildings, the solar photovoltaic panel (PV) has been recently matched with the battery and regenerative fuel cell (RFC). In understanding and developing my building energy system model for power loads, I create an energy logic system to generate reliability algorithms for back-up systems to an electric grid. However, combining vehicles with buildings to define a more comprehensive energy system is not accomplished in this thesis except for plug-in hybrids to the grid (where the building is technically a power plant). Since the timing of these two systems and the potential interaction between them suggests unique synergies, this thesis is motivated to develop more rigorous energy flow analysis for this combination. However, due to time constraints, this will be further explored in future work after this thesis.

The third mechanism is consumption. Currently, industrialized countries consume significantly more energy than developing countries as can be seen in the next section. As these developing countries design and build their infrastructure, the human development needs must be addressed in the process. Prioritization of energy loads is imperative in terms of critical needs versus ideal needs and is clearly defined in this thesis.

This thesis will focus on (1) whether an energy system is available and reliable, (2) when energy is not available, what are the options possible, versus (3) when energy is available, but unreliable, what are the options possible. Availability is defined in terms of whether or not the electric grid is available at a site. In developed countries, almost all people have access to electricity versus in developing countries where only 2-50% of people do not have access to electricity. Reliability, on the other hand, is defined in terms of how often the electricity is available. In developed countries, almost always people have access to reliable electricity versus in developing countries reliability can be 50% or lower due to load shedding and faults of the electric grid.

### 2.1B Human Development and Energy Systems Concepts

This thesis will examine whether a country's human development might be related to its energy consumption and how researchers define and measure human development. Two data sets are examined: human development and energy consumption. The human development index was calculated by the United Nations Development Programme (UNDEP) based on measurements of education, health, and Gross Domestic Product per capita (GDP/capita). Energy consumption data was reported by the Energy Information Administration (EIA). Figure 3 graphs the exponential correlation of electricity consumption per capita versus the human development index in 2003.

## Exponential Correlation – 2003

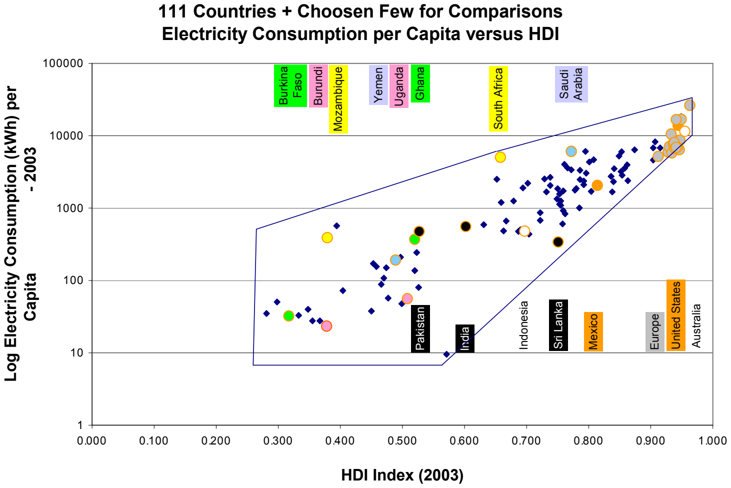


**Figure 3: Electricity Consumption per Capita versus Human Development Index**

The $R^2$ of 0.85, for an exponential correlation of the 173 countries common to both the UNDP and EIA 2003 data, pushed me further into understanding the common interactions. The human development index is calculated from three indices: education, life expectancy, and GDP/capita. For example, the life expectancy in Uganda is 40 +/- 5 years versus in the United States is 78 +/- 3 years. What part of our health system is dependent on electricity? Would the United States life expectancy decrease if electricity was not reliable?

The correlation between energy consumption and a country’s human development ranking was a major source of motivation for the energy microsystem being proposed here. An energy micro-system is a building-vehicle system which meets human development needs. These human needs desire electrical devices.

Because of this thesis’ interest in human development and energy, a theoretical microsystem was created to address the HDI issues (building and vehicles). Considering past failures to include poor communities (not government or non-government organizations), a fourth component was added as essential: community [10, 15]. Together these four components help to frame the energy system. Due to time constraints however, the building and vehicle systems will be merged together in future work. This merging will define a building-to-wheel paradigm that will compliment the well-to-wheel paradigm of fossil fuels energy efficiencies from pumping oil from a well to using the fuel in a vehicle.

**Energy Micro-system for Multi-use Pavilion**

| Education | Economic | Health | Community |
|---|---|---|---|
| School – | Business – | Clinic – | Pavilion – |
| Lighting | Lighting<br>Cell Phone | Lighting<br>Refrigerator | Lighting |
| Water Sterilization<br>Computer/TV<br>Copy Machine | Depends on business: Barber, Saloon, Bar, Video Hall, Internet, Copying, etc. | Sterilizer<br>Oxygen Concentrator | Water Sterilization |
| Fans | Fans | Transmitter & Receiver | PA System<br>TV |
|  | Vehicle:<br>Delivery Truck | Vehicle:<br>Ambulance |  |

**Table 2: Appliances and vehicles needed to meet a set of human development needs.**

In table 2, an energy microsystem (or multi-use pavilion) has four programs: a school, a business, a health clinic, and a pavilion. The remote village business and health clinic needs access to a vehicle to meet their functionality whereas the school may or may not need a minibus. The pavilion is a place for community functions such as weddings, funerals, spiritual gatherings, baby celebrations, etc. Together remote villages can develop nodes of human development where electricity increases human activity efficiencies. Understanding how electricity interacts with these four areas is explored in some detail in Chapter 4 of the thesis.

In the industrialized world, especially in the U.S., countries have dispersed these components with enormous community footprints which require transportation. The disadvantages of these dispersed systems are pushing designs for multi-use structures. An assumption of this research is that an energy system which can address several uses together is superior to isolated systems. For example, if a health clinic does not share the same energy system as a school, then double the energy infrastructure will be needed. Moreover, a microsystem which combines a community's needs opens the door for immersion into the community. This can enable community members to define what they need and how they want to address human development issues – health, education, and/or economic growth [69]. Whether or not the energy systems are incorporated into existing infrastructure or are built as a microsystem into a multi-use pavilion, the interdependence of electricity and human development must always be explored holistically.

### 2.1C Energy Crisis: An Energy System fails to meet Human Development Concept

At my Energy Resource Group Colloquium at University of California, Berkeley in 2009 before President Obama's new announcement for boldly increasing FE standards, I proposed that motor gasoline consumption would not decrease to 1990 levels by 2020 without a crisis. Little did I know then that the crisis which would open this door would be an economic crisis where the US government would become part owners with some of the automobile corporations. However, this is the great strength and weakness of a crisis: all predictable bets are off. In the area of energy and human development, this means that energy systems can fail in two ways: availability and reliability. When they fail, the predictability of what choice a community will choose depends on the level of the crisis. At hospitals and businesses, when patients' lives and employers' livelihoods are dependent on quick action, then decisions can be rash (i.e. the first set of bailouts handed out by the United States government to banks). For example, in extremely remote Ugandan villages, my research illustrates that electric grid unavailability leads villagers to pay upwards of $10/kWh to charge their cell phone versus in cities electric grid unreliability leads hospitals and businesses to pay a large percentage of their budget on fuel and operation and maintenance for their back-up diesel generators. During the 1970's oil embargo, the US government chose to ratio gasoline to 10 galloons instead of allowing gas stations to charge an exorbitant amount of money.  Which is a better policy to address an energy crisis? It is here that I diverge from typical policy-based research methods. The real issue is to think outside the box: typical methodologies. The problem with a crisis is that it is a situation which is not the normal situation.

## 2.2 Energy and Equity Research – Human Development

Global energy consumption per capita varies widely among countries as introduced in chapter one. Human development as viewed by access to economic growth, education level, and medical facilities also varies greatly. The relationship between the two is difficult to understand and research. Previous researchers have noted the energy requirements necessary for health clinic refrigerators, lights for education and cell phones for business. Without refrigerators, vaccines cannot be stored or distributed properly. Without lights, students cannot do homework or study in the evenings. Without cell phones, market farmers have been taken advantage of by middle men who can claim city prices for agricultural products are much lower than its actual worth. The farmers have no way to verify this information. By having a cell phone, the farmers can call the city markets and demand more money for their products. In this section, I will outline previous research on equity issues in individual countries and hybridization in stand-alone facilities used to address poverty through technology.

As shown in Arne Jacobson, Anita Milman and Dainiel Kammen's 2005 Energy Policy paper, energy consumption is not equally distributed within the population of a country. The impact of this disparity on health, education and economic growth is significant. The authors agree that energy consumption, especially in the developing world, is directly related to these mileposts. For example, in their figure below, Norway and Kenya have dramatically different levels of energy equity [11].

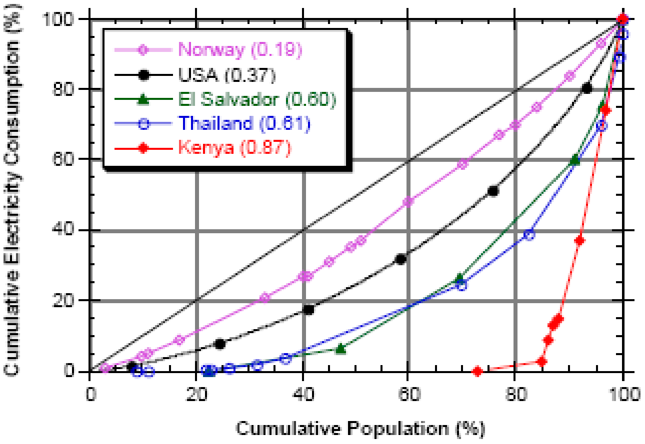


**Figure 4: Reproduced from Arne Jacobson, Anita Milman and Dainiel Kammen's 2005 Energy Policy paper.**

Here Jacoson et. al. use the Gini coefficients to compare five Lorenz curves of equity. In Norway, the top 20% of the population consumes 30% of the electricity consumption; whereas, in Kenya, the top 15% of the population consumes 98% of the electricity [11]. This is significant when one considers how important electricity consumption is for health care, education, and economic growth.

Equity is further illustrated by the many unnecessary deaths due to low human development. There are unnecessary deaths (especially among children) throughout the world due to lack of basic health care. The incomprehensible high levels of unemployment have led to unsafe working conditions and unnecessary deaths (especially compared to the US safety standards). The many educated people who leave developing countries have led to what is termed brain drain and lower development growth. One example is the many nurses and doctors who upon receiving their education do not return to their home country for employment [56].

The most appealing argument for investigating equity issues in African electricity services comes from the African Energy Policy Research Network's recent publication called Energy Services for the Urban Poor in Africa [57]. The discussion of government subsidies for (1) electricity consumption costs (UgSh/kWh) versus (2) subsidies for upfront costs in utility connections, household wiring, and electric household appliances is compelling. For example, most extremely poor Ugandan families have the ability-to-pay 31 kWh/month for lighting based on what they pay for kerosene lanterns. However, they cannot afford the utility connection and household wiring which is a prerequisite for electrical lighting options.

Recently researchers have considered community-based hybridization for the stand-alone generation of electricity to address community issues. In one study, the authors considered solar, wind, and micro-hydroelectric sources with a set of batteries. The hybrid system was designed to meet the demands of lighting and a radio [12]. It was argued that hybridization dramatically decreases the capital cost because each individual unit can be sized based on its benefit to the overall energy system. The article also argued that electricity generation is important for "shops, schools, and clinics in village communities." However, this study's electricity consumption was not evaluated to this end. Understanding the balance between electricity consumption, equity, and community-based involvement is something this thesis touches on, but further work will be needed to go beyond on the qualitative foundation in Chapter 4.

## 2.3 Hybrid Energy Systems Research – Vehicles and Buildings

The foundation for this thesis and my future work is the research literature on storage device technologies, vehicle and building hybridization optimization studies, as well as energy policy analysis that includes energy and equity issues (previous section). Background literature on Ragone maps and computer simulations for various storage devices is discussed in section 2.3A. Section 2.3B illustrates the benefits of using two storage devices by examining the power management controls of hybrid vehicles. With buildings, the discussion in section 2.3C illustrates the benefits of using two storage devices by examining a study of energy storage for a PV array. Unfortunately, in this thesis there wasn't time to delve into designing hybrid building options. However, this thesis does analyze an innovative vehicle hybrid powertrain.

### 2.3A Storage Devices in Energy Systems

Energy storage devices (ESDs) are becoming integral to energy system design. For example, the hybrid electric battery or hydraulic accumulator vehicle not only uses regenerative braking technologies, but also incorporates power management options that increase efficiencies [1, 2, 18, 24] when excess power is not needed. ESDs are also important when it comes to renewable energy applications in buildings because of intermittent production inherent to on-site renewable energy. Whether at the power plant level or the residential level, when ESDs are implemented, they are matched to the production capacity for annual production. For example, wind farms and batteries are matched in terms of approximate average annual wind speeds (m/s) not for wind gusts. Energy systems should also be designed for daily and even hourly fluctuations. For example, if a wind farm overproduces electrical energy during a gusty day or hour, then typically it either quickly sells it at a low cost or stops the wind turbine from producing excess electrical production. Researchers are currently investigating using electrolysis to generate hydrogen during times of excess electrical production from a wind and PV system [20]. This hydrogen can then be used at a later time in a fuel cell. In these systems – vehicle and building, the timing of the power output/input as well as the storage capacity is vital to the design of the system. A classical way to compare these ESD options is through a Ragone plot.

Ragone plots compare the power and energy densities of various ESDs [21, 22] on a log-log scale. They are useful in understanding and choosing one technology over another based on the application. Figure 5 is a sample Ragone plot for vehicle storage devices.

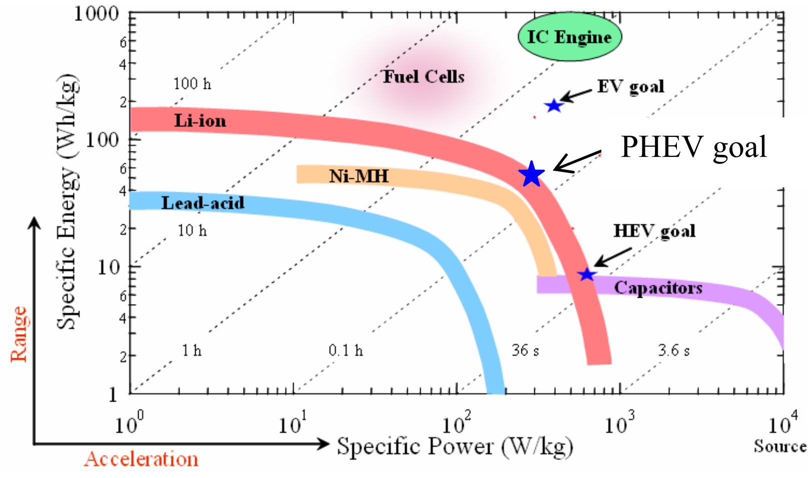


**Figure 5: Reproduced from Srinivasan, Ragone Plot of Energy and Power Density for a Vehicle.**

Figure 5 shows the reason why the internal combustion engine has been so successful [78, 79]. It is because it has the highest energy and power density combination. In contrast, the battery and capacitor have opposite attributes. The battery has good energy density, but lacks power density; whereas the capacitor has great power density and lacks energy density. Some researchers have used the Ragone map for optimization algorithms for a particular application [22]. However, they have not used them for optimizing power management. Power management is defined as an algorithm or set of procedures to choose how to produce, store, and consume energy for various timing sequences (in vehicles driving cycle and in buildings load curves). This is important because power management rules vary greatly depending on the level of hybridization and timing cycles of the power demand curves. The following section will build upon these issues as it relates to ESD’s hybridization of a vehicles‘ second-by-second demand curve and a building’s hour-by-hour demand curve.

### 2.3B Vehicles

The US manufactured 2004 hybrids discussed here are based on available published data. Table 3 gives the characteristics for the Ford Escape, Honda Accord, and Toyota Highlander.

| **Hybrid** | **Ford Escape** | **Honda Accord** | **Toyota Highlander** |
|---|---|---|---|
| Engine | 2.3 L I4 | 3.0 L V6 | 3.3 L V6 |
| Bore/Stroke | 87.5 mm/94 mm | 86.0 mm/ 86.0 mm | 92 mm/83.1 mm |
| Comp. Ratio | 9.4 | 10.5 | 10.8 |
| Power | 114 kW | 178 kW | 155 kW |
| Electric Motor | Permanent AC Synchronous | Interior Permanent Motor | Permanent Magnet Motor |
| Motor Power | 94 hp<br>(70 kW)<br>@3000-5000 rpm | 16 hp<br>(12 kW)<br>@ 983 - 6500 rpm | 68 hp<br>(50 kW)<br>@ 4610-5120 rpm |
| Battery | Ni-MH | Ni-MH | Ni-MH |
| Voltage | 330 V | 144 V | 288 V |
| New EPA city/highway | 30 mpg/ 28 mpg | 22 mpg/ 31 mpg | 28 mpg/ 25 mpg |
| Weight (curb) | 1443 kg | 1591 kg | 1850 kg |
| Transmission | Electronic CVT | 5-spd auto VCM | Electronic CVT |

**Table 3: 2006 Model year manufactured hybrids**

These vehicles are considered for their characteristics, power, and range. The main difference is the mechanical power of the internal combustion engines (114, 178, and 155 kW) versus the voltage (330, 144, 288 V) and electrical power of the motors (70, 12, and 50 kW). This trade-off is one of the big motivations used in Chapter 5 and for plug-in hybrids, in general. The fuel economy is measured by Environment Protection Agency (EPA) using the two power demand second-by-second curves as seen Figure 6.

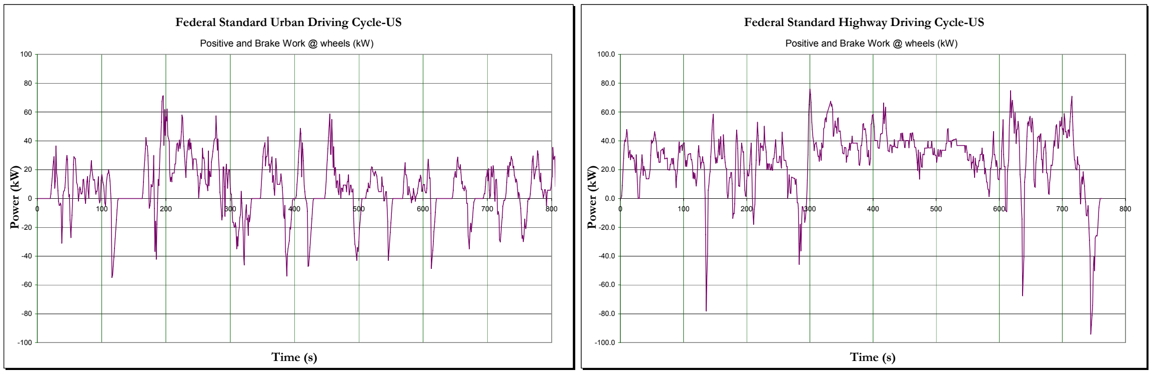


**Figure 6: 1997 Ford Explorer – Power Demand Curve for City and Highway EPA Driving**

Before hybridization, vehicles could not use engine-off modes or capture lost braking energy much less be plugged into an electric gird [55]. Now they can with benefits in fuel economy. In Figure 7, all U.S. hybrids are presented as having a "Vertical Leap" effect with respect to fuel economy.

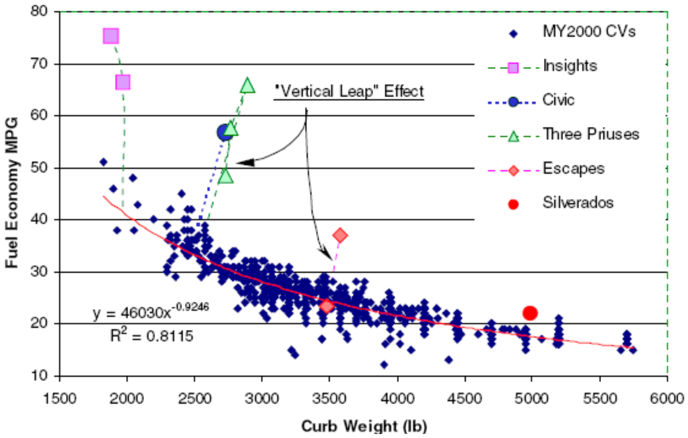


**Figure 7: Reproduced from An, Mass versus MPG relationship for conventional vehicles and "Vertical Leap Effects" for hybrid vehicles.**

This vertical leap affect is due not only to regenerative braking, but also a result of engine-off modes of operation [14]. Understanding the overall energy flows in various power management options is what this thesis will address. Other researchers have commented on the engineering rules of thumb which have been developed [24] and on how there should be more research to transition from rules of thumb to more rigorous physical understanding. I believe this can only be done by incorporating timing, energy, and power factors of hybridization storage devices to be discussed later. This issue is more fully developed when one studies the differences in demand curves with buildings.

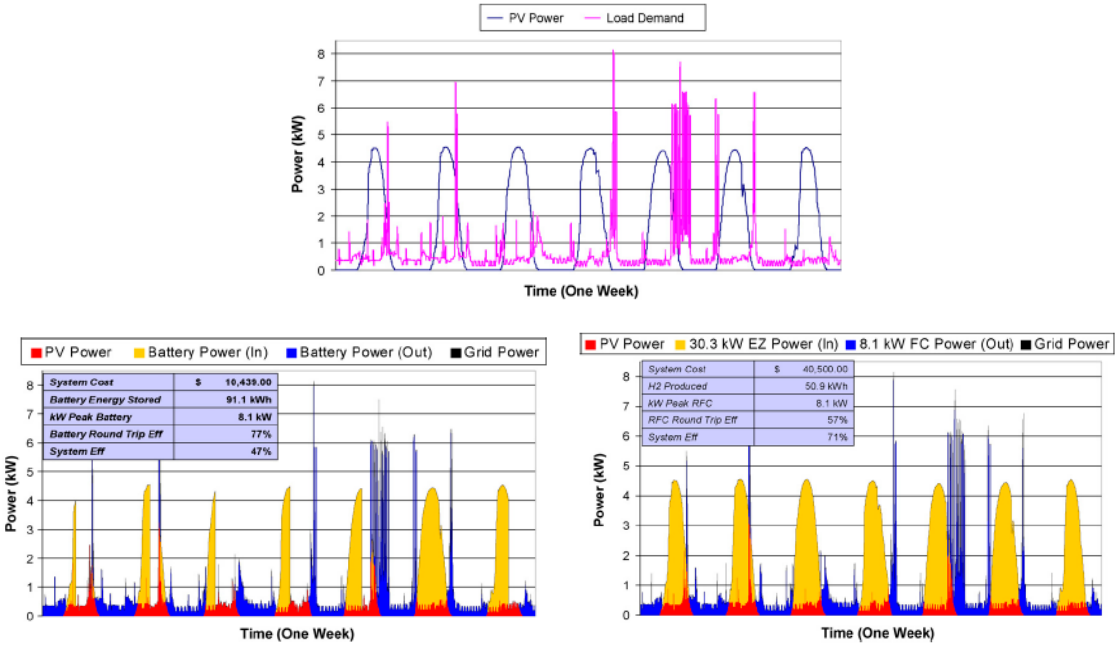
### 2.3C Buildings

Research on hybridizations available for a building microsystem is beginning to unfold in the literature. Two recent articles in the Journal of Power Sources outline the issues [16, 20]. One issue is the power production from renewable energy sources; specifically solar and wind. With solar energy, photovoltaics are intermittent and diurnal sources. With wind energy, turbines are intermittent with high peaks which can be hard to transmit and in need for storage. In both cases, production variability creates excess energy. Typically, this energy has been lost in a load or leak resistor or sold cheaply to the grid. A second issue is that excess energy can be stored in an additional ESD whose capacity is matched to the power demand and its timing. Finally, the third issue is that unpredictable residential power demand cannot be provided by the renewable energy capacity without excess capacity infrastructure. Smaller capacity renewable energy systems could be built with reasonable capacity and grid power might be used at times of excess demand load. Table 4, summaries these issues:

| | Solar | Wind | Grid |
|---|---|---|---|
| Production Curve | intermittent, diurnal | intermittent, high gusts | always available |
| Energy Storage | excess during the day | excess during gusty days | not necessary |

**Table 4: Production and Energy Storage Management for Solar, Wind, and Grid.**

Maclay, Brouwer, and Samuelsen compare three potential systems in an illuminating way. First, they gather data on a PV production curve and a residential demand curve. These curves are hour-by-hour data for one week. This is represented in Figure 8 at the top. The authors meet this power demand given the power production in two ways: bottom-left, and bottom-right.



| | |
|---|---|
| System Cost | $ 10,439.00 |
| Battery Energy Stored | 91.1 kWh |
| kW Peak Battery | 8.1 kW |
| Battery Round Trip Eff | 77% |
| System Eff | 47% |

| | |
|---|---|
| System Cost | $ 40,500.00 |
| H2 Produced | 50.9 kWh |
| kW Peak RFC | 8.1 kW |
| RFC Round Trip Eff | 57% |
| System Eff | 71% |

**Figure 8: Reproduced from Maclay et. al, PV Power Production versus Demand creates two options for ESDs: battery and RFC.**

The bottom-left graph illustrates a battery ESD provides the energy system. Here the black peak demand cannot be met by the battery alone and the grid has to meet this demand. Also, the battery cannot store all the excess electricity. In the bottom-right graph, the regenerative fuel cell (RFC) meets the demand in a similar way, but is able to store more of the excess energy. The regenerative fuel cell either creates hydrogen through electrolysis or creates electricity through a fuel cell. The question then becomes whether or not the RFC works better by itself or with the battery. Figure 9 simulates this question.

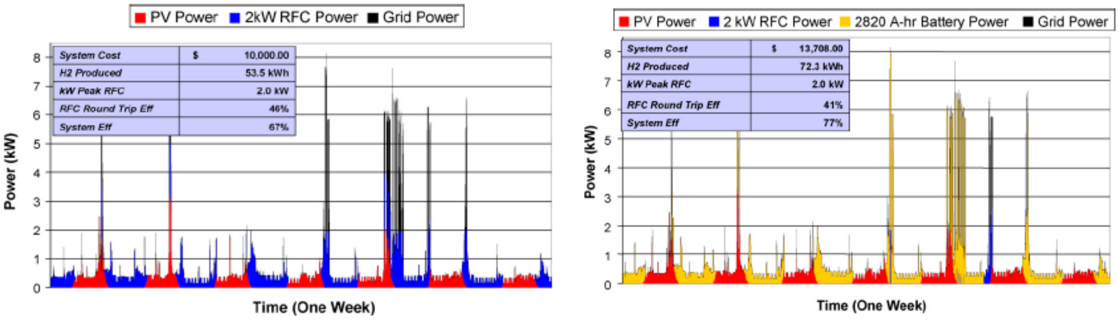


**Figure 9: Reproduced from Maclay et. al, One and two ESDs meeting power demand using PV and grid power.**

On the left, the RFC still uses the grid for all power above 2 kW. However, on the right, the RFC and battery is able to reproduce the energy for many of the power peaks above 2 kW. The only real drawback from this model is how the power management options affect these results which I consider with two types of battery banks in the two fuel hybrid powertrain in Chapter 5.

### 2.3D Power Management

When desiring to merge buildings with vehicles, the key physical attributes are time of driving cycle or power load curve, weight for vehicles, and space for buildings. In general, driving cycles are a second-by-second velocity demand curves; whereas, a building's power load curve is usually given an hour-by-hour kilowatt demand curve. For a micro-system, the energy system cannot rely on large aggregate results and therefore must design for individual constraints. These issues are discussed within distributed generation, microgrid, and vehicle to grid discussions. The only aspect of the thesis which touches on these issues is in Chapter 5 with the two fuel, three option, ten mode hybrid powertrain design.

Although understanding the timing characteristics of storage for vehicles and buildings are imperative from a technological perspective, understanding the societal advantages of managing the power (energy consumption under various time constraints) is as vitally important. Why is it that Kenya's availability of electricity so drastically different than Norway's or the United States' electricity? What is Kenya's reliability of the electric grid? If Norway faced years after years of energy crises (where only the rich had access to electricity) would this lead to the inequity?

The United States faced and documented the 1970's energy crisis where the political will of the country created the Corporate Average Fuel Economy (CAFE) policy regulation to avert another energy crisis on the light-duty vehicle fleet. So, this is where the thesis begins. After analyzing 1986 to 2004 manufactured vehicles, four pathways to sustainability are generated. However, if these pathways are not traveled on, the US will not be able to avert another crisis. This leads to the next chapter where weekly and monthly energy crises in Fort Portal, Uganda are documented. Solutions to these crises in Africa are suggested (1) to be site-based and characteristic of developing countries and not simply solutions developed countries would choose and (2) need to be locally designed and built to meet these site-based needs for hospitals, businesses, and schools. Finally, in the final chapter, the question of what vehicle drive train will be able to avert an energy crisis is asked. The answer relies on driver characteristics and diversification of the light-duty vehicle.

# Chapter 3. US Light-Duty Vehicle Transportation Sector: 1970’s Energy Crisis Changes to 2004 Status-Quo Manufacturing

Whether society chooses energy security or climate change as its motivation, the level of United States motor gasoline consumption and its current growth rate must change drastically. Models for calculating light duty vehicle’s fuel economy incorporate many vehicle-based parameters: 20 to 200 with some being proprietary and challenging for policy makers to acquire or use. This chapter describes a MatLab-based simulation model, MINPAR, which uses the three critical vehicle-based parameters: mass, engine size, and transmission characteristic. It is used to model over one thousand 1986 and 2004 United States offered vehicles from the EPA Test Car list (cars and light trucks) and four hundred 2004 Japanese offered vehicles’ fuel economy (FE). Offered vehicles consist of vehicle models and their different configurations. Status-quo vehicles are defined as offered vehicles modeled well with MINPAR by comparing modeled to measured fuel economies. Status-quo vehicles are modeled accurately and represent over 95% sales. Niche vehicles are defined using an easily understood and interpreted percent error methodology. Physically-defined niche vehicle configurations mirror economic realities of niche markets (5% of the total final sales market). By separating the high FE versus extreme power niche vehicle designs, a pattern emerges between (1) US 1986 versus 2004 and (2) US 2004 versus Japan 2004. Through Japanese policy, five of the top ten vehicle sellers in Japan are high fuel economic Kei vehicles. Whether the United States can accomplish anything similar or whether the Reformed CAFE policies open the door to create a next generation loophole in terms of alternative fuel or plug-in hybrid/electric vehicles is discussed.

## 3.1 Introduction to CAFE implementation after the 1970's oil crisis

The legal tensions surrounding automobile manufacturing and the regulation of fuel economy and vehicle-based greenhouse gas emissions can be summarized in terms of status-quo manufacturing versus niche manufacturing. The discrepancy between expert testimonies yields the basic policy flaw that complicates our understanding of fuel economy. Fuel economy is usually simple: mass of vehicle, energy source type/size (typically, IC engine displacement in liters), and power management design (either for power capability/effectiveness or energy efficiency). This chapter discusses the decisions made in the 1970s using a physics-based model of fuel economy to differentiate status-quo versus niche vehicle designs. The goal is to discuss how to make the niche vehicle designs of today the status-quo vehicles of tomorrow.

### 3.1A CAFE – Building on History

Why do we need to understand both the status-quo and niche technology vehicle designs? This answer rests on two issues. First, our need to make today's niche high fuel economy vehicles the status-quo vehicles of tomorrow and second, the necessity to quickly and decisively increase the fuel economies of today's status-quo vehicles with policies which promote decreasing mass and/or engine size or optimizations of fuel economy instead of power.

In the late 1970s, the oil crisis forced Congress to create the Corporate Average Fuel Economy (CAFE) regulations. Considering Figure 10, one could ask: did CAFE work?

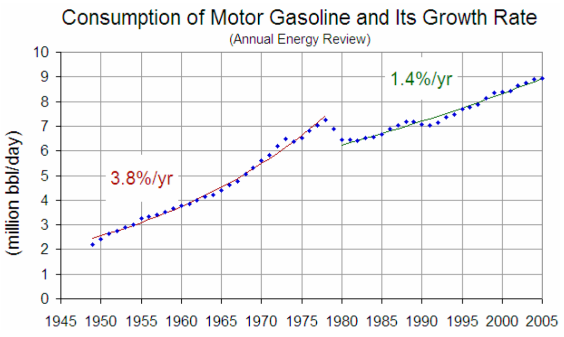


Figure 10: US motor gasoline consumption before and after oil crisis[63].

Yes and no [3,4]. During the major 1973 oil embargo, oil consumption decreased because of extreme shortages. With CAFE implementation in 1978, motor gasoline consumption significantly decreased. Since 1980, CAFE has kept the motor gasoline consumption growth rate much lower than pre-CAFE even though prices fluctuated greatly.

This could only be accomplished through either a reduction in the number of vehicles, a reduction in the number of vehicle miles driven (VMT), or an increase in the number of miles per gallon (fuel economy: FE); unless society changed the energy source for vehicles – which it did not. The main mechanism chosen was increasing fuel economy (mi/gal), or decreasing fuel intensity (gal/100mi).

Immediately after 1978, the vehicle designs which quickly decreased fuel intensity (gal/100mi) included decreasing the mass and engine size of new cars (see Figure 11).

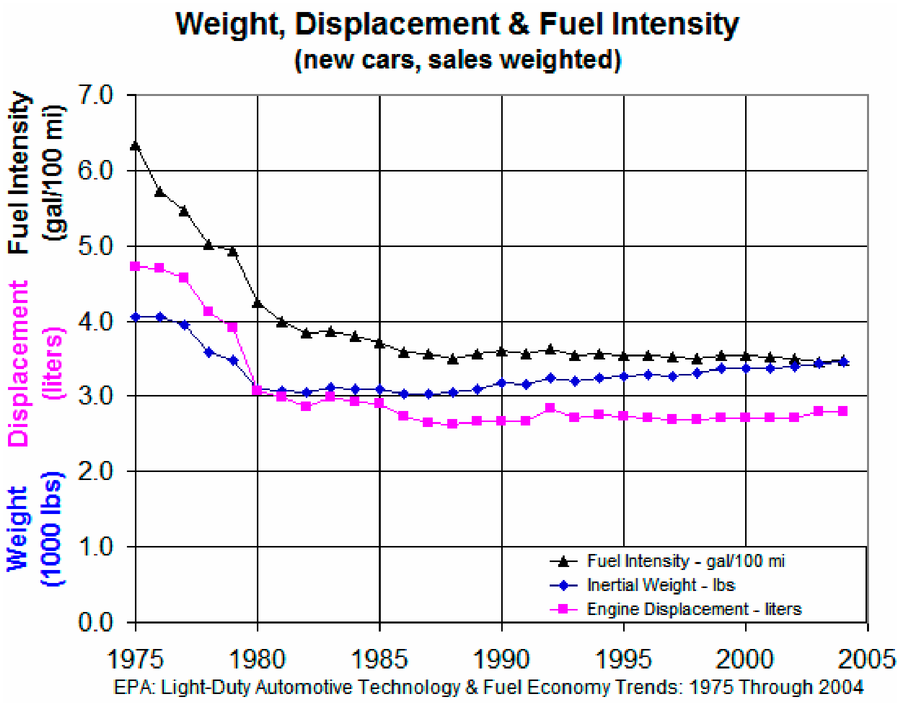


**Figure 11: US manufacturing response to CAFE [64].**

However, from 1990 to 2004, nothing further was done to significantly decrease the fuel intensity of new cars. Furthermore, light trucks have become a larger percentage of light duty sales. This chapter describes, investigates and presents the pathway to manufacturing status-quo (SQ) vehicles which increase fuel economy for light duty vehicles (cars and light trucks).

### 3.1B Policy-Based Methodology

After 1980, essentially all heavy cars above 4000 pounds were dropped from production. In the 1990s to early 2000s, the light truck policy loophole allowed heavy vehicles back on the road as sports utility vehicles. Throughout that entire time, manufactures offered high FE vehicles, but these vehicles only stayed within niche markets and most were soon dropped from production.

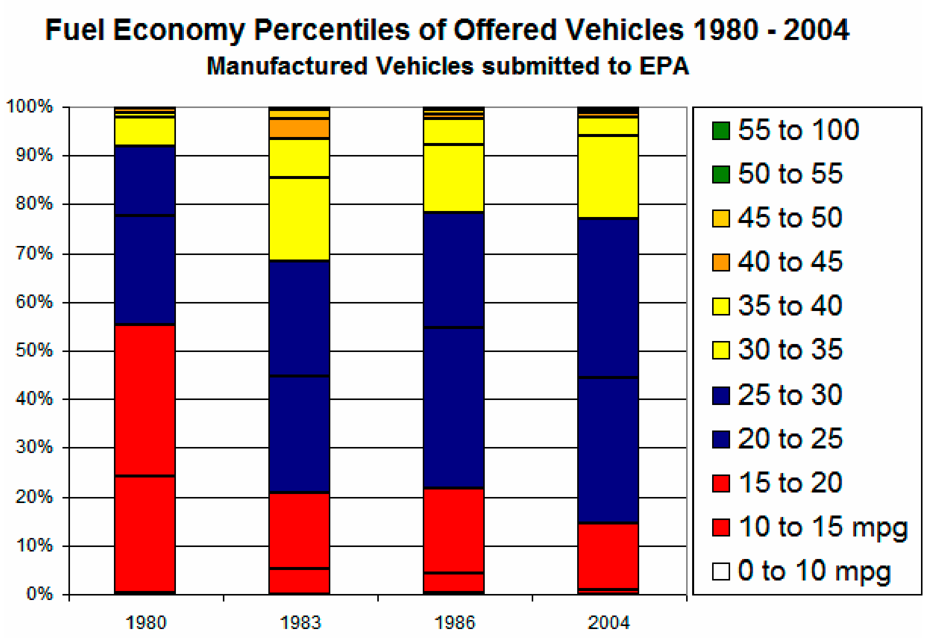


**Figure 12: Percentage of all offered vehicles within various combined (city and highway) fuel economy ranges for selected years from 1980 to 2004 [10, 11].**

As can be seen in Figure 12, there have always been 30 to 60+ mpg vehicles offered in the United States markets, but these vehicles never became part of the status-quo market or more than 5% of total sales [12]. Understanding the pathways from niche to status-quo manufacturing designs requires defining a status-quo vehicle physically in a manner that mirrors economic reality (see Figure 13).

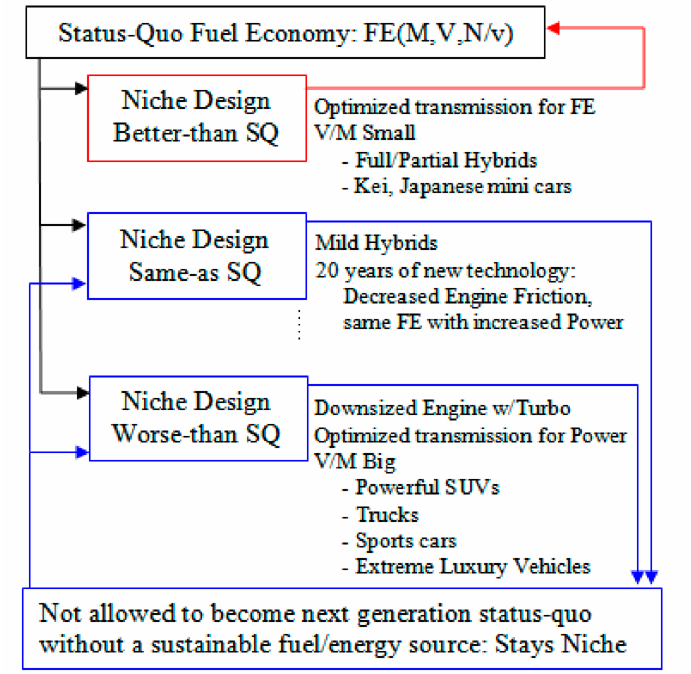


**Figure 13: Three Pathways from Niche Vehicles to Status-Quo Vehicles.**

The three physical variables used to calculate a vehicle's status-quo fuel economy are mass ($M$), engine size ($V$), and transmission engine-to-ground speed ratio in final gear ($N/v$) [1, 7, 8]. Sustainability, in terms of decreasing the motor gasoline consumed, requires (a) that the niche fuel efficient vehicles of today become the status-quo vehicles of tomorrow, (b) that the status-quo vehicles of today increase fuel efficiency by decreasing mass and/or engine size as well as choosing fuel economy over performance and/or (c) that an alternative fuel is utilized.

This chapter uses a Mat-Lab based simulation model to define status-quo and niche vehicle designs for 2004 and 1986[4]. These two years are then compared and contrasted in terms of differences of high and low fuel economy vehicle configurations. Finally, 433 Japanese vehicle designs are compared to 813 US vehicle designs in terms of (1) weight, (2) engine size, and (3) engine size-to-weight. The goal is two-fold. The first goal is to

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[4] Status-quo could be defined in terms of sales, but in this paper it is defined as the ability of each vehicle to be modeled physically. It turns out that these physically-based defined status-quo vehicles make up over 95% sales in United States. Other models are compared to MINPAR in the appendix.

highlight the automotive high fuel economy niche vehicle designs of today and discuss how to make them the status-quo of tomorrow. The second goal is to highlight how to design the status-quo vehicles for increased fuel economy.

## 3.2 MINPAR Simulation

As stated earlier, this MatLab-based minimum parameter model utilizes only three dominant variables for fuel economy of status-quo manufactured vehicles: $M$ , $V$ , and $N/v$ in final gear [1, 7, 8].

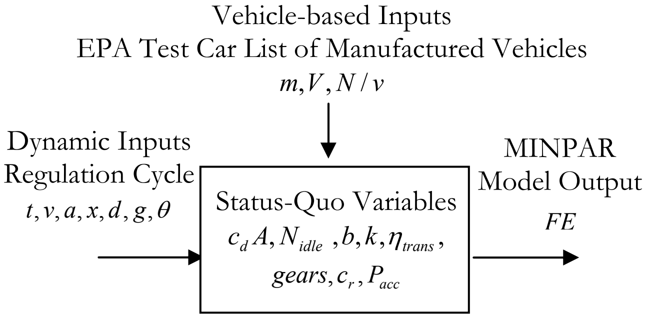


**Figure 14: All 1986 and 2004 US vehicles were modeled using MINPAR with the tw0 regulatory cycles, EPA Test Car List, and status-quo variables.**

In Figure 14, there are three variable groups. The first variable group is vehicle-based inputs: $M$ , $V$ , and $N/v$ in final gear [1]. The second group is dynamic inputs of the regulation cycle. The third group consists of status-quo variables for a specific year of offered vehicles. Each simulated fuel economy from MINPAR was compared to the measured fuel economy from EPA [7].

In a given year, the status-quo variables are easily estimated either based on (1) the fleet designs or (2) correlations of the vehicle's mass, engine displacement, or transmission ratio in final gear. Moreover, for a given year, the dominant vehicle-based variables are used to distinguish the status-quo from the niche vehicles. As has been said for twenty years, the manufacturing choice continues to be FE or power (e.g. 0 to 60 mph performance time versus miles/gallon) [3, 5].

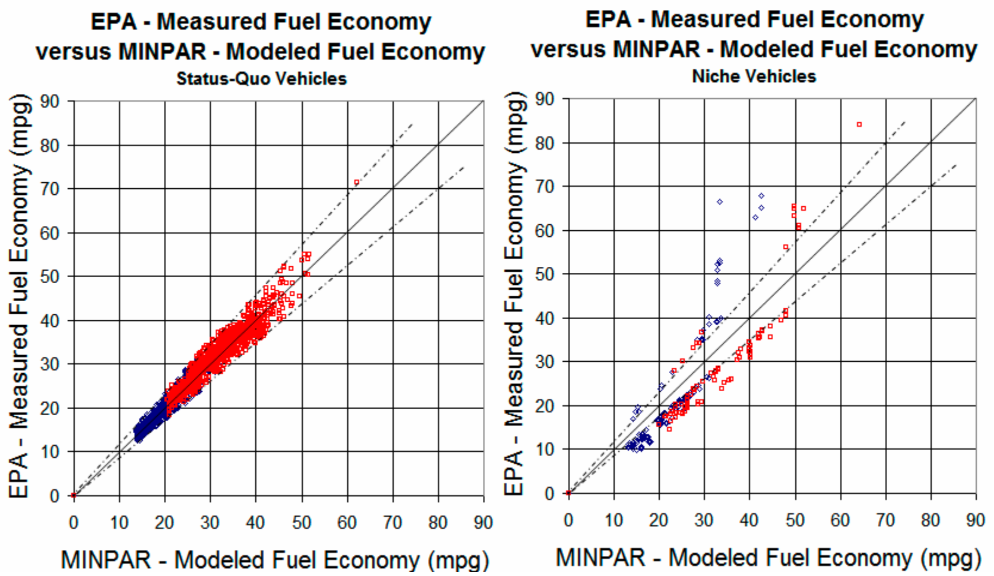
### 3.2A Status-quo Versus Niche in 2004

Using the MINPAR simulation model for 2004 vehicles, 92% of status-quo manufactured vehicles were modeled successfully while 8% were not[5]. What is presented in this investigation is the absolute value of the percent error.

$$\%Error = \frac{MINPAR - EPA}{EPA}$$

This allows for easy graphing of results and immediate interpretation and critique of status-quo versus niche designs.

In Figure 15, the dotted lines yield the cutoff differentiating between status-quo and niche vehicles. Furthermore, the status-quo manufactured vehicles represent 95% of the final market sales. This accomplishes the desired goal to mirror the economic reality of niche markets.


EPA - Measured Fuel Economy versus MINPAR - Modeled Fuel Economy

Status-Quo Vehicles

EPA - Measured Fuel Economy versus MINPAR - Modeled Fuel Economy

Niche Vehicles

**Figure 15: All 2004 US vehicles were modeled both for the urban (blue) and highway (red) driving cycle[6].**

In Figure 15, both plots together contain 813 different vehicle configurations for 1626

---

[5] Repeats within EPA's test car list were deleted.

[6] There were 1626 data points with 813 highway and 813 city fuel economies. There were 78 highway and 57 city outliers and only 37 vehicles with both.

data points (one data point for city FE and one data point for highway FE). The left plot, status-quo results, contains 1491 data points. The right plot, niche results, consists of 135 data points. After reviewing the 2004 data, a set niche groups were identified and are discussed in Section 3.

Given the three vehicle parameters, some designs were better-than status-quo fuel economy (above the dotted line) while other designs were worse-than status-quo fuel economy (below the dotted line). This distinction opened the door to physically discuss the pathways niche technology offers. Even though technology is touted as a way to improve fuel economy, many niche designs are not offered to consumers for this purpose.

### 3.2B Status-quo Versus Niche in 1986

Using the same logic as in section 3.2A, but applied to 1986 vehicles, a different pattern of niche vehicles emerges (see Figure 16).

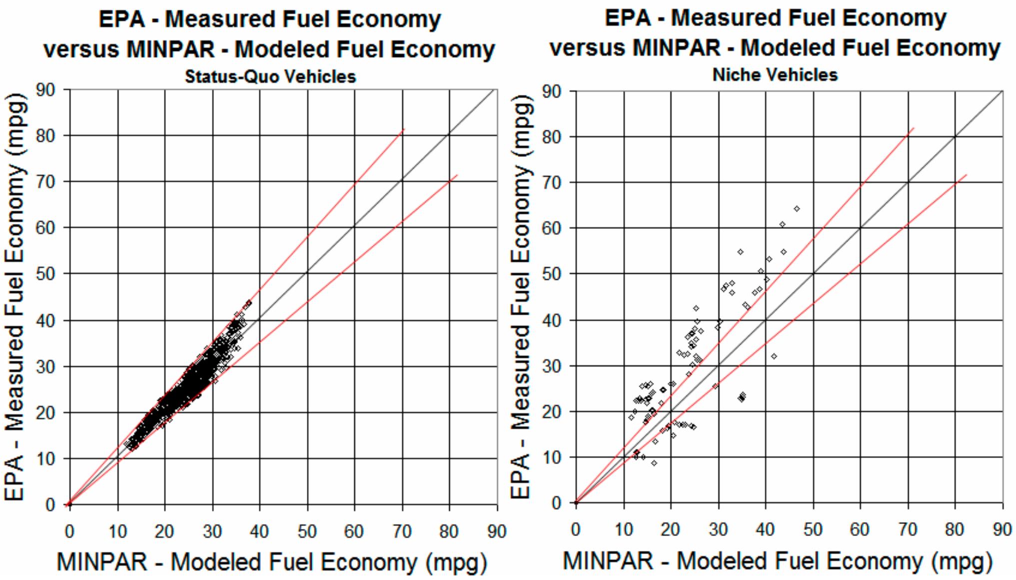


**Figure 16: All 1986 US vehicles were modeled for the combined driving cycle (55% city and 45% highway)[7].**

After reviewing the 1986 data, a set of niche groups were identified and are discussed in Section 3.3. Again there are niche vehicle designs which are better-than status-quo and

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[7] There were 889 data points for the combined driving cycle. There were 86 outliers.

worse-than status-quo fuel economy designs.

One result is that there are more vehicle configurations in the better-than status-quo high FE category in 1986 than in 2004. For example, the following vehicle models give a snapshot of the configurations for status-quo and the configurations for better-than status-quo FE.

| Vehicle Model | Year | Total Configurations | Configurations with High FE |
|---|---|---|---|
| Ford 150 | 1986 | 23 | 6 |
| | 2004 | 10 | 0 |
| Toyota Camry | 1986 | 5 | 2 |
| | 2004 | 5 | 0 |
| VW – Jetta | 1986 | 5 | 1 |
| | 2004 | 3 | 0 |

**Table 5: Comparing 1986 versus 2004 vehicle configurations for status-quo FE versus configuration for better-than status-quo FE (high FE configurations).**

In Table 5, the 1986 Ford 150 sent 23 vehicle configurations to EPA with 17 configurations in the status-quo FE regime and 6 configurations in the better-than status-quo high FE regime. Whereas in 2004, all ten configurations were in the status-quo FE regime and none were in the better-than status-quo regime. In the next section, this result is further discussed.

## 3.3 Niche Designs in 1986 versus 2004

Both in 1986 and in 2004, there were vehicles designed for niche markets. In 2004 and 1986, the author identified six distinctively designed niche vehicle groups. In 2004, the outliers of MINPAR make up only 5% of sales, i.e. mirroring the economic reality of niche markets.

Throughout this chapter, the niche vehicles' fuel economies are graphed to illustrate whether the niche design was better than a status-quo design (above red line), worse than a status-quo design (below red line), or status-quo designs (between the red lines).

### 3.3A Niche Technology for FE in 1986 versus 2004

During the 1980s, the United States widely debated diesel technology. The same manufacturers produced and continued to sell diesels to the European markets, but not to the United States markets. Now the new technology is hybridization. This section compares and contrasts these two technologies in 1986 versus 2004.

In 1986, there were a variety of vehicle models which had configurations with a diesel engine option. As can be seen in Figure 17, in 2004, there were no diesel cars without turbo charging.

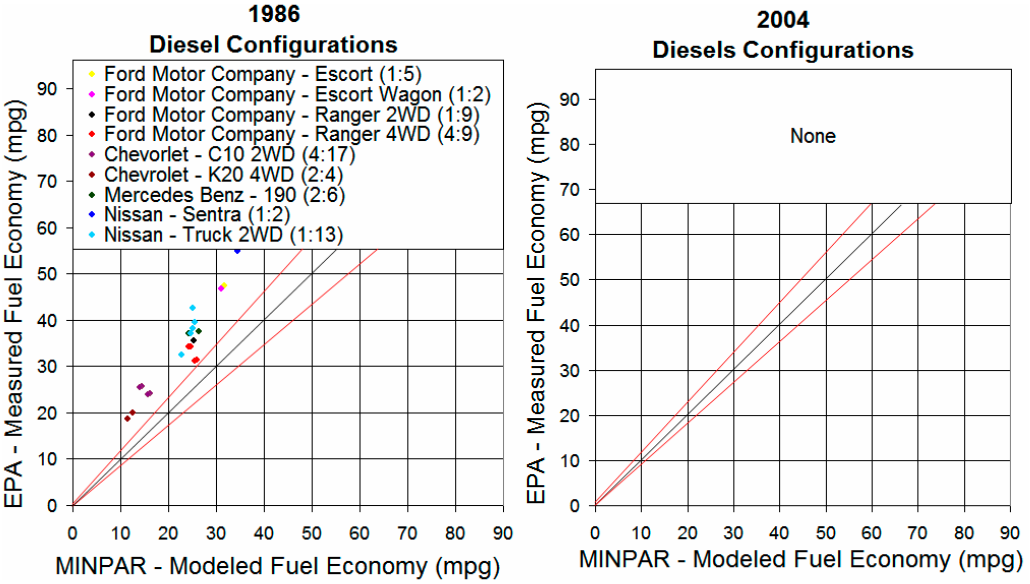

**Figure 17: Comparing 1986 versus 2004 diesel vehicle configurations without turbocharging**

However, diesels with turbocharging change the picture.

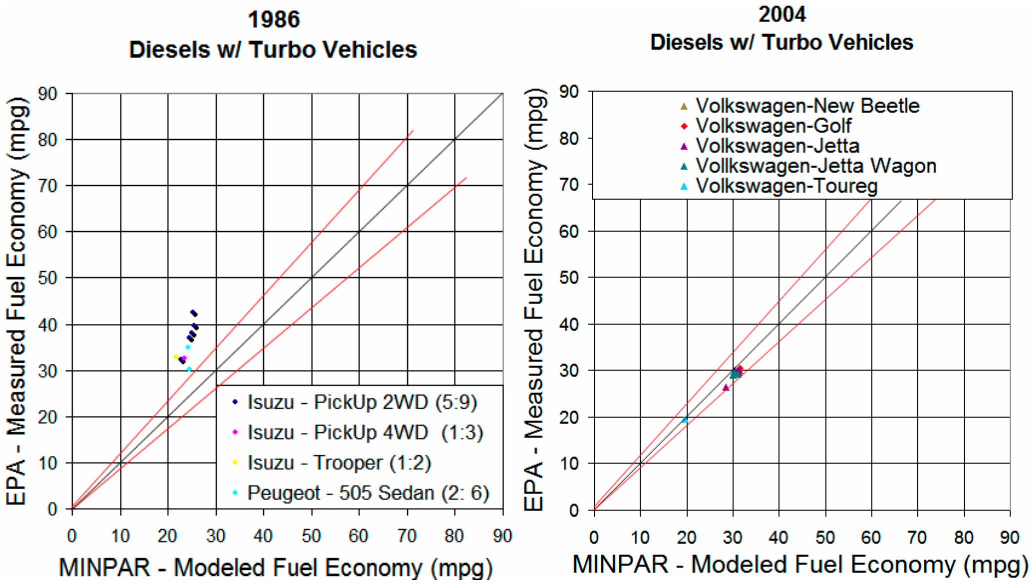

**Figure 18: Comparing 1986 versus 2004 diesel vehicle configurations with turbocharging**

As can be seen in Figures 17 and 18, all of the diesel model configurations in 1986 had better-than status-quo FE. Whereas, in 2004, there were only diesels with turbocharging and none of them were above the red line (better-than status-quo FE). These vehicle designs are described with the following two pathways for FE.

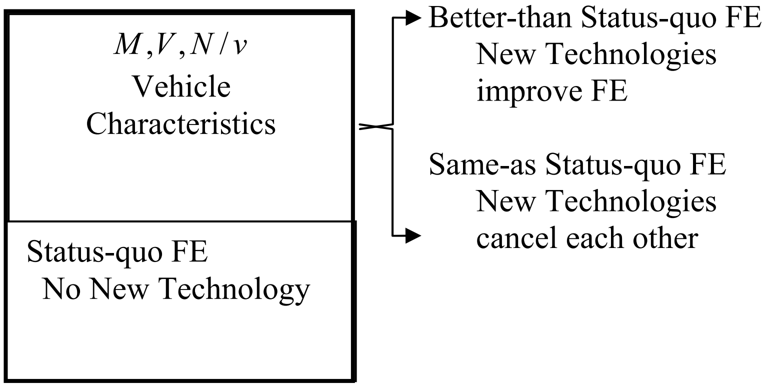

**Figure 19: Given this set of vehicle characteristics, the new technologies of diesels and turbocharging yielded two pathways for FE: Better-than and Same-as Status-quo FE.**

Considering a specific vehicle design ($M,V,N/v$), new technology can be added to design a vehicle for (1) Better-than Status-quo FE or (2) Same-as Status-quo FE by canceling out FE benefits with more power (see Figure 19). The added technology can increase the fuel economy as seen in the 1986 diesel vehicles with or without turbo-charging. However, the added technology can also approximately cancel as seen in the 2004 diesel turbo-charged vehicles.

Thus the tension between FE and power re-emerges. The technology in 1986 which was touted as good for high FE is now within the status-quo regime because it is combined with turbocharging for better performance. How does hybrid technology fit in?

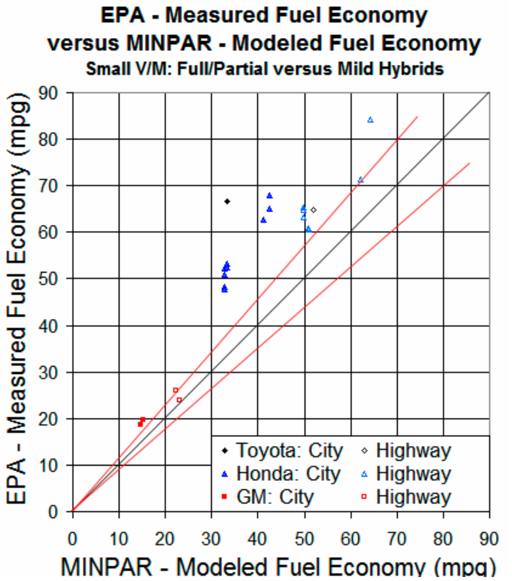

**Figure 20: Three manufacturers offered hybrids in 2004 with either Better-than Status-quo (above red line) or Same-as Status-quo (near red line) fuel economy vehicles.**

Although hybrid technology is generally accepted as a technology which increases fuel economy, there are two hybrids which were Same-as Status-quo FE vehicles as seen in Figure 20.

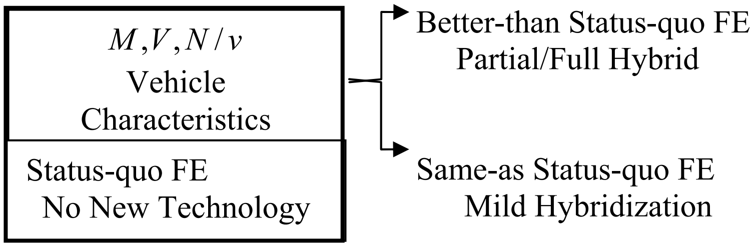

**Figure 21: Given this set of vehicle characteristics, the new hybrid technologies yielded two pathways for FE: Better-than and Same-as Status-quo FE.**

In Figure 21, there were two main pathways for additional hybrid technology. The full/partial hybrids all had V/M values approximately equal to 0.2; whereas V/M for mild hybrids was approximately equal to 0.6. These mild hybrids were equipped with new technology, but this technology did not exhibit large differences in fuel economy from a status-quo vehicle without this technological advancement. Moreover, some newer generations of the Toyota Prius are adding greater performance levels with a larger engine and thus will sacrifice high FE potential. The full and partial hybrids did originally exhibit substantial fuel economy benefits compared to a similar status-quo vehicle design, but whether or not these technologies will continue to be applied to FE instead of power capability is yet to be seen.

### 3.3B Niche Sports/Luxury for Power in 1986 versus 2004

In the majority of sports and luxury car options, power capability was chosen over FE. Consequently, sports cars are worse in terms of fuel economy compared to a similar FE level using status-quo manufacturing designs (below the red line) as seen in the figure below.

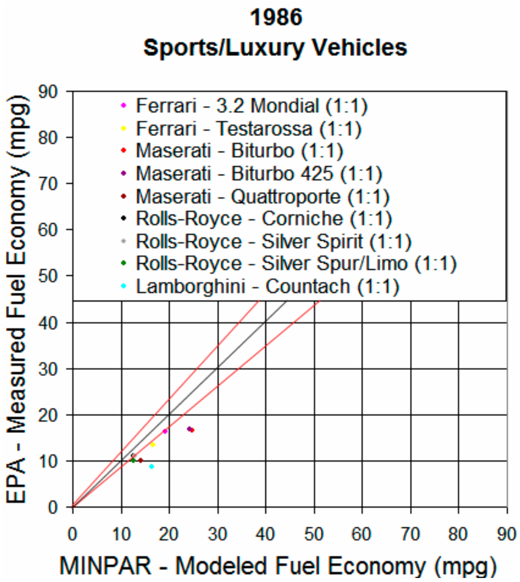

**Figure 22: In 1986, there were four major manufacturers of sports/luxury vehicles and all of the models were worse-than status-quo FE (below red line).**

The next table outlines these vehicles characteristics.

| 1986 Models with Niche Configurations<br>Lower FE than Status-Quo (SQ)Configurations | | |
|---|---|---|
| Manufacturer - Model Name (niche:# configurations) | Status Quo FE(M,V,N/v) - Niche FE | M (lbs), V (L) Rated Power (hp/kW) |
| **Sports Cars** | | |
| 1 – Ferrari<br>3.2 Mondial (1:1) | 19.1 – 2.9 | 3750, 3.2<br>260/194 |
| 2 – Ferrari<br>Testarossa (1:1) | 16.7 – 3.3 | 4000, 5.0<br>380/283 |
| 3 – Maserati<br>Biturbo (1:1) | 24.8 – 8.3 | 3000, 2.5<br>185/138 |
| 4 – Maserati<br>Biturbo 425 (1:1) | 24.3 – 7.5 | 3250, 2.5<br>185/138 |
| 5 – Rolls-Royce<br>Corniche (1:1) | 12.7 – 1.7 | 5500, 6.8<br>170/127 |
| 6 – Rolls-Royce<br>Silver Spirit (1:1) | 12.9 – 1.9 | 5250, 6.8<br>170/127 |
| 7 – Rolls-Royce<br>Silver Spur (1:1) | 12.7 – 1.7 | 5500, 6.8<br>170/127 |
| 8 – Lamborghini<br>Countach (1:1) | 16.3 – 7.6 | 3750, 5.2<br>420/313 |

**Table 6: 1986 Sports and luxury vehicles status-quo FE minus the niche design characteristic FE (added niche design decreased status-quo FE).**

The center column of the next three tables illustrates the loss of fuel economy for each vehicle design due to the added niche characteristics. For example, in Table 6, the 3.2 Mondial by Ferrari was modeled to have a status-quo fuel economy of 19.1 mpg; however, with their niche design, EPA measured the fuel economy 2.9 mpg lower or at 16.2 mpg. Furthermore, the Maserati Biturbo's design is 8.3 mpg worse than a status-quo designed vehicle with the identical $M, V$, and $N/v$ characteristics.

The average rated power of sports cars in 1986 becomes the average rated power of status-quo vehicles in 2004. In 2004, the rated power doubled in almost every group as can be seen in Tables 7 and 8. The natural question arises: What if all the technological advances from 1986 to 2004 where placed into fuel economy instead of increasing rated power? What would the new fuel economy distributed of status-quo vehicles be? These questions are explored in Chapter 3, Section 4 of this thesis.

| 2004 Models with Niche Configurations<br>Lower FE than Status-Quo (SQ) Configurations | | |
|---|---|---|
| Manufacturer - Model Name (niche:# configurations) | Status Quo FE(M,V,N/v) - Niche FE | M (lbs), V (L) Rated Power (hp/kW) |
| **Sports and Luxury** | | |
| 1 – Aston Martin V12 Vanquish (1:1) | 21.1 – 4.0 | 4250, 6.0<br>460/343 |
| 2 – Ferrari 360 Modena (2:2) | 22.5 – 7.9 | 3625, 3.6<br>394/294 |
| 3 – Ferrari 575Maranello (2:2) | 18.4 – 4.9 | 4250, 5.8<br>510/380 |
| 4 – Lamborghini Gallardo (1:1) | 20.5 – 7.0 | 3750, 5.0<br>500/373 |
| 5 – Lamborghini Murcielago(1:1) | 18.5 – 6.1 | 4000, 6.2<br>580/433 |
| 6 – Maserati Cambriocorsa (1:1) | 20.7 – 4.6 | 4250, 4.2<br>385/287 |
| 7 – Porsche Carrera 2 911 GT3 (1:1) | 25.2 – 4.5 | 3375, 3.6<br>280/283 |
| 8 – Porsche Carrera GT (1:1) | 19.3 – 5.0 | 3375, 5.7<br>605/451 |

**Table 7: 2004 sports and luxury vehicles' rated power doubled and their status-quo FE increased due to decreases in engine friction from 1986 to 2004; however, the measured FE (Status-quo minus niche FE) was increased only marginally**

In Table 7, these sport and luxury cars did not include turbocharging configurations. For example, the 2004 Lamborghini models have gargantuan engines and during both regulatory cycles (city and highway), these vehicles' engines barely leave the idling engine speed for the power load. Thus the engine friction is much greater than MINPAR uses for the 2004 status-quo variables. As expected, all of the niche vehicle designs and configurations have worse-than status-quo FE.

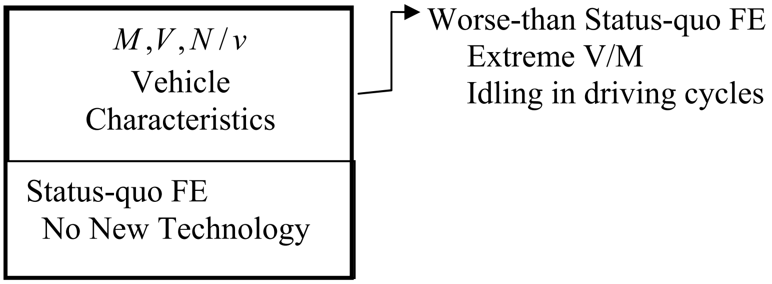

**Figure 23: Given this set of vehicle characteristics, there is one key pathway: decrease fuel economy with extreme V/M**

In Table 8 are the 2004 models and configurations which do have turbocharging:

| 2004 Models with Niche Configurations<br>Lower FE than Status-Quo (SQ) Configurations | | |
|---|---|---|
| Manufacturer - Model Name (niche:# configurations) | Status Quo FE(M,V,N/v) - Niche FE | M (lbs), V (L) Rated Power (hp/kW) |
| **Sports/Luxury w/ Turbo** | | |
| 1 – Audi<br>TT Coupe (1:1) | 34.5 – 6.7 | 3250, 1.8<br>180/134 |
| 2 – Audi<br>TTCoupe Q (1:1) | 32.4 – 5.3 | 3625, 1.8<br>225/168 |
| 3 – Audi<br>TTRoadster (1:1) | 33.3 – 6.6 | 3500, 1.8<br>180/134 |
| 4 – Audi<br>TTRoadster Q (1:1) | 31.9 – 5.0 | 3750, 1.8<br>225/168 |
| 5 – Bentley Motors Ltd<br>Arnage (1:1) | 17.7 – 3.9 | 6000, 6.8<br>412/336 |
| 6 – Bentley Motors Ltd<br>ContinentalGT (1:1) | 18.6 – 2.8 | 5500, 6.0<br>552/412 |
| 7 – SAAB<br>9-3 Convert. (1:13) | 33.0 – 6.0 | 4000, 2.0<br>210/157 |
| 8 – Lotus<br>Esprit V8 (1:1) | 26.0 – 5.4 | 3375, 3.5<br>350/261 |
| 9 – Porsche<br>2 911 GT2 (1:1) | 26.0 – 4.9 | 3875, 3.5<br>350/261 |
| 10 – Porsche<br>4 911 Turbo (1:1) | 26.1 – 6.1 | 3750, 3.6<br>415/310 |
| 11 – Porsche<br>4 911 Turbo C (1:1) | 25.7 – 6.1 | 4000, 3.6<br>415/310 |

**Table 8: 2004 sports and luxury vehicles characteristics with turbocharging**

In all but one case, the status-quo fuel economy is greater than the sports cars without turbocharging. This is because with turbocharging the engine could be downsized and this sometimes corresponds to less vehicle weight. Given this smaller engine size and weight, a status-quo vehicle would have higher fuel economy. However, with 2004 turbochargers in these vehicles and transmissions designed for power, the potential fuel economy gain is lost.

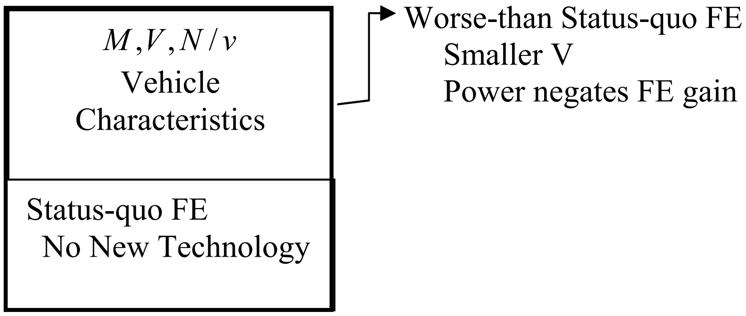

**Figure 24: Given this set of vehicle characteristics, there is one key pathway to increase fuel economy: smaller engine size, but this is canceled out by designs for power.**

### 3.3C Niche Trucks for Power in 1986 versus 2004

Similarly, massive and large-engine trucks are designed specifically for power output.

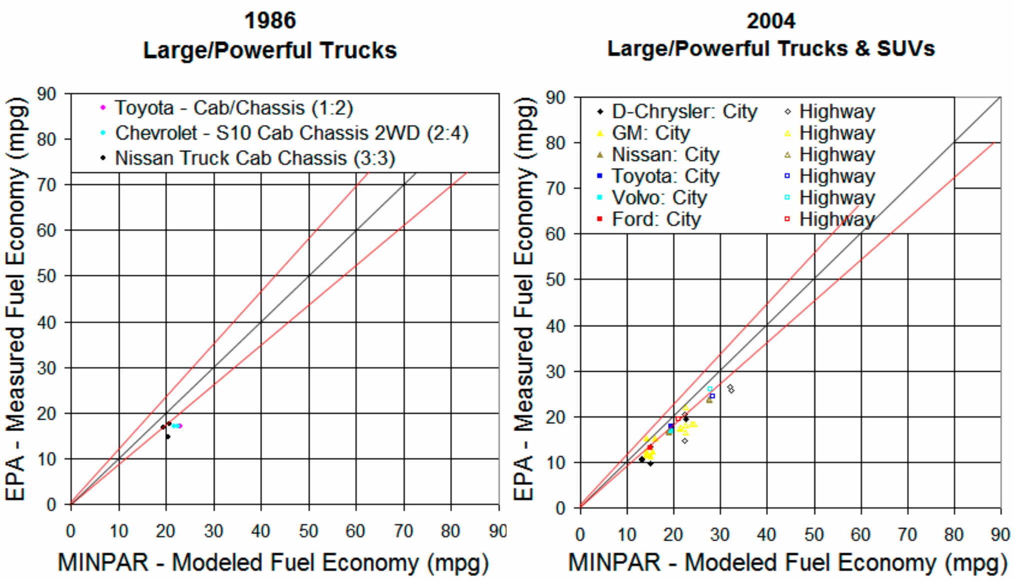

**Figure 25: Whether in 1986 or 2004, there have always been niche markets for large and/or powerful trucks**

In Figure 25, all of these models are worse-than status-quo FE for large trucks and SUVs.

### 3.3D Unique Configurations for FE in 1986 versus 2004

This was a difficult group to decipher. John Komey's work illustrates the benefits of unique transmission optimizations for fuel economy instead of power and the cost effectiveness of this design choice [6]. Moreover, this design option never became a status-quo configuration.

In this chapter, I put forth an argument that this group of the 1986 and 2004 niche vehicle configurations was optimized for fuel economy. However, the lack of publicly available data cannot confirm or deny this assumption. With that said, this niche vehicle group was designed to have a Better-than Status-quo fuel economy.

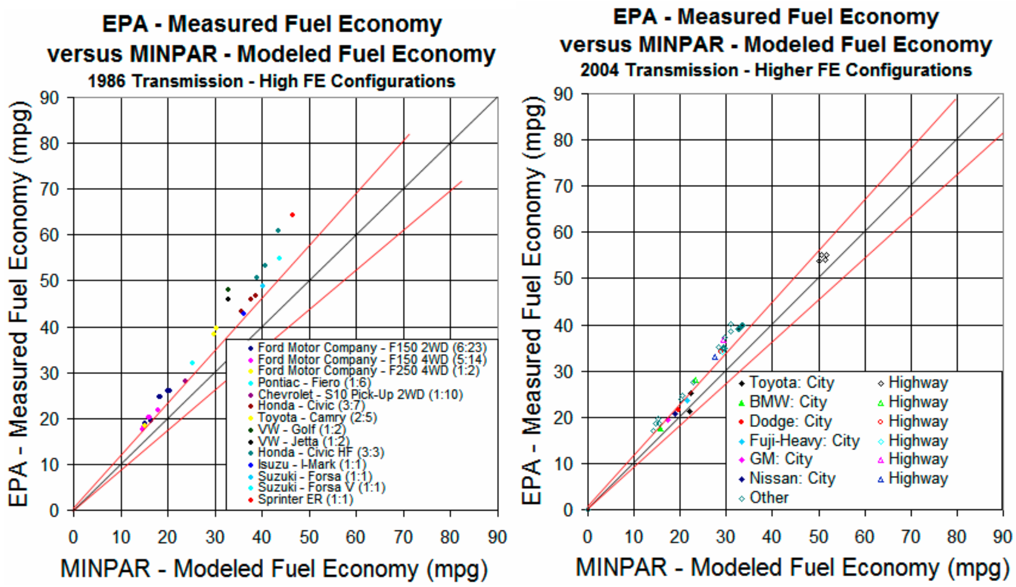

**Figure 26: There are similar numbers of configurations to increase fuel economy in 1986 than in 2004**

In Figure 26, there are similar numbers of configurations for fuel economy in 1986 and in 2004. It is rarely stated that fuel economy can be improved without technological advancements, but this can be done. Here a designer optimizes the transmission for fuel economy instead of power, as in the Honda HF configurations Koomey describes. In 1986 there were vehicle models which had configurations which were (1) status-quo and a few with (2) better-than status quo fuel economy. For example in 1986, the Chevrolet S10 pick-up had 10 model configurations with one configuration which had a better-than status quo fuel economy. However, there were also vehicles models which had all configurations with better-than status-quo fuel economy

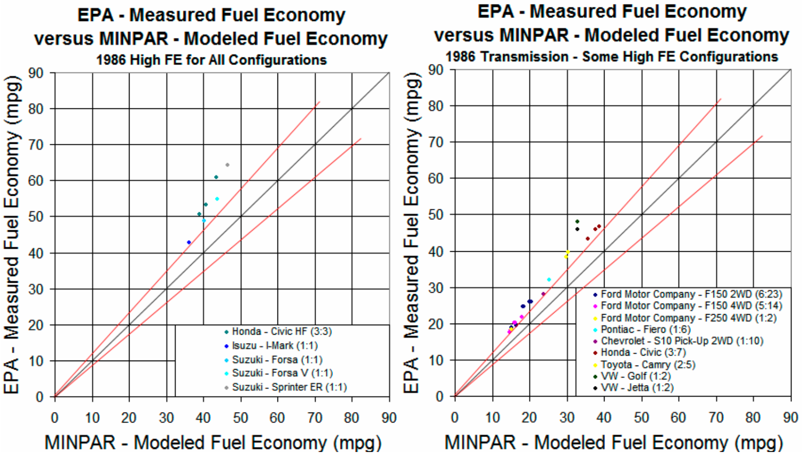

**Figure 27: A few 1986 models had all the configurations with better-than status-quo fuel economy; whereas, other models only had one or two such configurations.**

In Figure 27, the most notable vehicle is the one where all configurations are better-than status-quo fuel economy; and this is the one John Koomey discusses: Honda HF [6].

### 3.3E Alternative Fuel Vehicles in 2004

This group illustrates the last niche frontier: new energy sources for vehicle

| Company | Fuel | Bi-Fuel | Number |
|---|---|---|---|
| Chevrolet | E85/Gas | Yes | 11 |
| | CNG/Gas | Yes | 3 |
| | CNG | No | 3 |
| Chrysler | E85/Gas | Yes | 4 |
| Dodge | E85/Gas | Yes | 5 |
| Ford | E85/Gas | Yes | 6 |
| | LPG/Gas | Yes | 2 |
| | CNG/Gas | Yes | 2 |
| | CNG | No | 1 |
| | HFV | No | 1 |
| GMC | E85/Gas | Yes | 8 |
| | CNG/Gas | Yes | 2 |
| | CNG | No | 2 |
| Honda | CNG | No | 1 |
| | HFV | N0 | 1 |
| Mercedes-Benz | E85/Gas | Yes | 5 |
| Mercury | E85/Gas | Yes | 4 |

**Table 9: The United States 2004 number of offered vehicle configurations by company, fuel type, and ability to operate with two fuels.**

Table 9 illustrates the vast uncertainty about the next fuel possibilities. This year did not include all the electric vehicle possibilities from past years. However, the failure of the electric vehicle might prompt one to wonder whether or not these niche vehicles will ever become status-quo to support sustainability, in terms of decreasing gasoline consumption. For example, the flex-fuel vehicle can be operated with gasoline and E85 mixes: given it the name flexible fuel options. These flex-fuel vehicles are sold in the United States, but they have not decreased the motor gasoline consumption (refer to Figure 9 in introduction). Thus these configurations could be considered another type of loophole. To stress this point, the 2008 Tesla manufacturer has a CAFE fuel economy of 244 mpg [15]. This means that the Reformed CAFE regulation in and of itself cannot adequately decrease motor gasoline without dealing with downstream energy consumption options. If the Reformed CAFE regulation assumes anything besides what is actually behaviorally being done by drivers, then the regulation is a loophole for decreasing motor gasoline consumption (even though the potential is there). If the Reformed CAFE regulation works with other regulation policies to promote sustainable driver behaviors (i.e. choosing more sustainable fuel sources), then the loophole is closed.

Whether or not alternative fuel vehicles are a loophole for the Reformed CAFE implementations should be debated in terms of various definitions of sustainability. In this dissertation, sustainability is defined in terms of decreasing gasoline consumption. Under this definition, a product which can be used for either energy or food is irrelevant. However, sustainability in a larger context should deal with whether or not this is a sustainable situation when energy and food resources compete in a capitalistic supply and demand global market especially where and when starvation is a continual issue.

## 3.4 Two Additional Sustainability Policy Implications

There are two justifications for alternative fuel vehicles: fuel shortages and climate change. Regardless of which justification is used, the previously discussed niche design vehicles are not significantly improving the gasoline consumption rate in 2009 or in the near future (next 10 years). However, there are 2 possibilities for what could be done in the near future: (1) implement a policy that encourages a US close cousin to the Japan’s Kei car and truck or (2) decrease all status-quo vehicles’ mass and/or engine size while keeping 2004 performance capabilities: modestly or drastically.

### 3.4A Offered Vehicles in 2004 for US versus Japan

I note that the constraints on the US and Japanese automotive vehicles are different in terms of various non-vehicle-based characteristics: status symbol, parking lot sizes and availability, average traveling trip distances, number of trips/day, public transportation availability, etc. Keeping these constraints in mind, the following figures compare the 2004 offered light-duty vehicles (cars and trucks) between the US and Japan.

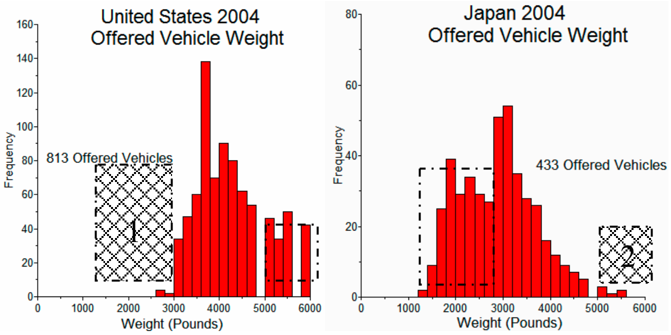

**Figure 28: United States and Japan's 2004 offered vehicle weight**
**Box 1: Low weight options missing in US market**
**Box 2: Multiple heavy weight options missing in Japanese market**

In the above figure, the United States offers the majority of vehicles within +/-1000 pounds of 4000. Over time, the range could be shifted downwards 3000 +/- 750 lbs. However, Japan has a much larger range of weight options and has a more sustainable personal transportation vehicle fleet with a large number of low weight vehicles (nonexistent in US) and few high weight vehicles.

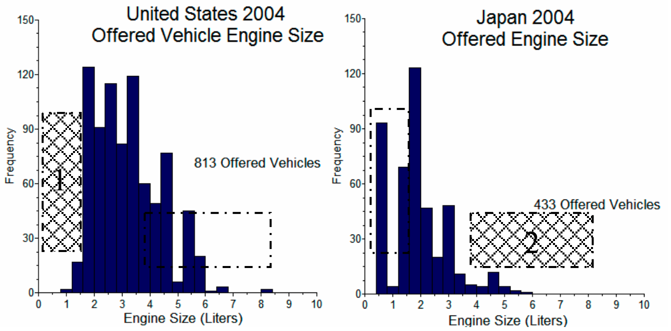

**Figure 29: United States and Japan's 2004 offered vehicle engine size**
**Box 1: Low engine size options missing in US market**
**Box 2: Multiple large engine size options missing in Japanese market**

This is accomplished by the well-known mini van, truck and car, Kei-Jidosha, which accounts for a significant percentage of total new sales (25% in 2004) and is illustrated graphically in Figure 30 as the box. This type of vehicle does not exist in the United States market, but it should.

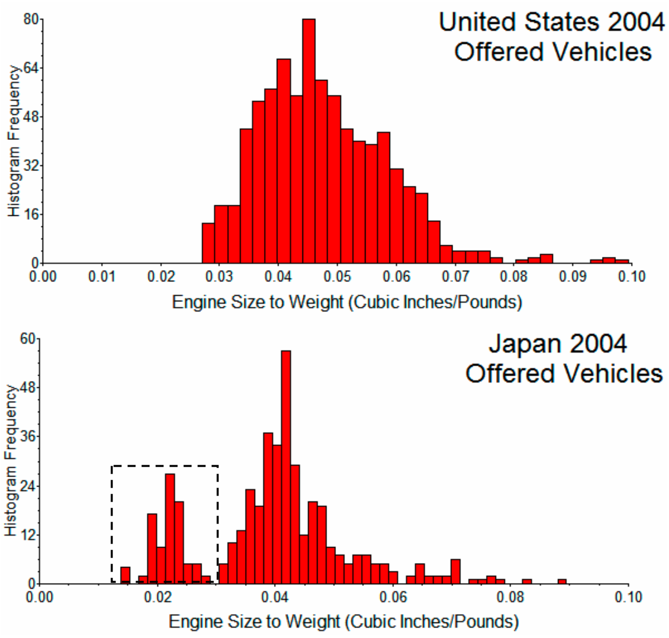

**Figure 30: United States and Japan's 2004 offered vehicle engine size to weight. Box is Kei mini car and truck[8] [5]**

### 3.4B Status-Quo Policy Consequences

Going back to what worked in 1980s with (1) decreasing mass and (2) decreasing engine size within a five year time frame; the following simulation results take the 2004 status-quo offered vehicle's mass and engine displacement and decrease each in turn by 10%, 20%, and 30%. These 717 status-quo vehicles' fuel economies are thus simulated with MINPAR three times: M10/V10, M20/V20, and M30/V30: where the letter M stands for decreasing mass while V stands for decreasing engine size and the number signifies the percent decrease – 10, 20, or 30.

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[8] Mini-cars and trucks law requires at height < 2 m: width < 1.48 m; length < 3.4 m; engine displacement < 660 cc. This policy takes the form of a yearly automobile tax.: Jidosha-zei tax.

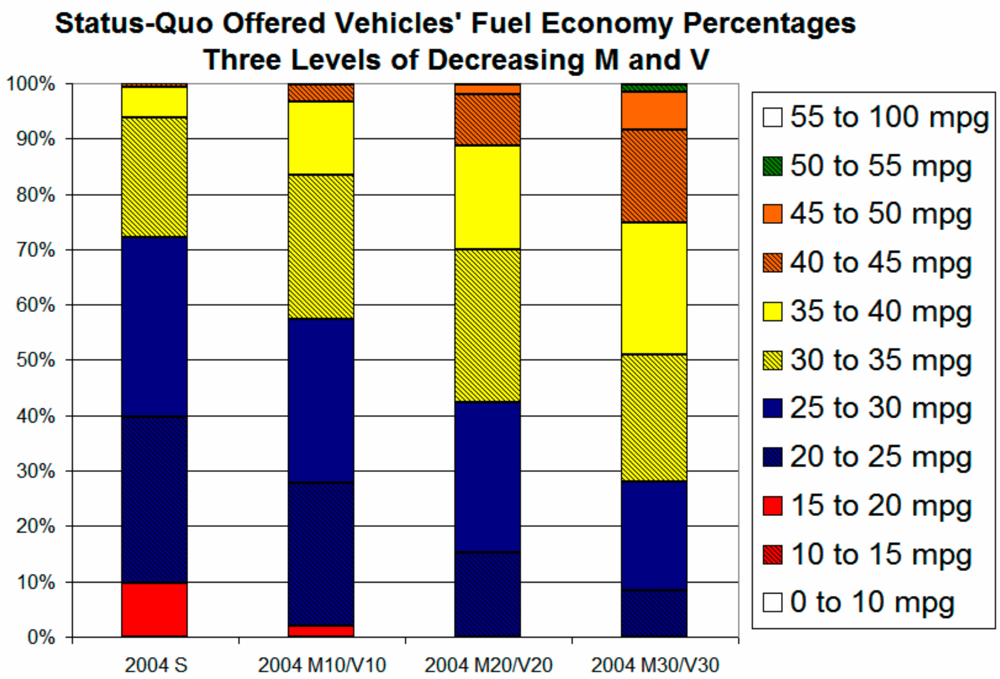

**Figure 31: Three levels of decreasing vehicle mass (M) and vehicle engine size (V) are simulated with MINPAR for all 2004 United States status-quo vehicles (717 in all)**

In Figure 31, it is only by decreasing both mass and engine displacement by 30% that the offered status-quo fuel economy distribution median and average is approximately 35 mpg: close to the Reformed CAFE goal for 2020. In 2004, the median and average for offered vehicle designed is 26 mpg. Reconsidering the technological advances since 1986, I asked how much decrease would have happened if all the technology was used for fuel economy gains instead of increasing power. This is a little bit tricky to follow, though.

First, consider the following: if the average technological capabilities (P/V) and average performance characteristic (P/M) are the same in 2004, how much is the rated power decreased with a 30% decrease proposal?

| 717 Modeled MINPAR Status-quo Vehicles | 2004 As-Is | 2004 Proposal 30% Decrease |
|---|---|---|
| $\langle V \rangle$ | 3.25 L | 2.28 L |
| $\langle M \rangle$ | 4000 lbs | 2800 lbs |
| $\langle P \rangle$ | 161 kW | 113 kW |
| $\langle P/M \rangle$ | 0.040 kW/lbs | 0.040 kW/lbs |
| $\langle P/V \rangle$ | 51 kW/L | 51 kW/L |

**Table 10: With a 30% decrease proposal and the same <P/M> and <P/V>, then the rated power of the average rated power would be 113 kW**

In Table 10, the average rated power would decrease from 161 kW to 113 kW as follows:

$$\left\langle \frac{P_{2004\,As-Is}}{V_{2004\,As-Is}} \right\rangle = \frac{\left\langle P_{new-policty} \right\rangle}{\left\langle V_{S-M25/V25} \right\rangle} = 51\,kW/L$$

$$\left\langle P_{2004\,As-Is} \right\rangle = 161\,kW \rightarrow \left\langle P_{new-policty} \right\rangle = 113\,kW$$

However, in 2004 the rated power capabilities varied greatly. BMW's mini cooper's rated power was 92 kW/L (new technology) and Toyota's LX 70 was 37 kW/L (a heavy SUV with older powertrain technology). Furthermore, 51 kW/L is a fairly typical characteristic.

With that said, the same methodology can be applied to 1986, but this time to calculate what the decrease in mass and engine displacement would have been given 2004 technology: the same 2004 average performance (P/M) and the same 2004 average technological capabilities (P/V), but with the average 1986 rated power (see Table 10).

| 717 Modeled MINPAR Status-quo Vehicles | 2004 As-Is | 1986 As-Is | 2004 Proposal 54/53% Decrease |
|---|---|---|---|
| $\langle V \rangle$ | 3.25 L | 3.05 L | 1.76 L |
| $\langle M \rangle$ | 4000 lbs | 3500 lbs | 2100 lbs |
| $\langle P \rangle$ | 161 kW | 87 kW | 87 kW |
| $\langle P/M \rangle$ | 0.04 kW/lbs | 0.025 kW/lbs | 0.040 kW/lbs |
| $\langle P/V \rangle$ | 51 kW/L | 29 kW/L | 51 kW/L |

**Table 11: With a 1986 rated power of 87 kW and 2004 technology, the average mass could have decreased by 54% and engine size by 53%**

Taking these averages and previous calculation methodologies to fill out Table 11, what percentage change would characterize the status-quo MINPAR model?

$$\frac{\langle V_{extremem\ policy} \rangle}{\langle V_{2004\ As-Is} \rangle} = \frac{1.76}{3.25} \rightarrow 54\%\ decrease$$

$$\frac{\langle M_{extremem\ policy} \rangle}{\langle M_{2004\ As-Is} \rangle} = \frac{2100}{4000} \rightarrow 53\%\ decrease$$

Consequently, MINPAR calculates the fuel economy for all 717 status-quo vehicles with 54 % smaller engine size and 53% less mass. The fuel economy distribution result for the 2004 MINPAR's status-quo vehicles' fuel economy is in Figure 32.

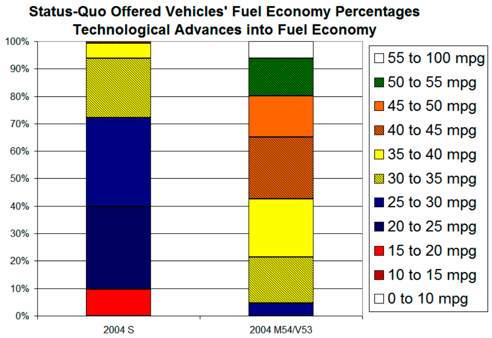

**Figure 32: Final scenario: 2004 MINPAR results for status-quo vehicles' fuel economy. The median fuel economy is approximately 42 mpg.**

In Figure 32, this final fuel economy distribution is something that few, if any, have imagined practical. However, the smallest proposed mass and engine size vehicle has an engine displacement of approximately 0.81 L and mass of 1100 lbs which is similar to a Japanese Kei car (0.65 L, 1200 lbs, 86 kW/L, and 0.046 kW/lbs).

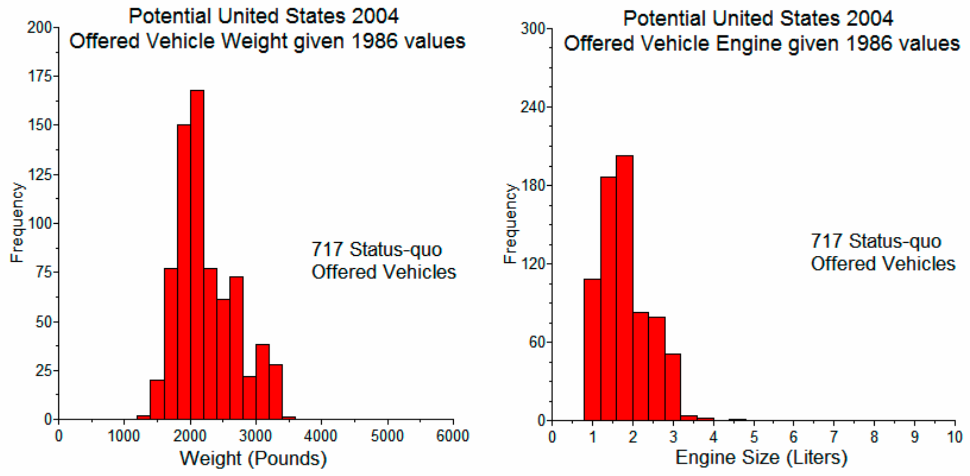

**Figure 33: 2004 Status-quo vehicles histograms of weight and engine size for the extreme policy case where all technological advances from 1986 were placed into fuel economy.**

In other words, if the United States would have placed all the powertrain technological advances into fuel economy instead of performance, then the United States offered vehicles would have had a close cousin to the Japanese Kei car, van and truck option, but it would have been designed for a somewhat higher V/M value than that of the Japanese Kei options (see Figures 33 and 34).

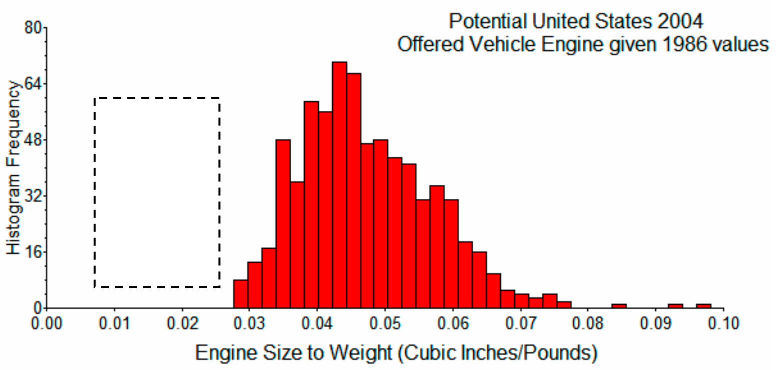

**Figure 34: 2004 status-quo vehicles engine size to weight distribution for the policy case where all technological advances from 1986 were placed into fuel economy.**

In Figure 34, there is still no 0.02 $in^3$/lbs offered Kei car option in this hypothetical analysis (empty box). The reason is that the average US performance factor (P/M) was kept the same, but it is only in decreasing this factor (i.e. increasing the mass) that one designs a Kei car, van, and/or truck.

This result would have taken political action to encourage consumers to purchase these vehicles and to help manufacturers insure proper safety constraints, but it is scientifically feasible and interesting to ask policy makers to create a policy which promotes the close cousin Kei car/truck or smaller mass and engine size vehicles as strongly as Japan did and does.

## 3.5 Conclusion to Project One Investigation and Analysis

It would take political, consumer and manufacturing will, and not necessarily new technologies to decrease oil consumption as seen with CAFE in the late 1970s. The United States must choose as an energy-consuming society among legal regulations, business policies, and consumer choices to either (1) make the niche energy efficient designs of today the status-quo manufactured vehicles of tomorrow or (2) use status-quo manufacturing vehicles designs of today. The cultural and geographic constraints between Japan and the United States have yielded uniquely manufactured vehicles. However, the policy of a year automobile tax specifically has promoted five of the top ten sellers in Japan to be fuel efficient mini-vehicles; whereas, in the United States, not one extremely high fuel efficient vehicle is a top ten seller. Furthermore, since 1986, most of the higher fuel economy vehicles were taken out of production in the US.

### 3.5A Four Policy Issues that Reformed CAFE must consider

In conclusion, these are the four policy issues discussed in this paper.

(1) New Niche Technology: The US must be leery of policies which focus solely on new technologies for decreasing motor gasoline consumption. Moreover, high fuel efficient new technology vehicles must be supported to become status-quo quickly (hybrid credit). There must be a distinction between technology implementation which yields better-than status-quo FE versus same-as status-quo FE: e.g. mild versus partial/full hybrids. Furthermore, niche technologies which are worse-than status-quo FE must be the first to change to an alternative energy source.

(2) Status-quo Technology: The US must encourage all status-quo vehicles to decrease mass and engine displacement by perhaps 30%. This can be done using status-quo technologies (P/V) without sacrificing performance standards (P/M) when all technological advances from 1986 went into fuel economy in a proposed 2004 scenario. No new technological advancements are needed to reach a 35 mpg target.

(3) Missing Key Offered Vehicle: The US could develop, support, and implement a cousin to the Kei car, van and/or truck with a policy-based support mechanism equivalent to or stronger than what Japan implemented.

(4) Potential for a New Loophole: If the US wants to decrease greenhouse gas emissions and enhance security, then the US is obliged to watch carefully that the Reformed CAFE regulations do not create a new loophole: alternative fuels (e.g. Telsa's 244 mpg CAFE or the flex-fuel credit). In other words, upstream and downstream policy regulations must be implemented with or in conjunction with the Reformed CAFE regulations.

However, if these policy issues continue to be ignored, then the average fuel economy will continue to stay flat and all the technological advances will go into power as can be viewed in the figure below.

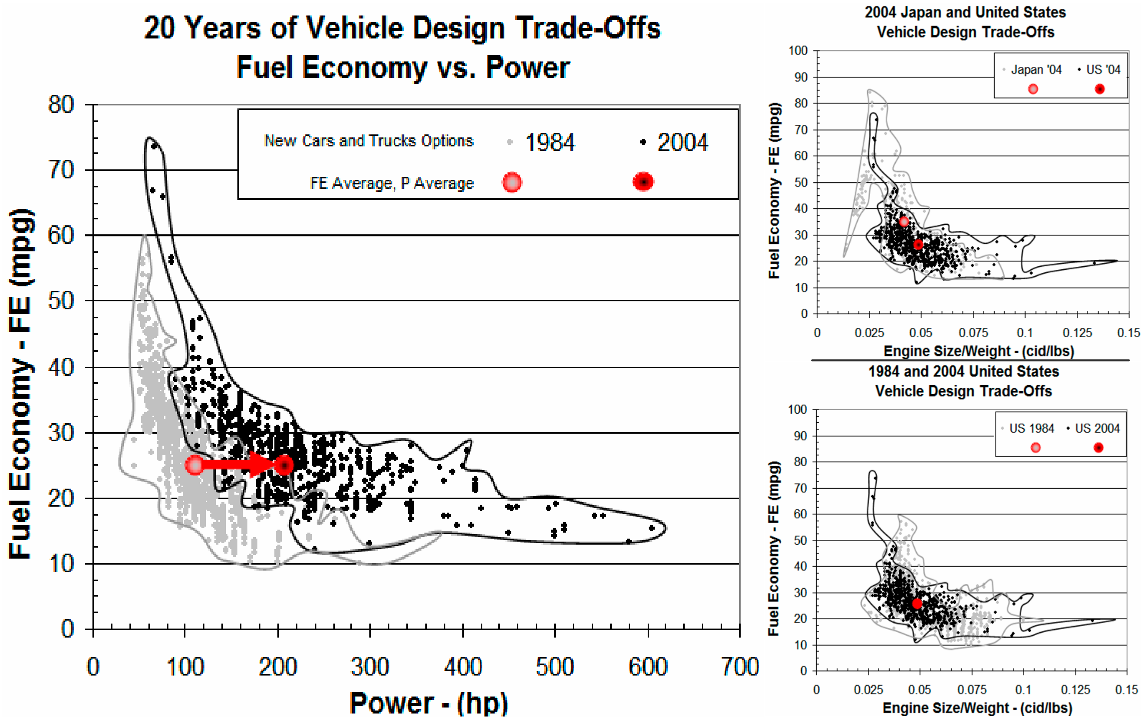

**Figure 35: US 1984 and 2004 new vehicle design trade-offs for light-duty FE versus Power. The red arrow highlights that technical advances went into increasing the power capability of vehicle designs. FE versus Engine Size to Weight ratio illustrates design differences from 1984 to 2004 and US and Japan.**

As illustrated in the figure above, after 20 years of vehicle design trade-offs between fuel economy and power, the average fuel economy did not change (note: not sales weighted here) while the average power dramatically increased. Pointing again to the Japanese Kei car, van, and truck, the average fuel economy in Japan is greater than the United States even though these vehicles are heavier than what US manufacturers design in terms of average P/M. Whether one looks at performance or engine size to weight ratio, the conclusion is the same, fuel economy did not change after 20 years of engineering technology feats. There is an issue which must be noted here that deals with light weighting vehicles: risk versus vehicle weight.

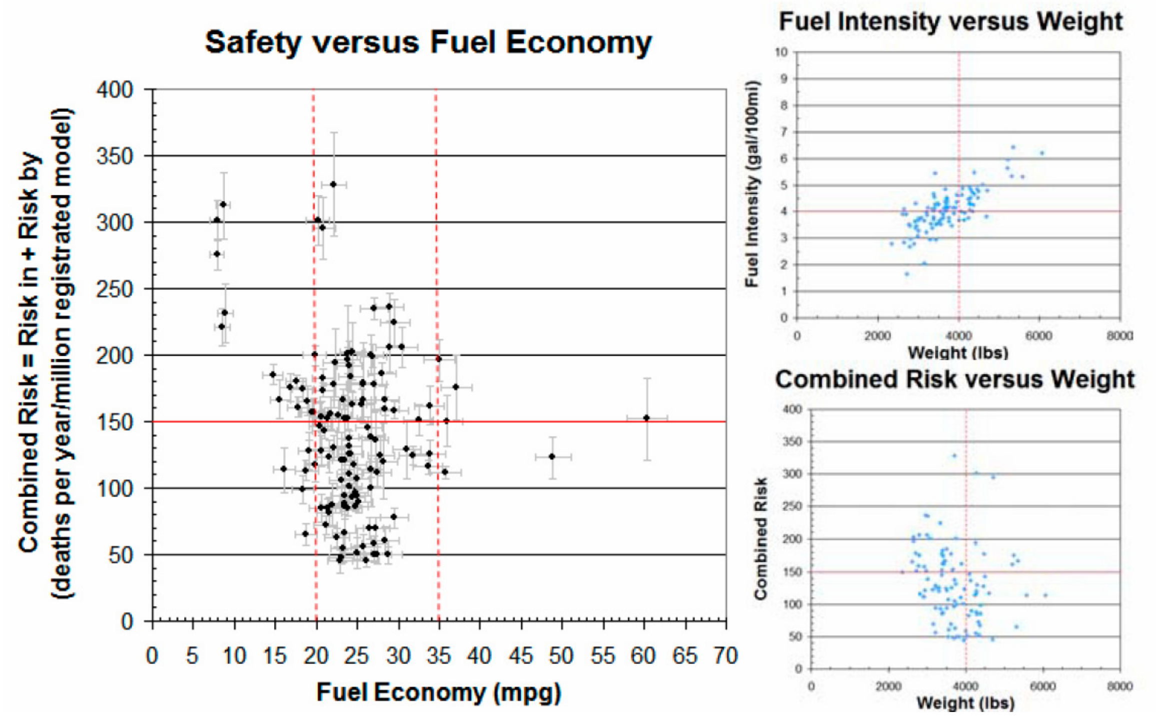

**Figure 36: "Combined Risk" is driver deaths per year per million registered vehicles of a specified model [9], combined with driver deaths in all vehicles that crash with the subject model. Fuel intensity (and its reciprocal, fuel economy) correlates strongly with curb weight. But combined risk correlates poorly with weight.**

For years, many researchers, including the National Highway Traffic Safety Administration (NHSTA) and the Insurance Institute for Highway Safety (IIHS), have argued that low mass vehicles pose a safety risk for their occupants. However, in Figure 36, the combined risk for the driver in the vehicle and the driving hit by the vehicle doesn't correlate with the weight of the vehicle. That is because as the risk of one vehicle may increase, the other vehicle decreases. Or if all vehicles weighed the same, then weight is not a dominant factor for risk. Consequently, it is vehicle compatibility which determines the risk in vehicle-to-vehicle collisions and not the weight. Light weight vehicles can, and have in many cases been designed to protect their occupants, as seen by Ross and Wenzel.

Ultimately, sustainability is defined here in a very simply form; as decreasing the United States' gasoline consumption. If in ten years the Reformed CAFE policy only decreases the growth rate, then the US will have made progress, but not addressed the real issue: greenhouse gas emissions and/or energy security. The next section deals with whether or not the Reformed CAFE regulations will meet 1990 levels of motor gasoline consumption.

### 3.5B US may not decrease Motor Gasoline Consumption to 1990 Levels

In the previous section, the discussion focused around manufactured designs of niche and status-quo light-duty vehicles. Here there are three additional pathways to reduce motor gasoline consumption: on-the-road fuel intensity, vehicle miles traveled, and changing energy source (Figure 37). In 2009, the United States' best-case scenario for 2020 will not reach 1990 levels much less the Kyoto Protocol target of 7% decrease from 1990 levels, given the current Reformed CAFE framework.

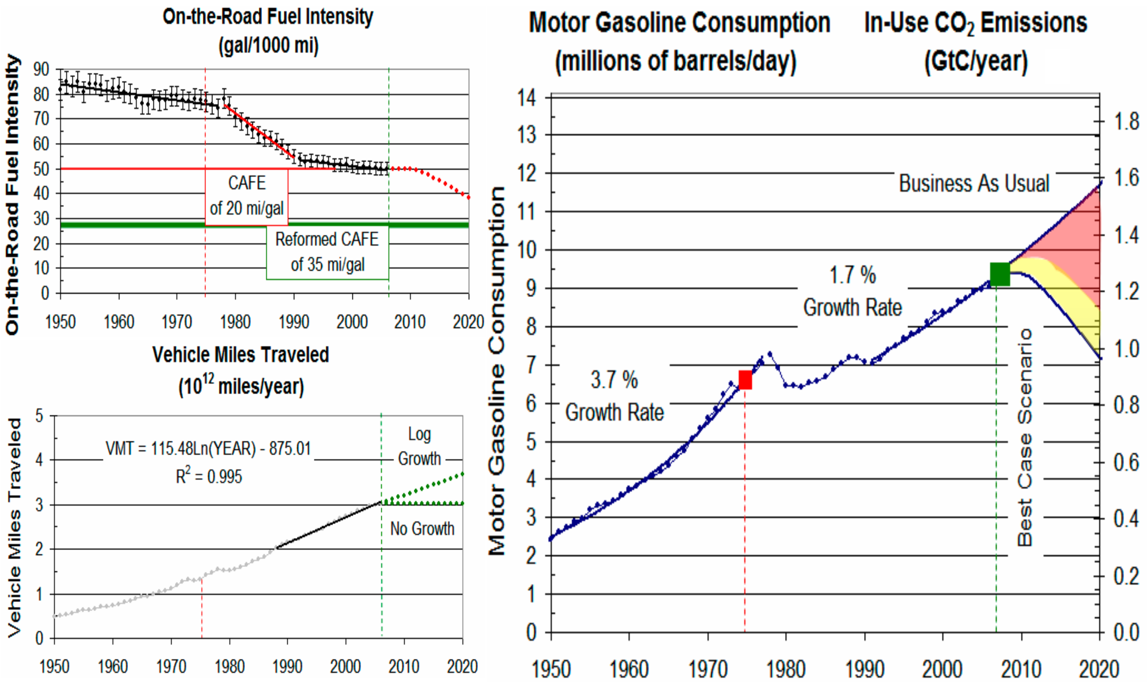

**Figure 37: US On-the-Road Fuel Intensity, Vehicle Miles Traveled (VMT), and Motor Gasoline Consumption since 1950 and projected into possible scenarios for Reformed CAFE impacts. The red dotted line is 1975 -adoption of the CAFE standards. The green dotted line is 2007 - adoption of the reformed CAFE standards.**

With CAFE only focusing on new light-duty vehicle purchases, On-the-Road Fuel Intensity gradually reached 50 gal/1000 mi or CAFE’s fuel economy regulation of 20 mi/gal between the years 1990 to 2000. With the Reformed CAFE regulation, the influx of new vehicles into the fleet will be dramatically less. Moreover, due to the time lag, nothing will be implemented until after 2010. Furthermore, regardless of what vehicles are purchased or what vehicles are on-the-road, how many miles consumers drive is also a key factor. In the scenarios presented, a log growth rate and no growth rate was considered. Regardless of the permutations one takes, the Best Case Scenario does not reach 1990 levels of consumption by 2020. Thus without serious political motivations to drastically change the mechanisms of our light-duty vehicle transportation sector, nothing will be done. There was only one time in history this was achieved and that was following the 1970’s oil crisis.

### 3.5C United States must Diversify the Vehicle Powertrain to Avert an Energy Crisis (Chapter 5) or Face Energy Crises (Chapter 4)

The United States is not on a pathway to avert an energy crisis based on an analysis of 1986 and 2004 niche and status-quo manufacturing of light-duty vehicles as well as projections of motor gasoline consumption. In Figure 35, there is a key point which might have been missed and that is the average manufactured vehicle’s fuel economy is higher than CAFE’s fuel economy. This means that customers choose to purchase lower fuel economy vehicles offered to them by manufacturers and this offering and purchasing dual decision pushed the average down. So, if the government cannot pass more stringent laws and manufacturers cannot sell higher fuel economy vehicles and customers cannot purchase high fuel economic vehicles based on their preferences and what is offered, then the United States is at an impasse. Here I propose that it is our culture which is flawed. Unlike Japan and the European Union who have site-based constraints which are potentially forcing them to be more sustainable, it is the United States which must diversify its vehicle powertrain to avert another energy crisis. However, it will be difficult to do that without understanding what an energy crisis looks like. The next chapter illustrates what weekly and monthly energy crises are.

# Chapter 4. Uganda Electrical Energy Crises

Motivated by Dr. Gro Brundtland's research and work, a particular quote resonated in this research, "Above all we must be uncompromising in our determination to eradicate poverty". A large component of global poverty is defined within the context of human development. The Human Development Index (HDI), as defined by the United Nations Development Programme (UNDP), is a gross measure of human development. It claims that economics, education, and health should not be separated and therefore are combined into a single index. Figure 38 indicates that extreme electricity energy consumption does not lead to greater development beyond say 0.90 (denoted by red dotted box containing extreme electricity consumption data points).

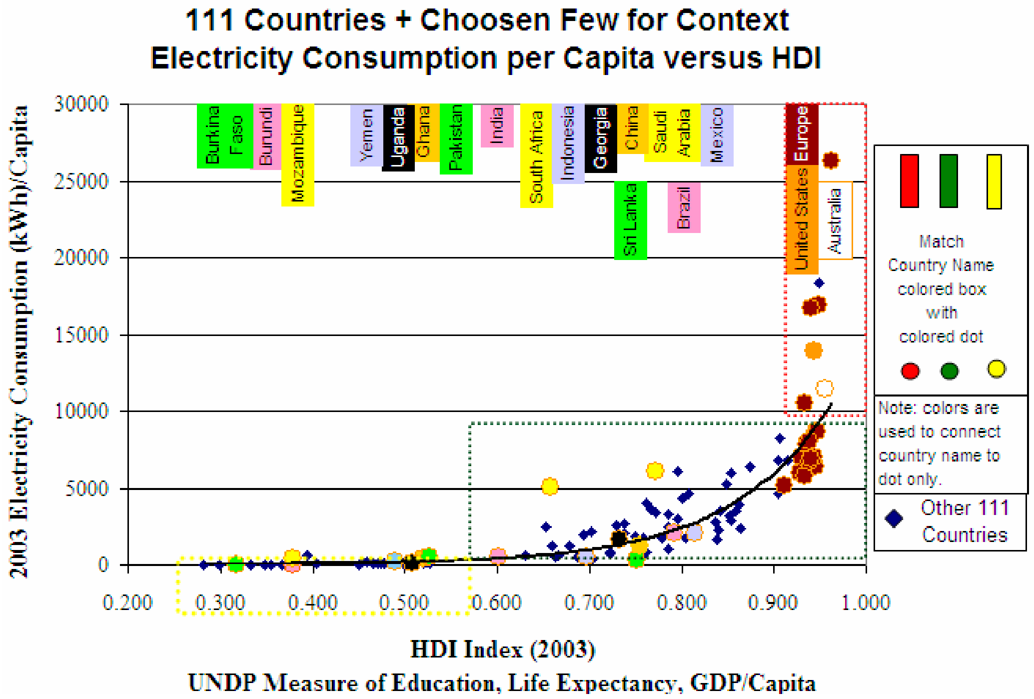

**Figure 38: Exponential correlation of electricity consumption and UNDP's human development index**

Focusing on the extreme[9] electrical energy consumption box overlooks the yellow and green electrical energy consumption boxes. The yellow box, in particle, arises from unavailable and unreliable electricity. Moreover, the correlation between electricity consumption per capita and HDI is exponential (line drawn black – $R^2$ of 0.85).

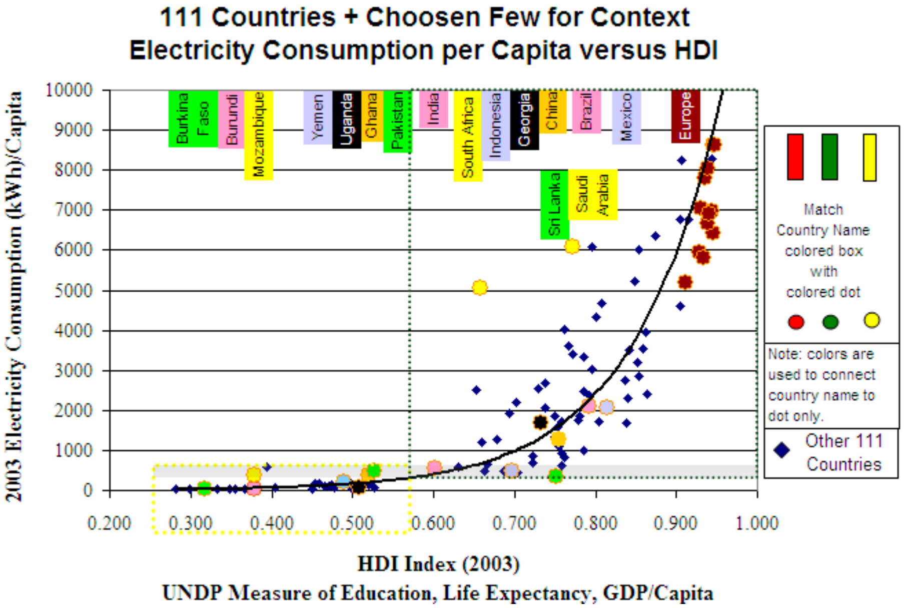

**Figure 39: Exponential correlation of electricity consumption and UNDP's human development index for the two regimes**

The interpretation of this exponential correlation is that growth at low power - even human power (31 kWh/capita for 2003) - could bring a tremendous amount of growth improvement in human development and should be studied more closely in terms of local manufacturing. For example, the extreme electricity consumption area (red box) is discussed as a saturation effect by Martinez and Ebenhack [67]. However, whether a physicist describes the policy implications from an exponential function or a chemist uses a saturation effect, the policy issues discussed in this chapter are that (1) the three different regimes should not address their energy issues necessarily identically and (2) an extremely small amount of power in the lowest regime can bring about (a) tremendous development in terms of using electricity to increase the efficiency of human activities and (b) development in terms of increasing reliability and availability of electricity in hospitals, schools, and businesses.

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[9] Extreme in the sense of country's average electrical energy consumption.

In section 4.1, this dissertation presents ethnographic results of how electrical energy crisis events occur in an Ugandan hospital and how lack of electrical availability creates Ugandan independent power producers (IPPs) private business. The power management strategies of the hospital have a direct impact on peoples' health. Due to the unreliability of electrical energy there have been cases of deaths in surgery (theatre) and delivery wards. The power management strategies of the IPPs illustrate the local knowledge of economic efficiencies (balancing consumer demand and supplying power). Finally, a brief discussion of a merry-go-round generator highlights the innovative solutions possible with human power that complements the back-up hand-crank surgical lighting system and the tv/cell phone charging bicycle generator.

In section 4.2, this dissertation presents qualitative results of a set of locally co-designed and built electrical energy generating devices in Fort Portal, Uganda. These devices were co-designed and built in conjunction with a Physics and Business of Energy curriculum implemented by me and Professor John Vianney Makanda, of Mountains of the Moon University. There are five electrical energy producing devices co-designed and built with local technicians at a technical institute using only locally available materials: bicycle generator, merry-go-round generator, hand-crank surgical lighting system, wind generator, and micro-hydroelectric generator.

In section 4.3, a brief critique of the current microeconomic situation is given in terms of the capitals costs versus the social benefit costs for these five electrical energy generation devices. Here I argue to support a hybrid economic system which Mohammed Yunnus argues for in his book, Creating a World without Poverty [74]. The 2003 approximate value of a statistical life (VSL) in the United States, around \$6,000,000, versus in Uganda, around \$150,000, illustrates how this affects the value of a back-up surgical lighting energy system for a Ugandan hospital. Thus the tension of inequity surfaces in terms of what money is available to build these devices versus the value of human development.

Together education, health and economics are weaved into a telling case of how human development and energy co-exist and interact.

## 4.1 Ethnographic Results of Electrical Energy and Crisis Events

The most successful researchers who immerse themselves into a different culture are anthropologists. They study the interactions of people and their environment with high degrees of reliability and validity using qualitative methods first, and then, building upon that work with quantitative analysis. Scientists and engineers, on the other hand, have consistently entered a new culture with their own values (norms, roles and relationships, etc.) and tend to immediately investigate quantitatively, especially focusing on technology to solve human development issues. In this paper, I illustrate how a scientist can and should start with qualitative methodologies as a framework for subsequent quantitative research to investigate the question, “How are electrical energy consumption and human development interdependent?” Throughout this work, I begin to understand the role that assumptions play in energy system analysis for hospitals, schools, and businesses. Assumptions of our energy system models, for example availability of human power for electricity generation, can be more important than the energy systems quantitative calculations themselves.

According to H. Russell Bernard’s book on Research Methods in Anthropology: Qualitative and Quantitative Approaches, there are five categories of fundamental variables used in anthropological research:

1. Internal states. These include attitudes, beliefs, values, and perceptions. Cognition is an internal state.
2. External states. These include characteristics of people, such as age, wealth, health status, height, weight, gender, and so on.
3. Behavior. This covers what people eat, who they communicate with, how much they work and play – in short, everything that people do and much of what social scientists are interested in understanding in the first place.
4. Artifacts. This includes all the physical residue from human behavior – radioactive waste and sludge, tomato slicers, arrowheads, computer diskettes, penis sheaths – everything.
5. Environment. This category includes both physical and social environmental niches and characteristics. Amount of rainfall, amount of biomass per square kilometer, presence of

> socioeconomic class indicators, location on a river or ocean front, political 'climate,' and so on.

For example, using category three, we can examine the case of a University of Michigan master's thesis group with whom I worked [69]. Their project optimized the community multi-use pavilion electrical energy generation based on a Ghanaian village's ability-to-pay. While in Ghana, this group was thrilled to have so many interviews of villagers' willingness-to-pay and ability-to-pay for this multi-use pavilion. However, when they got back to the US to study the quantitative results, they realized the willingness-to-pay was much higher than their ability-to-pay for electricity. Furthermore, the researchers optimized for an energy system based on the villagers' stated willingness-to-pay and ability-to-pay which resulted in a 100W solar photoelectric (solar PV panel) system (this village had 1,165 able-to-pay men, but only 100 villagers at a time could use the multi-use pavilion). All of the researchers' conclusions and policy implications were based on the energy software tool they used which did not include human power. The group did not include human power as an option because the software program they used did not give that as an option. An energy system analysis algorithm which is based on developed world assumptions or paradigms may fail to provide the most realistic results for developing world real-life conditions. In this example, a 100 Watt hybrid energy system of a bicycle generator based on human power (50 W – with on demand capability) and solar PV (50W – no human power needed) would be cheaper, use the same electrical system (storage to battery), and the bicycle generator could be locally built meaning that the operation and maintenance is easier to sustain. An investigative methodology that incorporates anthropological research techniques allows energy system solutions to emerge from ethnographic research which will build the foundation for quantitative simulations in future research.

With this in mind, I began my qualitative investigation. In general, this qualitative research focuses on observed response to grid unreliability (Category 3), on observed cognitive abilities of local technicians (Category 1), and an artifact analysis of electrical energy devices used in hospitals, businesses, and schools (Category 4)[10]. Specifically, these observations led to my theory that some developing countries have what they need to design and build their own energy producing devices[11] (a) to decrease the number of energy crisis events in hospitals and businesses and (b) to increase the availability of electricity to schools and villagers. I applied this qualitative hypothesis to a technical school in Uganda and was successful in terms of local technicians designing and building five energy producing devices based on all locally available equipment and expertise. To take this to the quantitative level or reproducible results, an association and/or the government of Uganda would need to implement this empowerment curriculum throughout the technical school system and answer the following questions: (1) do the cognitive abilities of other technical schools match this first technical school, (2) are the same energy crisis events and lack of access to electricity situations occurring such that there is a market for such devices, and (3) are the same materials used in this first technical school available at all the technical schools?

In general, developing countries are known to continue to keep equipment working when developed countries throw away the old device. For example, in Uganda there exists a local technician job called a rewinder. The role of this person is to rewind broken generators. The expertise exhibited by these technicians was beyond my expectations or imagination. But before getting into specifics, I want to discuss the pathway from ethnographic investigations in Ghana to Uganda.

### 4.1A Reliable Hospital Energy Systems and Medical Equipment

Traveling through Ghana and Uganda, I visited and investigated three regional hospitals and ten health clinics. I always received permission to look at medical equipment from the director or CEO of the hospital or health clinic. At all three hospitals, I interviewed

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[10] See list of categories taken from anthropology textbook cited.

[11] However, they might benefit from a physics and business of energy curriculum which encourages co-designing and building these electrical generation devices within their technical school curriculum.

the engineer in charge of keeping equipment functional and in charge of the reliability of the electricity[12]. Working with these engineer technicians, I was able to create a logic chart of how back-up energy systems worked as well as an understanding of the medical equipment available and used (with approximate power consumption noted). The two most interesting findings from this investigation are (1) medical equipment donated by developed countries are often electric even when some of this equipment does not need to be and (2) back-up energy systems to the electric grid are not 95% reliable and therefore surgery has crisis events every year when the grid and back-up system both fail. This can and does lead to crisis events for doctors and patients resulting in the inability to provide certain key services and in extreme cases can lead directly to the death of the patient. Furthermore, when interviewing the CEO and surgeon at Virika hospital, located in Fort Portal, Uganda, as well as the in-charge nurses, I presented the United States 1970's energy crisis images and asked them: (1) How does this energy crisis compare to their current energy crises? and (2) What images would they present to the world as their weekly and monthly energy crisis? (More on this below).

Working with Detroit's World Medical Relief (WMR) non-governmental organization (NGO), I interviewed volunteer technicians. WMR's mission is to take donated medical equipment from US hospitals and organize shipments to hospitals and clinics around the world. The technicians interviewed stated how they are careful about the anesthesia machines they choose to send out to developing countries. One of the worst things that can happen during surgery is for the patient to wake-up during surgery (usually in pain). When old anesthesia machines are donated to WMR, many are purely electrical. Thus when the electricity goes off, they do not work. Overall, it is WMR's goal to not send these out to developing countries. However, sometimes visiting health professionals are in such need that they ask for these machines despite the risks. In general, WMR technicians tell them to wait until a machine with a back-up manual mode is available; however, these are harder to find these days. I was asked how to create a simple method

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[12] The reliability of the electrical systems at the hospitals means being in-charge of the back-up systems to the electrical grid. The electrical grid is usually unreliable.

to retrofit the electrical machines to have a back-up manual mode. I hope to develop that project as part of my future research. The challenge of providing appropriate medical devices in areas with high electrical unreliability and/or availability remains acute.

Both in Ghana and Uganda, I collected many stories about being in theatre (surgery) when the electric grid goes off. One heart breaking event occurred at the teaching hospital in Kumasi, Ghana, where during an open heart surgery the grid went off. It takes minutes to have the back-up diesel generator trip on (due to the fact that the surges from the grid sometimes blow out simple triggering circuit mechanisms). In the middle of this crisis, the nurse got out the back-up flashlight only to find the batteries were dead. In this case doctors were unable to complete the surgery successfully and the patient died. In Uganda, I came with a hand-crank flashlight to illustrate to the technicians how to build one. We took it apart, but then the in-charge nurse in theatre asked to have it for surgery. Hesitantly, I gave it. It has already been used many times. Consequently, I began working with University of Michigan's M-Heal student group to design surgical lighting back-up systems [77]. We built the first alpha prototype and brought it to the Ugandan technicians. Not only did they re-design and build it with local parts, the technicians designed and built a hand-crank back-up energy lighting system. It incorporates three LED torches which can be charged from the grid or charged from the hand-crank generator. The fact that this device is (and these devices are) locally created is vital to their chances of being maintained.

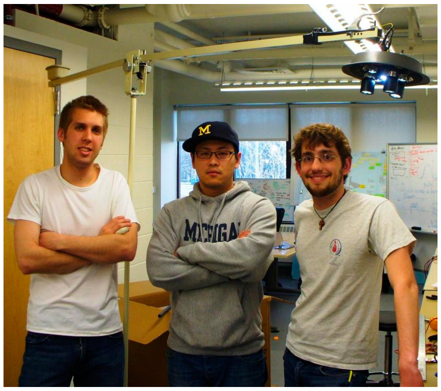

**Figure 40: M-Heal Surgical Lamp Design brought to Fort Portal, Uganda**

This problem appears to be wide-spread and even organizations devoted to assisting the developing world face this issue on a regular basis. For example, no matter what projects I investigated from Engineers Without Borders (EWB), I could not find examples where local technicians were engaged to co-create designs. To date, I have met few who believe the technicians have the skills and resources available to create their own devices (and in this case does it better). Because of this, project after project and device after device is imported to Uganda and used until it breaks. Once it breaks, if the part cannot be found or easily (i.e. cheaply) fixed, the device becomes useless.

Besides surgery, oxygen concentrators are devices nurses worry about constantly. Due to the lack of readily available oxygen tanks, these concentrators are essential. However, they break down frequently and they are electric. They should have a back-up manual mode, but many do not. These machines were donated from developed countries where electricity is reliable, but here it is unreliable. Thus patients are at a risk of unnecessarily suffocating due to lack of oxygen. It is a very hard situation for nurses and these interviews were tearful for both of us. The surgeon at Virika Hospital told me that the worst case of an energy crisis was when an infant died because the oxygen concentrator did not work without electricity. Again these sample ethnographic stories suggest the need for quantitative investigations of the frequency of these events. Currently, the World Health Organization and the Millennium Development Goals do not include electrical energy as a key ingredient to development and decreasing deaths [70, 71].

While lighting is important for surgery, education, and business, it is also important for the delivery of children. In another example, in Uganda, the electric grid went out right after an episiotomy. When the doctor tried to sew the mother up, he could not see well with the inferior solar lighting back-up system. As a result, the needle meant for the mother was inserted into him and since the woman has AIDS, he has a higher probability of contracting AIDS from this unnecessary event. Furthermore, lighting is important for administrating drugs in the form of shots. Several nurses relayed stories of these events. For example, one patient ran away from the hospital when the grid went off because at least at home she had a torch (flashlight). The nurse said to me, “My image of an energy crisis would be giving a shot to a patient in the dark” and explained how no one teaches you how to do that!

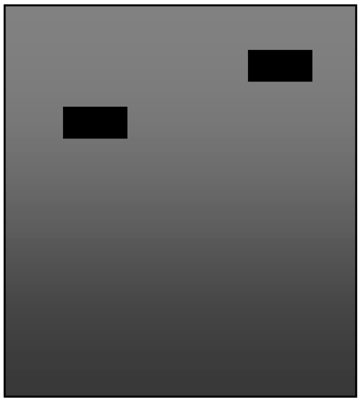

**Figure 41: Nurse's quote, "My image of an energy crisis would be giving a shot to or taking blood from a patient in the dark" and explained how no one teaches that!**

In Uganda, there were many stories of decreases in hospital performance due to grid outages and/or maintenance on the diesel generator. From the x-ray machine to the autoclave (which are both too powerful for the back-up diesel generator), there are incredible inefficiencies to the health system and overall care of the hospital. For example, at Virika Hospital, patients are asked to choose between waiting for the grid to turn back on or to be transferred to another hospital for an x-ray (if it is possible to be transferred and there are cases when they cannot be transferred). In another example, if the grid has been off for a long time, then Virika has to pay additional money to contract out sterilization. This is not only costly, but also requires transporting all the equipment to another hospital and back. Moreover some health facilities resort to sterilization with traditional coal fired stoves. At University of Michigan, the hospital does not sterilize any of their equipment – it comes pre-sterilized. Although the electricity issue plays no real role in this decision, sterilization is a time-consuming process even with electricity working like clockwork.

At health clinics, the same types of stories emerged, but two new ones surfaced. The first was that solar panels are stolen in remote places where security guards are not present. Therefore, many hospitals and health clinics in remote places have to provide security guards to protect the electricity generating equipment. The second was that when the weather is cloudy and/or rainy for days or when the electric grid goes off for days, then refrigerators do not work and everything has to be thrown away: blood, medications, and vaccines. Since shipments do not come frequently, this can be a great cost and burden to the medical community.

Given that electricity is vital to health care and given the above set of key appliances which require electricity, one can imagine the possible complexity of back-up energy systems which emerge when a primary diesel generator fails. At Virika Hospital, this happened after having the new diesel generator for only seven years. Doctors, nurses, and staff told me that generator failures happen frequently at hospitals and health clinics because people run the generator too long and it overheats. Although David Kline at the National Renewable Energy Laboratory (NREL) told me that some researchers have tried to hybridize the generator with batteries, electric grid spikes in developing countries are known to blow up circuits which are not well protected. The x-ray machine at Virika has a protection system which costs more than the x-ray machine itself. Figure 42 outlines Virika's stage-one electrical energy system.

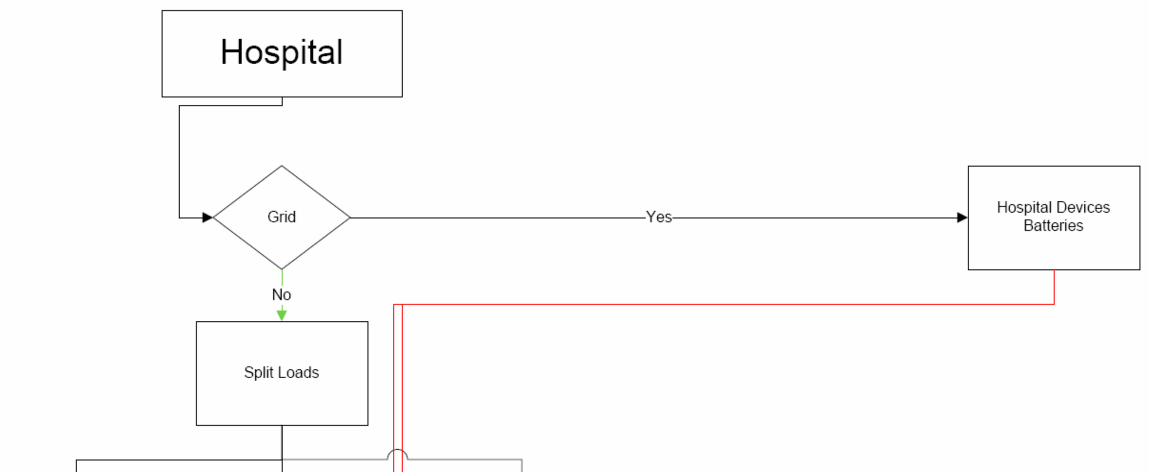

Figure 42: Energy Logic for Back-Up Systems

Figure 43 outlines Virika's seven back-up energy systems:

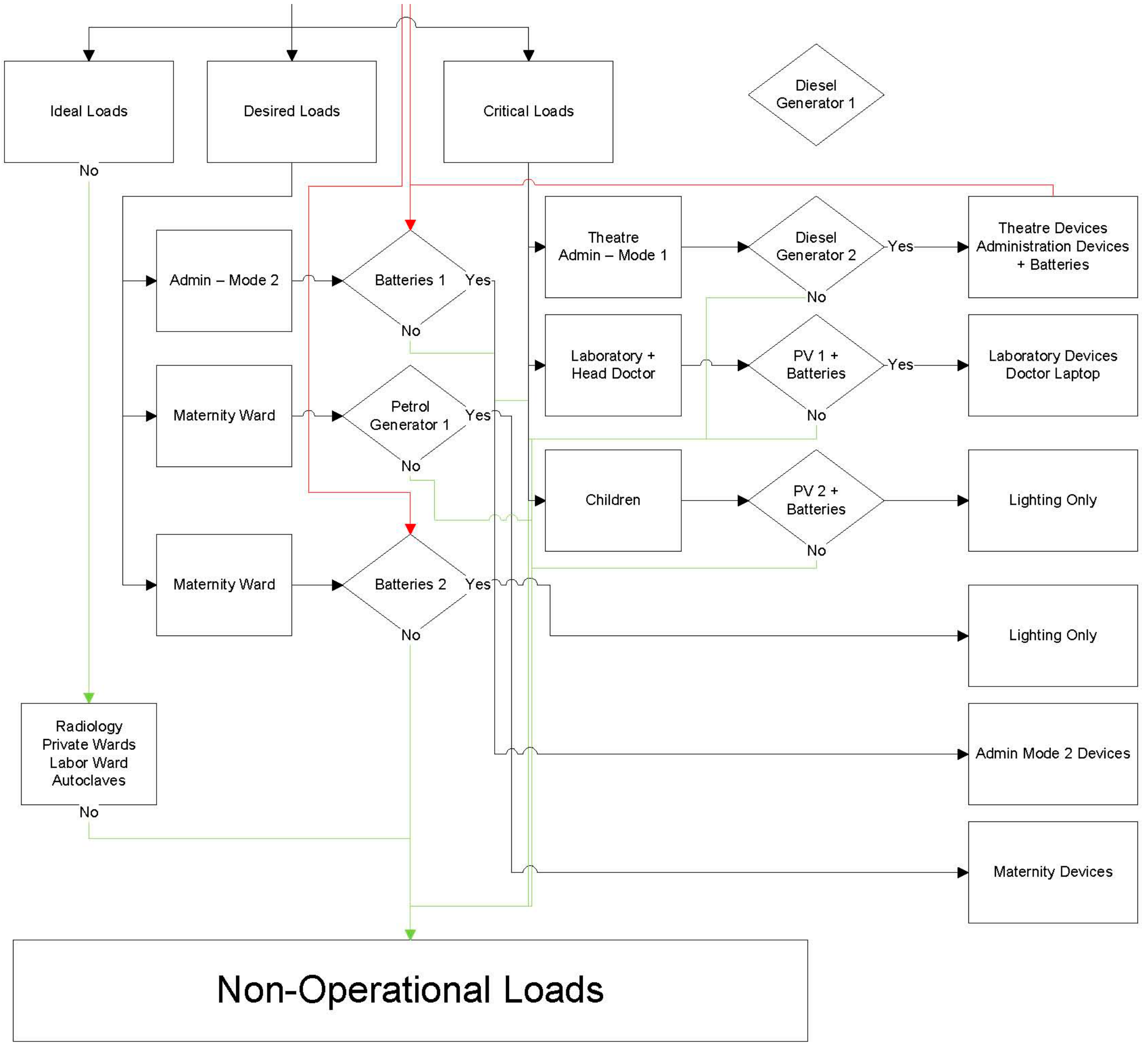

**Figure 43: Multiple energy back-up systems depending on health care prioritization.**

Unless a hospital has a donor or serves the wealthiest in the country, it cannot afford an energy system which supplies electricity to all parts of the hospital when the electric grid goes off. Consequently, in the case of Virika, when diesel generator 1 (which was donated) broke, the hospital tried to have local technicians called rewinders fix it (by rewinding the coils), but the system had too many kinks and turns to rewind it reliably. This is because the generator was designed with the top-of-the-art technological manufacturing capabilities for increased efficiency. If an older more common generator had been donated, then the rewinders would have been able to fix it. Consequently, the hospital has developed three medical prioritization levels for what services have back-up energy systems and what services do not. The three medical prioritization levels are categorized in my dissertation as **critical**, **desired** and **ideal**.

Before examining these issues, there is one more story to tell highlighting the motivation for creating a methodology for locally designed and built energy producing devices. As noted above, when the new 68 kW diesel generator broke due to overheating (running it for too long without allowing it to cool down) and the rewinders could not fit it, the only diesel generator the hospital could afford was a 9 kW refurbished generator for $7,000 (USD or 12,000,000 UgSh). When I asked what the first generator would have cost to replace, no one knew. So, I called the manufacturer and after two weeks of constantly going back and forth with questions about which generator we had and what was broken and how much it costs to ship with insurance, I learned that the total cost would also be $7,000 USD. Knowing this result helped me understand the issues of how important operation and maintenance is in Africa. One might determine to replace it with the new imported technology, but if every five years the electric grid is out for so long that one melts the wire insulation, then it is better to have an old generator which can be rewound relatively quickly, effectively, and efficiently. For example, another Ugandan hospital, the Kumi Hospital, had a situation where their technician said they have to turn off the generator for a couple of hours (the electric grid had been off for a long time). The hospital director said he knew that people on electric oxygen concentrators would probably die, with the children being at greatest risk. He made the hard choice and turned it off[13]. I will return to this discussion in Section 4.2.

**Critical Level Category**: This category consists of what the hospital administration has deemed absolutely necessary for the functioning of the hospital. At Virika, this is two-fold. First, the theatre (i.e. surgery) and the administration building were given the single phase 9 kW diesel generator for all their electrical devices. Second, a set of wards were given solar panels with batteries for lighting only. All of these devices are expensive in

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[13] I have been working on a design to hybridize the diesel engine generator with batteries to automatically turn it off, but many hospitals (including Virika) do this. The problem is that batteries cannot typically run all the AC oxygen concentrators and they choose to leave batteries for emergency DC lighting.

terms of capital costs. The diesel generator is expensive in terms of operation and maintenance (O&M), but the solar panels have low O&M costs. This will be explored further in future research.

In terms of surgical cases, there have been situations where the electricity went off and then the generator had to be turned on (as told below).

> Out-Patient Department (OPD Ward): The only lighted lantern in OPD was in an examination room, when a man dressed like a night watchman approached the nurses' station. The two nurses on night duty, thought he was a watchman, but he had fallen from a tree and had sustained an internal injury. No sooner had he been examined power came back, and on closer examination it was discovered the man had internal bleeding and was going into shock. The theatre staff was informed, but power went off before he was taken to theatre. The night nurse supervisor called on the person responsible for the generator to switch it on, which she did and the man was operated on, he had a bust spleen the following day he was referred to a national hospital, since his relatives were in Kampala.

A related story is that of two women who were transferred to Virika hospital at 2:00 am for a c-section. In this case the generator was repaired and the two women and their children survived. These cases illustrate that even with a back-up system in place, electrical reliability can remain low enough for unplanned risks.

There are still about 7% energy crisis events where both the grid and back-up system are off. In the case of Virika, these events have been captured with Hobo power load monitors. I installed these monitors to design and build energy system solutions for the hospital. However, the data which emerged qualitatively has made me strongly reconsider the typical assumptions I would make for a developed country energy system design. The rest of this story (including the graph below and the next two categories) illustrates that it is not enough to design a system, but to design one which is reliable.

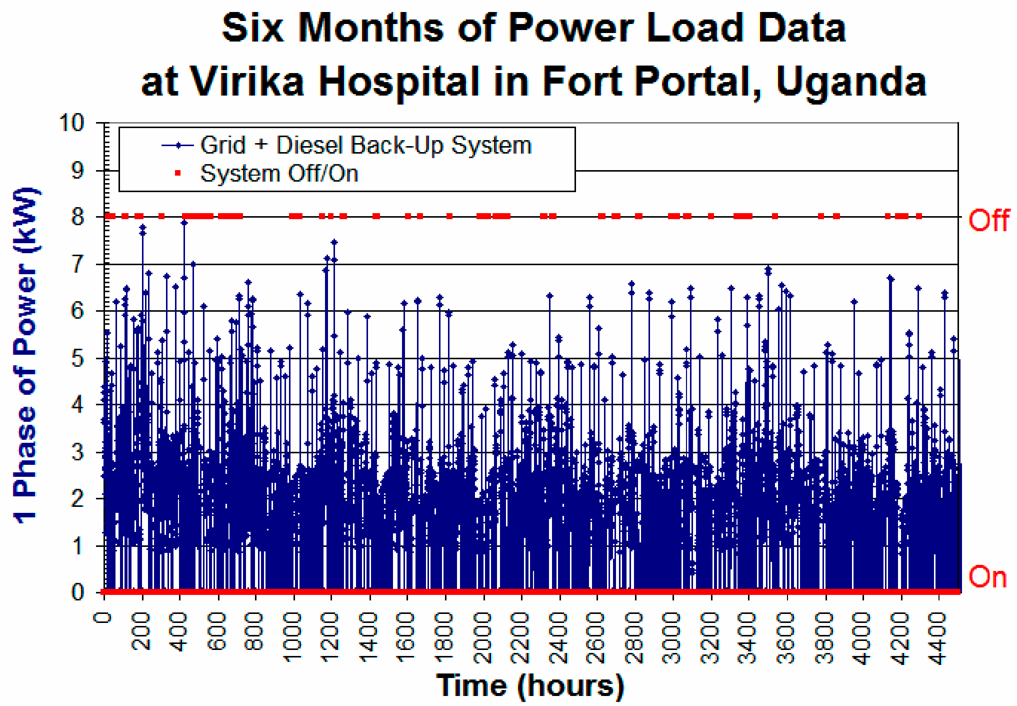

**Figure 44: Virika Hospital crisis events during surgery (5% unreliable even with back-up diesel generator).**

Each one of these events was about 30 minutes in length. An unreliable event is no voltage, no current, and no electric power at all for 30 minutes. A simple solution before surgery is explained by the following case:

> Surgical Ward: Name: ###, Age 3 years old, from Kyenjojo District came in with intestinal obstruction, severe dehydration and malaria. Laparatomy was done on the day of admission. He was received from theatre at 9:00 pm. Post operative observations were being taken when power went off. The nurse had to stop taking observations and started lighting a paraffin lantern; she resumed the post operative care after five minutes.

However, during surgery, back-up flashlights were used to quickly close the patient.

**<u>Desired Level Category</u>**: This category consists of what the Virika Hospital administrators can squeak out for known energy crisis events. For example, the earlier explained energy crisis events that happened at night in the medical wards which meant that some wards have inverters charging batteries when the electric grid is on and use the batteries for lighting when the grid is off. However, these batteries are not solar (100 Ah

– marine deep cycle batteries), but rather car batteries (25 Ah – shallow cycle). Here I learned that the acid is typically poured out into the local soil and new acid is purchased from a local store (sometimes once a month, but at least one a year). The environmental effects of this behavior must be seriously considered and evaluated in future research. Furthermore, these batteries are used on a DC circuit with compact fluorescent lamps (CFLs). However, when these CFLs are disposed of, mercury is released into the atmosphere and since the energy comes from the hydroelectric dam (not a coal fired plant, as in the US), the typical argument of environmental benefit does not apply. This led me to modify local LED torches (i.e. flashlights) to be used as back-up lighting for environmental reasons and because they use less electricity than CFLs. The following is a story of the batteries (from the inverters not having enough charge):

> Maternity Ward: Name: ###, Age 36 years came in approaching second stage of labor. The inventers had gone off since electric power had been off for three days. The mother had been in a regional hospital, and when her relatives realized she in too much pain they decided to bring the mother to Virika hospital. The mother had to deliver on her way to the labour ward. It was total darkness, the nurse removed a lantern from the postnatal ward and rescued the mother. The relatives refused to be admitted, since their mother had delivered before they were given a bed. The midwife explained to them that, the mother had to be examined as well as her baby before they go. She also managed to convince them to stay until morning since it was too late and dark at night for safe travel.

The problem with an energy crisis is that the normal laws of engineering design do not always apply. I read a similar story about the AMD Foundation setting up a school with inverters and batteries, but the system was not sized properly because the grid was so unreliable. As a result, the teachers kept turning the system on and off because they thought it was broken. Every time they turned it on it would run for 10-15 minutes. However, what they did not know is that for these batteries the state-of-charge (SOC) should not go below 20%. When they repeatedly activate the batteries, they are destroying the lifetime of the battery. Consequently, these batteries did not last their expected lifetime.

**Ideal Level Category**: This category consists of what the hospital administration would like to have but cannot meet during an energy crisis event (electric gird goes off). Although there is a long laundry list of appliances which are not used, there are three key appliances they would like to have available. The first is lighting everywhere in the hospital. The second is the autoclave for sterilization. Although I recommend they turn off all appliances at night and run the 7 kW one phase autoclave when nothing else is on, I am not sure they will act on this recommendation. Instead they send their equipment to another facility when the grid is off for a long time. The third device is the three phase x-ray machine. This tends to cause the most performance disruption to the hospital in terms of delays. Some patients are transferred to another hospital or facility, but many simply wait until the grid comes back on in order to receive an x-ray. The following is a sample case:

> Out-Patient Department (OPD Ward): Name: ###, Age 22 years, Sex: M, Tribe: Mukiga, Village: Kiguma, Next Of Kin: ###, Plan: x-ray knee. ### was received in OPD, the doctor ordered an x-ray of the patients' knee. The nurse informed the patient that he has to go elsewhere for an x-ray or wait for the power to go on again.
>
> Questions from the Patient:
> Isn't this hospital big enough to provide a generator? Don't you think you are retarding the hospital? It is not the first time I have been told to go elsewhere, I thought services had improved! He continued, I am a company patient; will the hospital pay for transport and x-ray charges? Well, I will obey the doctor's orders and come back to Virika.
>
> Nurses observations:
> The patient expressed more worry and anxiety when he left than when he came. He even thought that the machine might not be functioning. The nurse had to explain that the x-ray machine is functional, but there is no power to enable it to operate. She further explained that power shedding is a national problem.

Sometimes in extreme patient cases, the patient is moved to the buildings with the back-up generator (when the patient can be moved). The following is a sample case of this:

> Medical Ward: Name: ###, Age 32 from Kyarusori was received in Medical Ward on 16/5/2008. He was a known asthma patient and had an attack with respiratory distress.
>
> He was to be given nebulised salbutamol, but there was no power in the medical ward. The nurse consulted the doctor who told her to take the patient to the x-ray department[14] since the generator was currently supplying theatre and that department.
>
> The nurse wheeled ### to the x-ray department with the tray of drugs and a nebulizer. On reaching the x-ray department the plug of the nebulizer could not fit the sockets. She changed rooms with no success, later an extension cable form the ultrascan room was used and she managed to help the patient and he improved and was discharged in good condition after two days.

In events where the oxygen concentrators cannot be used, the following is a story of what outcomes may result:

> Medical Ward: Name:### was admitted in medical ward with congestive cardiac failure. The nurse on duty positioned him in a cardiac bed and gave medication as prescribed by the doctor. He was to be put on oxygen therapy using an oxygen concentrator; the machine was connected and the therapy eased his breathing. No sooner had he started improving, the electricity went off. He started becoming dyspric again. Meanwhile one nurse had to run to children's ward to collect an oxygen cylinder. On reaching that ward the cylinder was already on another patient. A student nurse was sent to collect a cylinder from the stores. The cylinder was connected and care continued amidst lit paraffin lanterns with dim lights. He improved on treatment, but another child who was on oxygen in the children's ward passed away when the oxygen was exhausted.

One question is how many times events are recorded in the health community as to the cause of death being failure of the body (quit breathing) instead of the electricity turning off. However, this will require a new system of tracking causes of death due to medical complications which currently is not set up in medical facilities.

---

[14] However, only the ultrasound machine can be on. The x-ray machine is three phase and cannot be run on the 9 kW one phase generator.

There are only two missing medical appliances from this discussion, but it is imperative to discuss them because they are atypical. One is the quality of water and the culture of tea and the related need to heat water from an electric water heater or kettle. Due to water being unsanitary, there is a daily expense and electricity needed to boil water for drinking. When the electric grid goes off, this is done in the administration building and is a tremendous load (3 kW for approximately 30 liters) equal to all other appliances in the administration building combined. The other appliance is a 1-2 kW iron for ironing laundry used to wrap sterilized equipment. Both of these are common in medical facilities and these appliances will dramatically increase peak power loads if multiple heating devices are turned on at the same time (especially for off-grid health clinics). The use of these appliances, and potentially others, will be evaluated in future research for demand-side management.

### 4.1B Available Business Energy System Configurations

Working together with a business professor at Mountains of the Moon University, John Vianney Makanda, my colleague, Peter Muhoro, and I explored the energy availability issues for the approximately 90% of Ugandans who do not have access to electricity [25]. The two most interesting findings from this investigation are (1) IPPs are creating electric utility-like solutions for villagers and (2) these IPPs have become interested in the electrical energy producing devices designed and built by the technicians in Fort Portal. Furthermore, they are pursuing the business marketing capabilities of these devices, but these investigations will be included in my colleagues' work, Peter Muhoro.

Given that electricity is vital to cell phones and that cell phone demand is growing at a high rate in developing countries [75], one can imagine the complex energy systems which emerge to charge cell phones where overall access to the electric grid is only approximately 10% [25]. With one IPP, the solutions depend on the customer demand.

Figure 45 outlines this energy system[15].

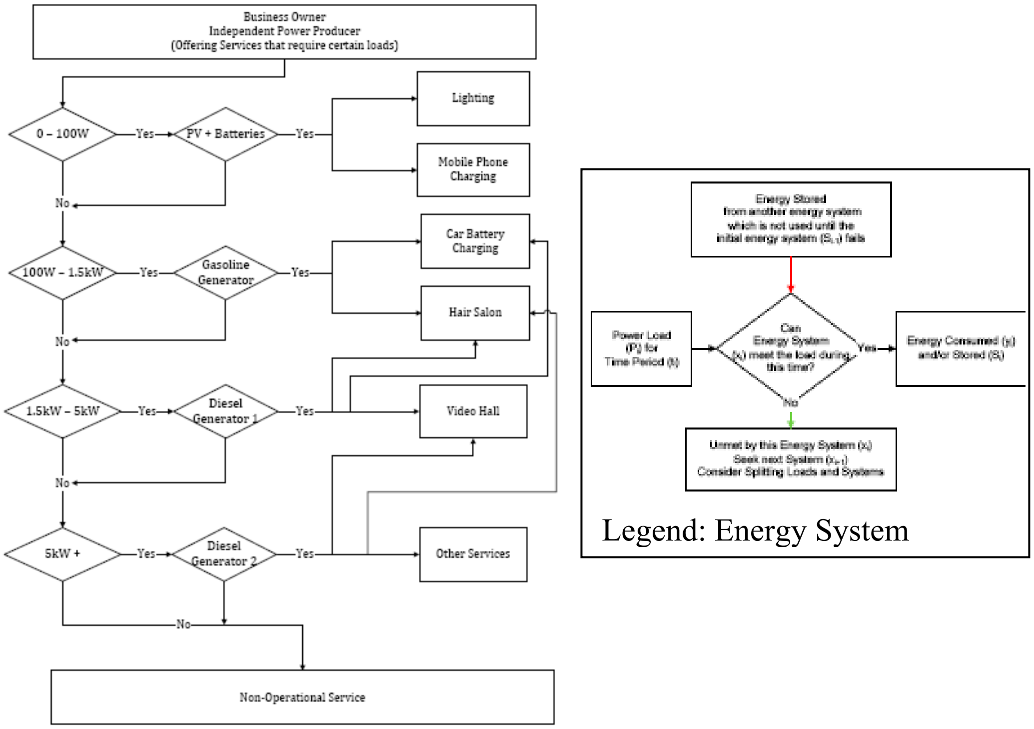

**Figure 45: Energy Logic System for an off-grid Independent Power Producer in Uganda**

For example, when a group of business customers come to the regional village (less remote, but not connected to the electric grid), then this businessperson analyzes what device or devices to use. After years of experience, the businessperson knows from experience that certain demands will mean the bigger diesel generator can be run and a profit will be made (i.e. revenue greater than the cost of operating the generator – fuel and O&M). However, other demands (like cell phone charging) are small and time consuming and should not require the diesel generator because not create enough revenue will be generated to pay for the fuel; thus solar panels (PV) are used. Since I could find no kWh meters, it was impossible for the first investigation to measure kWh for various charging services. In the second and third investigations, Watts-Up meters installed to capture this information caught on fire due to electric grid voltage instability.

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[15] Acknowledgement: Thanks to Peter Muhoro for collecting this data and working with me on a unified methodology. We will jointly publish this work in the upcoming months.

Consequently, at the time of this dissertation, I have only descriptive details of \$/kWh for two services: cell phone and battery charging. This service varies between 500 to 3,000 UgSh (or \$0.25 to \$1.50 USD) depending on the provider's energy source used (generator versus solar panel), time of day, and number of users. Considering that the energy needed to charge most cell phones is around 0.115 kWh, the price range for off-grid electricity is between \$2.17/kWh to \$13.04/kWh USD. To understand the significance of this, consider the following table [53]

| Calculation of Energy Needed for Cell Phone Charging | Cost for Cell Phone Charging | Uganda Off-Grid (\$/kWh) | Uganda Grid (\$/kWh) | US Grid (\$/kWh) |
|---|---|---|---|---|
| $P_{\text{cell phone: AC-DC}} = VI$<br>(240V)(120mA) = 28.8W = 0.0288 kW<br>$E_{\text{cell phone: AC-DC}} = Pt$<br>(0.0288 kW)(4 hr) = 0.115 kWh | 500 UgSh<br>1000 UgSh<br>3000 UgSh | 2.17<br>4.35<br>13.04 | 0.15<br>0.20<br>0.23 | 0.05<br>0.10<br>0.16 |

**Table 12: Due to the nature of high demand for low quantities of electricity (kWh), the pricing mechanism is quite variable, and high, for Ugandan off-grid services versus grid services**

Table 12 completely blew any expectations of electricity costing mechanisms in use in the United States for businesses. In general, the average cost is 1,000 UgSh or \$4.35/kWh for a cell phone charge. When the charging time is 2 hours, the costs will be more than double for the same service. However, one innovative housewife found another method:

> Mrs. Muyonjo is a housewife in a remote village of Ivukula in Iganga district, Eastern Uganda. She used to ride her bicycle for twenty miles in order to come to the nearest small town with electricity to charge her mobile phone battery. Not any more.
>
> One day, she fell victim to unscrupulous individuals. 'I will never give my telephone to the village battery chargers again. I gave them my new phone for charging, and they changed my battery and instead returned to me an old battery that can only lasts for one day.' Unable to find the money or time to charge the battery daily, she decided to find an alternative charging solution. 'I looked at what was readily available to me and came up with my own charger. I devised this method to enable me charge my battery every day. It works perfectly.' She uses ordinary size D batteries that are

> readily available in the village to power radios and torches. She wrapped five (5) batteries together, then removed the plug from the phone charger and attached the bare wires to the + and – terminals of the batteries. [54]

The question becomes what is the customer cost for this method? It happens that this is cheaper and provides the user more convenience than the method of charging cell phones from an IPP. However, the cost per kWh for charging car batteries is on the same order-of-magnitude as dry cell batteries. The only reason cell phone charging is such a lucrative electricity market is that it functions as more as a transaction cost than as an electricity cost. Furthermore, this illustrates the other end of the spectrum for energy security – availability.

Due to the low availability of electricity in developing countries, there is tremendous potential growth for electricity services, but not for traditional centralized electric grid systems. These systems' infrastructure (installing electric poles, power lines, etc) and entire house wiring is too expensive for the majority of Ugandans [57]. However, locally designed and built devices installed at the local level can be competitive and will be explored in section 4.2.

### 4.1C Interesting Available School Energy System Configuration

Working together with a principal at St. Joseph's Technical School, a science professor at Mountains of the Moon University (Moses Muhumuza), and the Catholic diocese director of education, I explored the energy availability and reliability issues for Ugandan schools which do not have access to electricity or have intermittent access [25]. The two most interesting findings from this investigation are (1) merry-go-round generators could replace kerosene lanterns for K-12 borders and (2) exercise gyms with inverters and batteries can be used for some universities' computer and scientific laboratories, but not for technical schools. Technical schools have higher power demand and therefore such strategies are less practical; however, technical schools have other options.

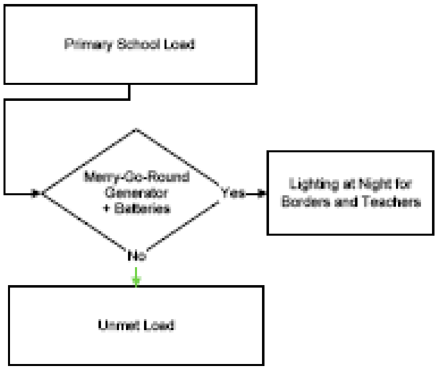


**Figure 46: Simple locally designed and built merry-go-round generator with battery system for night and morning lighting.**

Figure 46 illustrates an energy system which can be used for dual purposes: children's play and electricity generation. It replaces the kerosene lantern which is a fire hazard and which creates indoor air polution [58]. Although a similar system was designed and brought to Ghana for schools [59], this thesis focuses on the co-creation of solutions which empowers people to solve their own energy problems with the physics and business of energy curriculum discussed in the next section.

## 4.2 Ugandan Technicians' Cognition and Local Manufacturing Capabilities

Beginning my thesis journey in Ghana, I came across extensive of information about Polytechnical schools (what we call vocational schools in the United States). Graduates from these schools are trained not only with skills, but with the mathematical and physics-based knowledge useful to design energy producing devices. Moreover, newspapers I read commented that the graduates from the technical schools are more valuable to their country than university graduates for many reasons: no brain drain issue (i.e. do not leave the country), applicable knowledge, and capacity for innovation being the three main reasons. Thus I constructed a qualitative hypothesis which everyone I knew (including my thesis chair and husband) disagreed with: local technicians had all the experience and knowledge to design and build their own energy producing devices. I built this hypothesis on the knowledge a technician must know in order to fix an automobile, but I will come back to this point later in section 4.2B. First, I needed to understand the scale of the energy generation need which I discuss in section 4.2A in terms of what the Ugandan government had done over the years. Then in section 4.2C I ask what should five designed and built devices cost, based on the reliability and availability issues I explored in section 4.1. In the end, I explore the inherent unfairness of our economic global free-market within this energy system discussion.

### 4.2A Local Manufacturing using Physics of Energy Curriculum

In 2004, Uganda's Ministry of Energy and Minerals' Annual Report discussed in detail the inclusion of solar PV technology in the technical institutes. There were 106 instructors from 43 government funded technical institutions who offered an Ordinary Diploma in Electrical (ODE) and Electrical Installation (EI) courses. These programs were expanded into the private sector. St. Joseph Technical Institute Virika in Fort Portal, Uganda, was one of the later schools. These technical schools produce the following professionals: welders, electrical diagnostic and installation technicians, auto mechanics, auto electric mechanics, and solar electric mechanics. With this knowledge, I again qualitatively hypothesized that Uganda has all the viable technology and available technical experience to begin locally manufacturing electricity generating devices. The goal was to create a first step device which could be designed and implemented in a single day without bringing any tool or equipment from the United States. In Section 4.2A will discuss how human power is the first step. Section 4.2B will discuss how the system was implemented and the first level validation to the three-tier physics and business of energy curriculum discussed in Section 4.2C.

In reading about renewable energy, there is little to no discussion of human power [60]. An article by Arne Jacobson and Daniel Kammen [61] discusses the prevalence of 10 W solar systems to provide power to Kenyan villagers with interesting performance characteristics. In Uganda, there is an array of 7 W to 100 W solar systems sold and marketed to villagers and for back-up energy options for the unreliable grid; however, many villagers and city dwellers cannot pay for even the most modest system by industrialized standards. Furthermore, while government rural electrification programs supply villagers with solar systems to address this financial constraint, my interviews in

Ghana suggested that these programs fail because the off-grid solutions are considered inferior to the electric grid. Moreover, some villagers say that these programs are the governments attempt to keep them from developing. This tension between wanting the government to solve the problem on the one hand, and wanting the people to solve the problem on the other hand, led me to the potential new policy of electrical empowerment innovation through merging technical schools, university business students, and government funding for a physics and business of energy curriculum.

If the government brings an inferior system, then the people blame the government. If the people cannot provide the solutions, then they blame the government. If the government brings a system to the people and they fail to use it properly or it brakes sooner than expected, then the government blames the people. Needing a program that grows from one solution into another solution must be done by breaking the cycle of blaming each other. It must be a grassroots empowerment program that the government supports only after the people demand to implement the program in other places. This is my hope for empowering the people of Uganda.

In designing a methodology of empowerment within economic and design constraints, human power was evaluated by me as a first step to empower local innovation and ability. Before jumping into the technical aspects of this issue, what is the scale of human power compared to the needs of developing countries? Consider for example converting all the kWh/capita electricity consumption per year into W/capita of electrical power capacity needed.

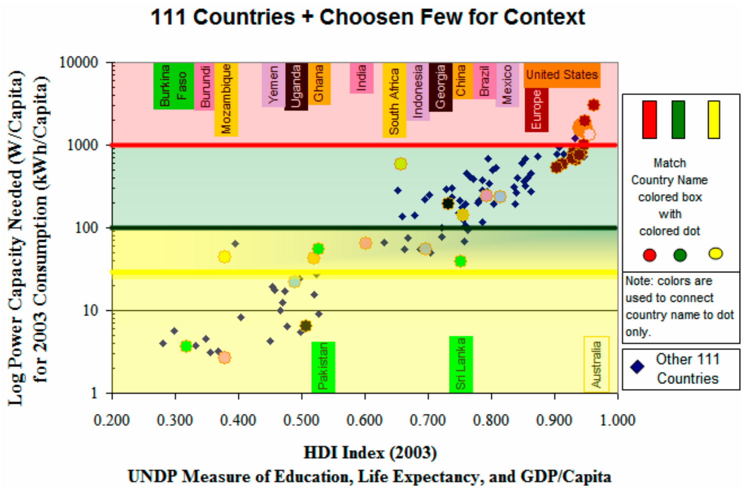


**Figure 47: Countries below the yellow line illustrates where human power (HP) would impact that country. Between the yellow and red line are countries in which might or might not be impacted with HP. Above the red line are countries in which HP is not significant**

In Figure 47, below the yellow line illustrates countries where the level of human power (HP) would impact that country. Between the yellow and red line are countries in which might or might not be impacted with HP. Above the red line are countries in which HP is not significant.

Even though there are large differences to consider within a country, the countries above the red line have approximately 99% availability and reliability of their electric grid. On the other extreme, the countries below the yellow line have only approximately 10% of electrical energy available and the electrical demand growth outweighs the capacity such that a country load sheds their electric grid between cities (decreasing the electric grid reliability in a given country). Therefore, the total electrical energy consumption is quite low for the majority of people. This is the situation where even human power can play a significant role.

I imagine working with electricity versus without electricity. There are activities which are easier to perform with electricity than without electricity. For example, cutting wood is easier and more precise with electrical cutting tools (e.g. jig-saw) than with manual saws. Therefore, there are human activities that would need to consume less calories with electricity (including electrical human power to power the device) than the needed calories to perform the human activity without electricity (discussed in detail later).

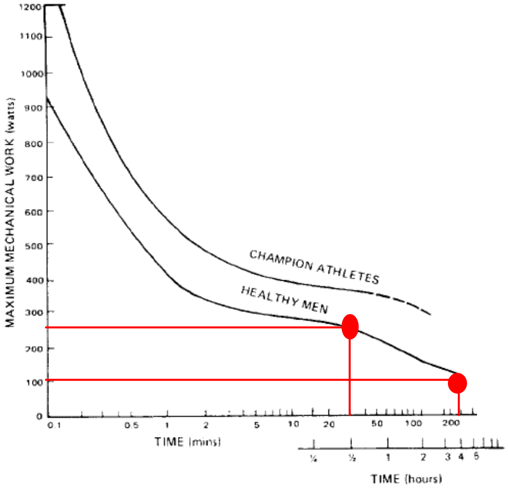
To understand at what scale human power may or may not impact a country, a couple of technical aspects to human power must be discussed.

There are three first or zero$^{th}$-order physics variables to consider: power, time and energy. Human-power is constrained by these issues: typical capacity (W) for various activities and maximum sustained power of human muscles (t and W). With these constraints, energy is calculated.

Human Energy Rate (Cal/hr to Watts)

| Activity Type | METS (ratio) | Cal/hr[16] | Watts In[17] | Watts out[18] (22%) |
|---|---|---|---|---|
| Sleeping | 0.9 | 72 | 80 | |
| Inactitity | 1.0 | 80 | 90 | |
| Holding Baby | 1.5 | 120 | 140 | 30 W |
| Tourist Traveling | 2.0 | 160 | 190 | 40 W |
| Baking | 2.5 | 200 | 230 | 50 W |
| Tayloring Weaving | 3.5 | 280 | 330 | 70 W |
| House Cleaning | 2-4 | 160-320 | 190-370 | 40-80 W |
| Farming | 3-8 | 240-640 | 280-740 | 60-160 W |
| Walking | 4-7 | 320-560 | 370-650 | 80-140 W |
| Soccer | 4-12 | 320-960 | 370-1100 | 80-250 W |
| Bicycling <10 mph | 3-4 | 240-320 | 280-370 | 60-80 W |
| Cycling >13 mph | 8-9 | 640-720 | 740-840 | 160-180 W |
| Running 12min/mi | 8-9 | 640-720 | 740-840 | 160-180 W |
| Running 7min/mi | 14-15 | 1120-1200 | 1300-1400 | 290-310 W |
| Running Extreme | 18 | 1440 | 170 | 350 W |

Human Power Sustained Timing (Watts)



**NASA experimental results on sustained maximum power**

**Table 13: Juxtaposing human energy consumption rates to human energy output rates offers a reference point for researchers to understand the assumptions within human power calculations.**

---

[16] This is for an average healthy 80 kg person.
[17] These values and the next column are rounded with approximate values given.
[18] This is the mechanical rate of work that human muscles exert.

On the left side of Table 13, well known factors for energy consumption are given from medical kinesiology research [61, 62]. These values are typically used in understanding whether one should eat more or eat less depending on level of activity and diet. It is also understood that human bodies have evolved into approximately 22% efficient organisms in terms of biological (chemical) energy in and mechanical energy out [63, 64]. Traditionally, the mechanical energy out has been used to work against gravity in the cardiovascular system (i.e. sleeping ~ 25 W) as well as to complete tasks such as farming and cleaning (~80 W). In the modern industrialized world, humans do less mechanical work and therefore have a choice: eat less or exercise. Thus the circle of human energy consumption in and mechanical work out has, in part, come full circle. People in developed countries have created human societies which are so efficient that they need to exercise in gyms in order to burn the amount of chemical energy absorbed into the body or risk the body turning the energy into fat. However, people in developing countries have more traditional societies where machines rarely their work. Consequently, the added benefit of electrical machines, for example, could increase the efficiency of their society and thus enable people to do less total mechanical work. As non-obvious as this seems to be, a person using a bicycle generator every day for one hour could consume less energy producing electricity than the energy consumed by a person doing the same type of work without electricity.

Another way to say the same thing is that there is a spectrum of electrical devices humans have designed and built to meet some need. Consider the following figure:

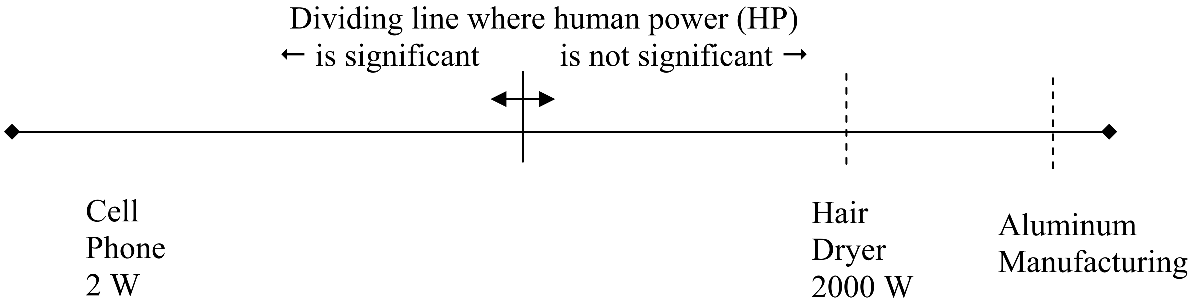


**Figure 48: Spectrum of electrical devices power demand.**

In Figure 48, one can argue that there is a level of electrical power demand in which a human could produce the electricity. This device could then decrease the total amount of energy needed (energy to accomplish task with electricity versus energy to accomplish task without electricity). However, the converse is also true. There are a set of electrical devices in which a human could not produce the electricity to power it. To understand this point clearer, I will give a couple of examples.

For example, take Mrs. Muyonjo, who we heard from earlier in this dissertation, biking twenty miles to charge her cell phone battery. Assuming she bikes 10 mph on rough roads (60 Watts rate of work), it takes her 4 hours to go get her battery charged, and come back home. She outputs approximately 240 Wh of mechanical energy making this trip and needs to consume 1.1 kWh of chemical food energy for this human activity. However, if she was to ride a bicycle generator (60 Watts rate of work), she could charge her cell phone in 2 hours at home (30 Wh with 50% efficiency of bicycle generator), save energy, and have two more hours for an afternoon activity like enjoying life without physical effort (biking for two hours = 0.55 kWh plus 0.18 kWh of inactivity). Thus she would need to consume 1.1kWh of energy for biking to and back from the nearest IPP to charge cell phone versus 0.73 kWh to bike on her theoretical bicycle generator at home and then rest.

Imagine this idea in terms of walking to watch a football game at a local video hall. If it takes an hour to walk to the video hall for a group of ten guys from the village, they output approximately 200 Wh (there and back) each or 1.2 kWh. If instead each bikes ten minutes on a bicycle generator directly connected to the television (100 W), then they would only consume 0.80 kWh (with 50% efficiency for bicycle generator) for four hours. The energy for the group to walk is 1.2 kWh and more than the group taking turns biking on the bicycle generator which is 0.80 kWh. There are a myriad of potential strategies from pumping water to cooking with a family owned and operated merry-go-round generator to a multi-use community-based pavilion where the energy consumed with human power generated electricity is less than the energy consumed without electricity.

One example, often mentioned to me in Uganda, was hooking up a human powered generator (e.g. reversed DC motor) to bikes which are already doing business on the road (carrying bananas, people, etc.). Although I was reluctant to support this idea, I have almost been convinced that a generator which could be connected and disconnected to the bike's tire could be an option especially for charging cell phones. For example, the Hy mini [76] is a company which sells a mini wind turbine for bikes to charge cell phones while biking. A human would hardly notice the added friction to the bike and it would successfully charge cell phones (again, there are many electrical devices for which this would not make sense).

The societal choices and policy options related to empowering humans to generate electricity have not been considered in previous research. Only in relation to high technology for soldiers' backpacks, ankle-based, or shoe-based electricity generation with piezoelectric devices, has human power been considered [65]. In Uganda and for soldiers, solar-PV systems are either too expensive or not a good choice for crisis events. So, first, how does human power compare in terms of cost and power output? Second how feasible is it? Third, how can it be used to inspire a more sustainable energy-producing locally-manufactured market? Fourth, can it be hybridized with solar power systems?

On page 86, Table 13 represents the maximum sustained power a man and champion athlete can mechanically output based on experimental results from NASA. The two red points in the figure are chosen to illustrate the calculations for each bike ride: (1) 200 Watts for 30+ minutes and (2) 100 Watts for 210+ minutes. The third point is based on 75 Watts of mechanical work for 250 minutes. This third point is not within NASA's data, but is at the 50 W level typical for tailoring, weaving, house cleaning, farming, and walking. Based on physics the energy generation for these three points would perhaps be the following:

$$Energy_{human}(Wh) = Power_{human}(W)Time(hr) \tag{1}$$

High Power $$E_{200W} = (200W)(0.5h) = 100Wh = 0.100kWh \tag{2}$$

Medium Power $$E_{100W} = (100W)(3h) = 300Wh = 0.300kWh \tag{3}$$

Low Power $$E_{75W} = (50W)(4h) = 200Wh = 0.200kWh \tag{4}$$

This is mechanical output energy output. The device could be rigged to an already existing system (like a mechanical sewing machine) or could be a generator system (like a bicycle generator or merry-go-round generator). Moving onto the next order of magnitude, I now want to expand this argument to the entire country of Uganda per year. Assume every person in Uganda who does not have access to electricity in 2005 bikes seven times a week for one hour[19]. How does this potential amount of electricity compare to the national total electrification consumption per capita in Uganda?

$$\frac{N_{without-electricity}Energy_{human}(kWh)N_{biking-events}}{N_{total-population}}\eta_{efficiency} = \frac{(25{,}000{,}000)(0.200kWh)(364)}{(28{,}000{,}000)}(0.50) \tag{5}$$

$$Energy_{human} / capita = 33kWh / capita \tag{6}$$

$$Energy_{Uganda-2005} / capita = 67kWh / capita \tag{7}$$

The human energy production level would be approximately 50% of the total 2005 Uganda electricity consumption/capita level including a 50% efficiency rate for a bicycle generator. Compare this to a solar power pv panel system of 25 W which is similar in cost to a human powered system which was built at the vocational school[20]. Solar power is constrained by two issues: variability of the sun and not on-demand. In Fort Portal,

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[19] This is a rough calculation. Obviously there are people without access to electricity who cannot bike (lower number needed). As well, it is obvious that there are human power systems which can be better than 50% efficient (higher number needed). However, this calculation yields an energy scale.

[20] According to 2007 prices of solar panels in Kampala, a 25 Watt solar panel was $150 US. A bicycle generator was made in Fort Portal with a used bike, used auto or motorcycle alternator, and a belt for $150 with a capacity over 100 Watts. However, these prices should always be re-verified for future research analysis.

Uganda, the solar radiance profile is the following according to NASA satellite data:

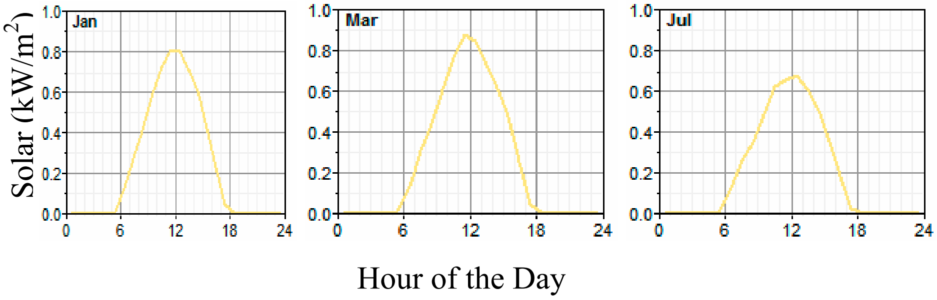

**Figure 49: Solar radiance versus time of day as measured by NASA using satellite information.**

The graphs in Figure 49 show the average, maximum, and minimum solar radiance based on two main seasons: rainy and dry. These values are used to approximate comparison of low and high human power. Analyzing this information, three important issues emerge: (1) approximately four hours of peak solar power per day, (2) 8 hours of less- than peak solar power per day, and (3) majority of solar panels brought to villages do not track the sun. Thus the total energy generation for this hypothetical purchased 25 W solar PV system (not including true efficiencies) can be approximated as the following:

$$Energy_{solar}(Wh) = \sum_{day} Power_{solar}(W)Time(hr) \tag{8}$$

Peak sun
$$E_{4hr} = (25W)(4h) = 100Wh = 0.100kWh \tag{9}$$

Morning and Evening Sun
$$E_{8hr} = (10W)(8h) = 80Wh = 0.080kWh \tag{10}$$

Total
$$E_{total} = E_{4hr} + E_{8hr} = 0.180kWh \tag{11}$$

Compared to the solar system, the human power system has a greater capacity (W) and depending on the implementation, systems can be designed to have similar or higher energy production (kWh)[21]. The question becomes: can a human power system with functionality similar to a PV system be designed and built with available local resources and using viable technical expertise? If it can be done, then why not design and build other electrical generation devices locally?

### 4.2B Local Manufacturing within Physics Cognition

According to Uganda's Ministry and Minerals Annual 2004 Report, St. Joseph's Technical Institute Virika instructors were trained with a Solar PV training workshop with the following three national goals in mind:

- Introduce the National Solar PV Curriculum to the instructors
- Train the instructors in solar PV Technologies and practices
- Equip the technical institutions with solar PV equipment and training materials

Consequently, the instructors have been trained to become conversant in the following professions and trades:

- Welders
- Auto Mechanics
- Auto Electric Mechanics
- Electrical Technicians
- Generator Winders and/or Technicians
- Solar Electric Technicians

With this wealth of knowledge and apprentice-based expertise, participant roles were evaluated both in talking with the technicians and in watching them work and innovate on-the-spot solutions to a customer's request. To design a typical human power device there are five physics variables to consider and viable local experts who teach and use these physics concepts were identified:

---

[21] These calculations are based on PV manufactured ratings of 25 Watts. In real-life, the 25 Watt rating is below optimal conditions.

| Physics Variables of Human Power | Knowledgeable and Viable Local Experts |
|---|---|
| Rotational energy from human foot (pedaling) or hand (hand crank) | Auto Mechanics<br>Welders |
| Stability: center of mass issues | Welders |
| Gear system to take human angular velocity (100 rpm) to what is needed for a generator or alternator (700 – 1000 rpm) | Auto Mechanics |
| Generator or alternator to transform rotational energy into electrical energy | Auto Electric Mechanics<br>Electrical Technicians<br>Generator Winders and/or Technicians<br>Solar PV Technicians |
| Electric power level, voltage, current, inverters, rectifiers and transformers | Solar PV Technicians<br>Electrical Technicians |

**Table 14: Outlining the physics variables in human power compared to the active local knowledge and everyday use of physics.**

In Table 14, these Ugandan experts actually represent a case-study of experts which should be verified by visiting all the technical institutes; however, the Ugandan Small Scale Industries Association told me that these technicians are common not only in Uganda, but throughout African countries with similar technical institutes. There are more welders in developing countries than in developed countries. Moreover, auto mechanics in developing countries are known for their impressive abilities to keep automobiles functioning for 20 years; whereas, in developed countries the useful life of a vehicle is 13 years [66]. Electrical and Solar PV technicians in countries with high electric grid unreliability and high $/kWh of electrical costs have more experience installing various back-up or alternative electrical devices than in countries without this situation. These synergistic relationships opened the door for me to walk into the Institute with no tools, textbooks, or equipment and start the first step in local manufacturing of energy generation. This was accomplished with the equipment that was available within the Institute: parts of an automobile (alternator, belts, gears), bicycle, and metal available to build a stand. In Figure 50, the images illustrate the innovation in design for a human bicycle generator.

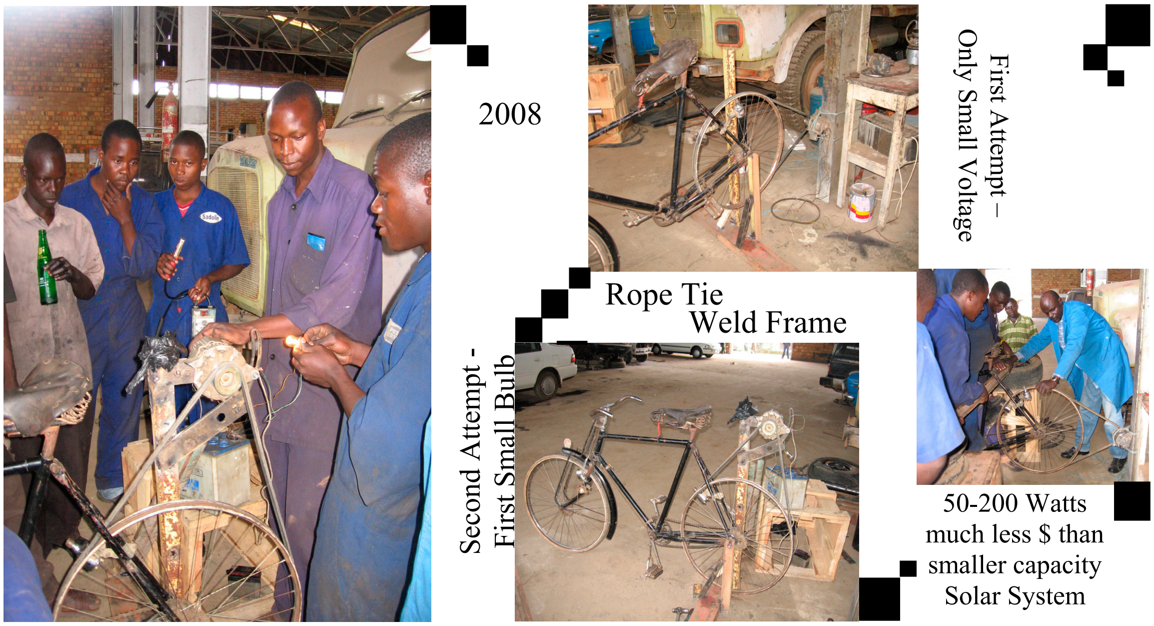

**Figure 50: Innovating on Human Bicycle Generator design at St. Joseph's Technical Institute Virika.**

Not only did the technicians at the Institute (instructors and students) not believe this would work initially, many laughed. When it worked, there was the typical shock and awe. One instructor came to me with a motor from an old radio which he ran backwards and rectified with a capacitor. He geared it up and then got 4 volts out with his finger rotating a flat cylinder disk. The welding instructor, after his initial disbelief, went to talk to the solar electric theory instructors about taking the alternator through an inverter and when he came back saying that yes it could done, everyone became very excited. Enthusiasm was the first step of this empowerment curriculum.

Before moving on, there is one story which must be told. The argument which ensued between the auto-mechanic and the electric auto-mechanic was profound because it illustrates the power of a qualitative hypothesis and because it showed how the interconnection for almost all electric generation is the alternator or generator.

> The auto-mechanic said to the electric mechanic, “I thought the energy came from the battery!” To this the electric auto-mechanic states that it goes both ways. Sometimes the battery discharges, but other times the dynometer charges the battery. Then the electric auto-mechanic says, “But I thought the transmission only rotated because of the engine and that you have to have an engine.” To this the auto-mechanic says, “No, rotation can come from anywhere.” Then they stared at the device that they had just built and started asking if they could get the energy from other motion: “What about wind?”, “What about water pushing a wheel?”, etc.

In the end, the first-step, locally designed and built system is shown in the image below:

**Figure 51: The final human bicycle generator produced at least 100 W. The multimeter wires began to melt and smell like burning rubber so we could not take an accurate measurement of the current.**

This system was completely locally manufactured and it empowered at least one immediate innovation as well as brainstorming about the cost comparisons to solar PV panels. Entrepreneurially-minded technicians and businesspersons asked two questions of me immediately: (1) what appliances can it run, and (2) can one run the car alternator with a wind turbine or a water mill? This prompted me to develop a complete three-tier curriculum based around the physics and business of energy on the spot; however, the social issues of trusting imported technology over local manufacturing should be further researched; and I will touch on these issues later in this thesis.

This thesis categorizes two types of electrical energy production devices: new designs and redesigns. New designs are typically manufactured in areas with either high technology factories (e.g. United States and Germany) or in cheap labor markets with reliable manufacturing and shipping capability (i.e. China and India). Redesigns can be constructed by using available technology in areas with little manufacturing and using them in innovative ways. Consider the following quote from the Dean of Engineering from Massachusetts Institute of Technology (MIT), Subra Suresh:

> "The modern engineer must be at least two things: a creator of new ideas and new technologies, and a re-inventor of those that are... less new."

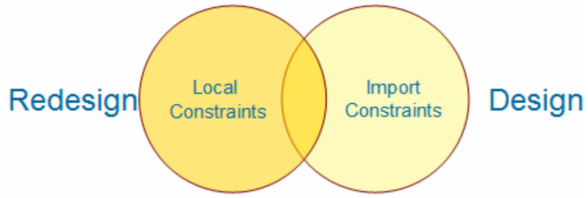

**Diagram 1: Technology choices between designing new and redesigning from available equipment**

In Uganda, almost all electrical energy production devices are imported. For example, solar PV technology is not manufactured in Uganda at all, and yet it is the main technology suggested for rural electrification. Other projects have been based on micro-hydroelectric turbines, wind turbines, and bio-fuel or bio-gas engines (either from waste or local agricultural vegetation). Almost all of these devices are designed and manufactured somewhere besides Uganda. Considering (1) the energy crisis events, (2) the importance of operation and maintenance to be done by local technicians, and (3) the locally designed and manufacturing capabilities within Uganda, it is suggested that the Ugandan government create a policy to empower technical schools to design and redesign electrical energy producing devices. Section 4.2D outlines a more developed three-tier methodology to move this policy suggestion into reality, including a discussion and presentation of the five accomplished electrical energy producing devices in Uganda and the one accomplished electrical energy producing device in Ghana. The Ghana story comes from Robert Van Buskirk from Lawrence Berkeley National Laboratory who took the first step of my methodology to Ghana and found that it was reproducible there.

### 4.2C Physics of Energy Curriculum with Five Successful Ugandan Built Devices

To have electricity is to have vaccines and retro-viral medications safely stored in a refrigerator and to have lights during surgery (theatre). To have electricity is to have cell phones connect businesses which previously were not connected. To have electricity is to have lights at night for studying or to have computers and copy machines for curriculum development and enhancement. However, it is not enough to have availability; there must also be reliability. In every developed country, there is a national electric grid which hybridizes energy production from multiple power plants. In Uganda, the electric grid consists mainly of hydroelectric dams with the beginning of interest in thermal and nuclear plants [68]. Breaking all the possible electrical power plants into energy conversion curriculum ideas, the following emerges:

| **Power plant type** | **Energy Conversion** | |
|---|---|---|
| Wind and Hydroelectric Dams | Mechanical to electrical | (ME) |
| Solar-Thermal, Geo-Thermal | Thermal to mechanical to electrical | (TME) |
| Fossil Fuel (i.e. coal-fired),<br>Sustainable Fuel (i.e. biogas-fired) | Chemical bonds to TME | (CTME) |
| Solar – Photovoltaic panels | Light to electrical | (LE) |
| Fuel Cell (i.e. hydrogen, methane) | Chemical bonds to electrical | (CE) |
| Nuclear (fission or fusion) | Nuclear bonds to TME | (NTME) |

**Table 15: Breakdown of power plant types into energy conversion categories.**

With this organization, there are six categories of power plants. Based on local manufacturing capability currently available in Fort Portal, Uganda, the last three categories were not considered in this Physics of Energy curriculum. The goal was to break the three available categories into specific technologies which could be designed and implemented locally. These categories are then turn into a strategy to study a three-tier hybridized methodology for local manufacturing empowerment in Uganda. At the writing of this thesis, only the first category (mechanical to electrical energy) was taught with the result of five co-designed and built electrical energy producing devices. The following table is a sample list of devices (including future work):

(1) Mechanical to Electrical
  a. Low human power (50-200 Watts): bicycle generator
  b. High human power (500-2000 Watts): merry-go-round generator
  c. Generator basics (designing coils – number of windings and size of wire) with permanent magnets versus electromagnets
  d. Micro- wind turbine: vertical design – savonious &/or darrieus
  e. Higher power wind turbine: horizontal design
  f. Micro-hydroelectric turbine: water mill
  g. Higher Power hydroelectric turbine: dam + generators
(2) Thermal to Mechanical to Electrical
  a. Low power stirling engine to generator
  b. High power solar thermal steam engine to generator
  c. Geothermal steam engine to generator
(3) Chemical to Thermal to Mechanical to Electrical (with a focus on sustainability)
  a. Bio-alcohol engine to generator
    i. Banana alcohol
    ii. Sugar cane alcohol
    iii. Pineapple alcohol
  b. Bio-diesel engine to generator
    i. Palm Oil
    ii. Jatropha
  c. Bio-waste engine to generator
    i. Incinerators
    ii. Animal waste

To date, the Ugandan government has tried many pilot programs in almost every category except human power. Many of the pilot programs stop after (1) the imported technology breaks down due to lack of knowledge of how to get the replacement piece of equipment (not sold in Uganda), and (2) the program is no longer supplied funds to overcome the learning curve of new technologies. However, the solar panel program has worked in terms of empowering a new technician (solar technician) and in terms of creating a local market for supplies and labor (even though this technology is imported) [68].

Building upon the successes of the solar curriculum-based program and learning from the lack of success of previous other renewable energy programs, I teamed up with three grassroots organizations to investigate my qualitative hypothesis[22] and to hopefully create the theoretical foundation for a national implementation program, beginning with the mechanical to electrical energy conversions. As mentioned previously, the first organization was the St. Joseph's Technical School located in Fort Portal, Uganda. The second organization was the Mountains of the Moon University (MoMU) also located in Fort Portal, Uganda. The third organization was the Uganda Small Scale Industries Association (USSIA) with its main office in Kampala and a district office in Fort Portal, Uganda. Together we are writing a Memorandum Of Understanding (MOU) for a Physics and Business of Energy program. Even though this new theoretical methodology has been successful to date and is compelling in terms of new synergies, I know from the experience of starting other programs that it will take at least two to five years to go through a complete validation cycle. The hope is that other physicists, engineers, technicians, as well as politicians, will begin to reevaluate the purpose of their technical schools. Is it enough to empower technicians to have employment (as is currently accomplished)? Or is there a higher pathway - to empower them to design and innovate in terms of electrical energy producing devices (and the policy implication of this work)?

The first step in this curriculum at Fort Portal was gaining trust, developing relationships, and networking technicians together. The bicycle generator was described in the previous section in terms of networking technicians - specifically the auto-mechanic and electric auto-mechanic. The device was built completely from parts found in the garage and cost virtually nothing. The beauty and simplicity of this step was two fold. First, it takes technicians only one day to design and build. This means that they see the fruits of their volunteer[23]-based labor immediately and effectively. The second benefit is that various technicians, who typically do not get together to innovate, start to immediately think and discuss how other devices can be locally designed and built. The level of interest and

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[22] The qualitative hypothesis was that Uganda had all the available materials and expertise to design and build electrical energy devices.

[23] I use the word volunteer because with some research programs working in Africa, people pay technicians to participate. These technicians wanted to work in this program. In fact, due to their normal business operations, the course only met from 2:00 to 5:00 in the afternoon.

excitability is only on the order of an initial spark. If it is not followed up, then it dies out.

The second step in this curriculum is to begin co-teaching during times which did not interfere with the technicians work or school schedule. Each step is split up into two parts: A and B. Part A consists of the outsider teaching the Physics of Energy. This begins and ends with the idea that a motor can be a generator and vice-versa. The electromagnetic theory in one direction is a motor (electrical to mechanical energy conversion) and in the other direction is a generator (mechanical to electrical energy conversion). This opens the door for technicians to brainstorm about converting old motors into generators (especially the squirrel-cage motor). Many lessons plan were created and some are included in Appendix B. Part B consists of the technicians taking control of the curriculum and teaching the outsider how they can build a device in their garage. One mechanical to electrical energy device is built. For those new to the program who doubt whether or not it can be done (many doubted and even started to get angry), we showed them the bicycle generator from step one. Not only did they get enthusiastic, everyone chipped in money to build the second device. They choose a wind turbine. It cost approximately $500 US to build from scratch (equivalent to two years salary in Uganda). The following are the images from this second step:

**Figure 52: Vertical wind turbine (behind group) designed and built in Fort Portal Uganda in five days.**

The third step is to build and design three more electrical energy producing devices as well as to design a generator which is matched to the wind turbine already built. A long discussion of matching revolutions per minute (rpm) of the wind turbine with the generator was worked out. Again, each step is split up into two parts: A and B. Part A now incorporated breaking the technicians into groups based on their interest and expertise. Each group reviewed the physics information from the first and second mini-courses. Then they choose a mechanical-to-electrical energy producing device to design and build. This time educational equipment was brought to build mini-models of their devices. These models were then used in Part B of the course. Part B was when the technicians took over and created a parts list for the beginning of a business plan. Once the equipment was purchased, then each group would volunteer to build the devices during times which did not interfere with their own businesses or school programs. The following are the pictures from this step:

**Figure 53: A handmade coil for one of the generators used on wind generator electrical device**

**Figure 54: A triple geared hand-crank generator for surgical back-up lighting**

Now knowing the capital costs to build these devices, the next step begins: the Business of Energy course. However, this part runs into a serious discrepancy in terms of what an electrical energy producing device should cost based on capital versus social benefits (decreasing risks of death during surgery). This will be discussed in section 4.3.

In all, this part of my thesis opened the door for locally designing and building electrical energy producing devices. As stated above, even though this new theoretical methodology has been successful to date and is compelling in terms of new synergies, I know from the experience of starting other programs that it will take at least two to five years to go through a complete validation cycle. However, it is promising to hear a story from Bolgatanga, Ghana, told to me by Robert Van Buskirk from Lawrence Berkeley National Laboratory. He took the first step of my methodology to Abdul Raman, an auto-mechanic he knows in Bolgatanga and found that the bicycle generator results were reproducible there, as well.

## 4.3 Electrical Energy Capital Costs versus Social Benefit

The debate in the United States political system has been capitalism versus socialism. The real fundamental issue is how we as a society choose to fund institutions which provide services that are for the welfare of society: justice (police and military), crisis mediation (fires and disaster relief), education, health, etc. Economists describe this in terms of maximizing a society's utility function. A utility function is a mathematical way to model how people attain their meaning in life using monetary means. The tension is that almost everyone knows that money is not all there is to meaning in life. So, parts of life are economic and other parts are so-called values, faith, community and family. However, the current economic structure over time has led to an approximate value of a statistical life (VSL) around $150,000 USD in Uganda (PPP $) and to an approximate value of a statistical life around $6,000,000[24] USD in the United States (PPP$) [72]. By considering only the capital costs of an electrical energy system means that few in Uganda have the ability-to-pay (actually this result in the United States is similar) including the government. Moreover, in the United States, the traditional infrastructure (mainly non-renewable electrical energy utility systems and connections) was within the government and people's willingness-to-pay and ability-to-pay, but not currently for the new renewable energy infrastructure. So, the question becomes, how are the funds allocated from the global economy to fund these social benefits of renewable energy systems given that the capital costs of these systems are above the willingness-to-pay for these systems? Even though this question is not answered in this section, I encourage readers to consider the answer to this question.

This section will develop a more qualitative economic discussion for an energy device using two economic frameworks. The first framework consists of the capital costs ($ USD) for a locally designed and built electrical energy generating device in Uganda. The second framework outlines the social benefit issues for each device. For example,

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[24] This number is calculated using value of statistical life (VSL) of 136*GDP/capita [72]: US 2008 GDP/capita was 47,000 (PPP$) and Uganda 2008 GDP/capita was 1,100 (PPP$).

method one calculates the cost of a back-up surgical lighting system in Uganda to be between \$10 to \$300 USD. Using method two, I outline a set of social benefits for this device which cannot be properly estimated, at the time of this dissertation: the surgical back-up lighting system would benefit Ugandan society up to approximately \$150,000 USD for a certain life lost/year frequency and \$75 USD for a rough estimated probability of life lost[25]. Why the tremendous difference? Because traditional capital costs do not take into account the externalities of failure of the electricity system (risks to patients during surgery when the electric grid is unreliable).

This section (1) calculates the cost of electricity producing devices based on capital costs in Uganda versus (2) discussing the social benefit terms for the five electrical devices based on saving lives, empowering technicians, creating new market competition, decreasing green house gas emissions, decreasing local pollution (NOx), etc. To understand this theoretical discrepancy, I will begin with a discussion of what Noble Laurite Professor Muhammad Yunus calls for: both profit maximizing business (PMB) and societal maximizing business (SMB) [74]. This can only be done through a hybrid system where the PMB becomes a corporate responsible business (CRB) by incorporating societal maximizing business practices.

### 4.3A Hybrid PMB and SMB discussion for Creating Five Electrical Systems

Throughout the Fort Portal, Uganda area, businesses, schools and hospitals are faced with tensions associated with electric energy (1) availability versus reliability, (2) ideal versus critical health care situations, and (3) capital costs versus social benefit costs. The benefits versus costs associated within these tensions represent a vast array of choices. In the following sections, I will present the capital costs of five new choices: bicycle generator, hand-crank lighting system, wind generator, micro-hydroelectric generator, and merry-go-round generator. The social benefit cost terms will be discussed, but not quantified due to lack of available data at the time of this dissertation.

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[25] This is the mean expected value for a 5% risk of losing electricity during a night surgery (with 10% chance of doing a surgery and 10% risk of patient dieing) where the approximate value of a statistical Ugandan life is \$150,000 USD.

Before beginning the discussion of the electrical systems built in Uganda by local technicians, I want to discuss Bill Gates interpretation of the capitalistic system. Nobel Laureate Muhammad Yunus wrote about Bill Gates speech in an Op-Ed editorial last year [80]. Take the four following quotes within the Op-Ed:

> I see traditional capitalism as a half-developed structure. It ignores the humanity within all of us.
>
> Moneymaking is an important part of humanity, but it is not the only part. Caring, concern, sharing, empathy – all of these aspects also must be considered when developing an economic framework that takes the whole person into account.
>
> A social business aims to maximize the positive impact on society while earning enough to cover its costs, and, if possible, generate a surplus to help the business grow. The owner never intends to take any profit for himself.
>
> Traditional capitalism doesn't tap into that universal desire. Capitalism delivers limited results because it takes too narrow a view of human nature, assuming people are one-dimensional, concerned only with maximizing profits.

Within these discussions, most energy system models not only calculate costs from a purely capitalistic framework, these models only consider what can be imported. They ignore human power energy systems and human empowerment issues. For example, importing technology may or may not be able to be repaired locally. When people use the equipment in ways in which it was not meant to be used (running a diesel generator in a hot room with no cooling system for two weeks straight), then the system breaks down quicker than modeled: ending in a worse-off system (see new 68 kW diesel generator versus refurbished 9 kW diesel generator discussions in Chapter 4, Section 4.1 - hospital system). Consequently, even understanding the qualitative terms for the social benefits of the five electrical energy devices is valuable. Future energy system models must take into account both (1) the capitalistic-based energy model issues and (2) the social benefits of a corporate responsible business paradigm.

### 4.3B Bicycle Generator

Figure 55 presents a product attribute comparison for a small PV system and the human powered bicycle generator.

| Product Attributes | One Human Bicycle Generator | One Solar PV Panel |
|---|---|---|
| C - Capital Cost: | $50, $200,<br>two value (used, new) | $150 - $2,000,<br>practically continuous |
| OM – Operation & Maintenance | $5/year<br>one value, approximate | $0/month<br>one value , approximate |
| R - Replacement Years: | 30<br>one value, standard | 15<br>one value, standard |
| P - Power Level: | 0 W – 250 W,<br>depends on alternator used<br>continuous | 5W, 10 W, 14 W, 25 W, 75 W, 80 W, 100 W<br>discrete |
| D – On-Demand | Yes | No |
| S - Storage | Same kWh and V (12DC) | Same kWh and V (12DC) |
| W - Level of Work: | 0.5 – 3 hours/weekday,<br>continuous | 0 hours/day,<br>one value |
| SP – Stolen probability | Low, Medium<br>two value - approximate<br>depends on where one lives | Low, Medium, High<br>three value – approximate<br>depends on where one lives |

**Figure 55: Product attributes comparing locally designed and built bicycle generator versus imported solar PV panels**

Many researchers calculate a comparison of energy in and energy out of a human eating biomass versus burning the biomass as fuel. However, this assumes that all human activity is the same (human activity with and without electricity). What can also be calculated is (1) human food energy consumption without electricity versus (2) human food energy consumption with electricity, as explained earlier in this dissertation?

For example, suppose the bicycle generator systems costs 100,000 UgSh. Then suppose ten people walk for one hour to watch a football game. The total energy consumed in walking (3.7 kWh) is more than that in biking (1.9 kWh). If the video hall charges 500UgSh/person to watch one football game and there are 10 games a year (50,000 UgSh), then this system pays for itself in 2 years. This discussion illustrates the capital cost of a bicycle generator (100,000 UgSh) and a social benefit term (pays for itself in 2 years). However, there are other social benefits which should be considered, but after the discussion of capital costs.

The cost of this new electrical energy generation system would be based on the capital costs to build the bicycle generator is summarized in Table 16.

| **Parts** | **Cost (UgSh)** | | **Cost (US$)** | |
|---|---|---|---|---|
| Used Bike | 40,000 | | $20 | |
| New Bike | | 200,000 | | $100 |
| Belt | 10,000 | 15,000 | $5 | $7 |
| Old Motor Cycle Dynometer | 15,000 | | $7 | |
| Old Car Alternator | | 70,000 | | $35 |
| Welded Stand | 20,000 | 30,000 | $10 | $15 |
| Wires | 5,000 | 10,000 | $3 | $5 |
| Small Battery (6V - 4 Ah) | 10,000 | | $5 | |
| Car Battery (12V - 50 Ah) | | 50,000 | | $25 |
| **New and Used Parts Subtotal** | 100,000 | 375,000 | $50 | $190 |
| Labor to Build: 10%[26] | 10,000 | 38,000 | $2 | $19 |
| **New and Used Parts Grand Total** | 110,000 | 420,000 | $52 | $210 |

**Table 16: Capital Costs for Bicycle Generator**

In Table 15, the range of costs for this Ugandan designed and built bicycle generator is approximately $50 to $200 USD depending on the equipment's size, new or used/refurbished state, and 10% charge of labor. It is interesting to note that the Business

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[26] The 10% charge for labor is apparently why solar technicians are more prosperous than other technicians. This norm for charging is considered by the Ugandan Small Scale Industries Association not a good business practice because many technicians charge the same amount whether it takes 1 hour or 10 days to fix. This will be incorporated (and is currently discussed) in the Business of Energy course.

of Energy part of the curriculum deals with the capitals costs as well as labor costs (see Appendix B).

**Figure 56: St. Joseph Technical Institute technicians' first design - the bicycle generator.**

The social benefits associated with local manufacturing of the bicycle generator system are hard to quantify at the time of this dissertation. However, a brief discussion will be given.

$$\text{Social Benefit} = \sum \text{benefit costs} - \sum \text{not benefit costs}$$

$$\text{Social Benefit} = \left\{ \begin{matrix} benefit_{1-pays\text{ for itself}} + benefit_{2-empowerment} + benefit_{3-\text{O\&M}} \\ -\,not\ benefit_{1-\text{create new market}} - not\ benefit_{2-\text{end of life}} \end{matrix} \right\}$$

The first term is fairly easy to understand, but hard to calculate. The second and third terms are harder to understand: (1) what is the social benefit to empower Ugandans to generate their own electricity and (2) how much value should be placed in the ability to pay for the operation and maintenance of a bicycle generator. The final two terms are also hard to quantify: (1) how much will it cost to create a new market and (2) what is the end of life costs for the bicycle generator[27]? As in all economic analyses which do not include the social and environmental externalities due to these difficulties, the benefit to cost ratio of this new system must be greater one.

$$\text{Social Benefit/System Cost} \geq 1$$

Rewritten, this means that if one could calculate the social benefits, then another value for the cost of this new electrical energy generation system could be quantified.

$$\text{Social Benefit} \geq \text{System Cost}$$

Whether or not these two frameworks of capital costs and social benefits could be used to create a hybrid corporate responsible business which both maximizes profit and societal impacts, will to be considered in my future work.

In conclusion, this section illustrated a methodology for the bicycle generator to compare (1) the local versus imported technology product attributes, and (2a) one cost for the electrical energy generation device based on capital costs versus (2b) another cost for the electrical energy generation device based on future calculations of the social and/or environmental benefits. In the next section, a compelling argument is given for these two costs based on the risks during surgery to patients when the electric grid is unreliable.

### 4.3C Hand-crank Back-Up Surgical Lighting Device

As the Lead Designer for a University of Michigan student organization, M-Heal, I co-designed and created a hand-crank back-up surgical lighting device with the technicians in Fort Portal, Uganda. As mentioned before, many engineers create a solution to be imported by developing countries. There are a set of small programs to build the specific devices based on local available parts, but none that I am aware of which incorporate a

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[27] This term might result as a benefit, if the bicycle generator end of life costs are less the than solar PV end of life costs.

Physics of Energy curriculum. Furthermore, as far as I know at the time of this dissertation, no one designs and builds with local technicians as well as local materials. As mentioned before with examples given in earlier sections, imported technology that cannot be repaired locally has a shorter usable life (lifetime) of the electrical device (see diesel generator example at Virika Hospital).

Below are two images of the surgical lighting device. The image to the left is built by University of Michigan biomedical engineering undergraduate and graduate students based on the student's understanding of what is available in Uganda and what they think is needed in Uganda. The image to the right is built by St. Joseph Technical School students and technicians based on what they can purchase in local stores and what they know of the needs of Virika Hospital.

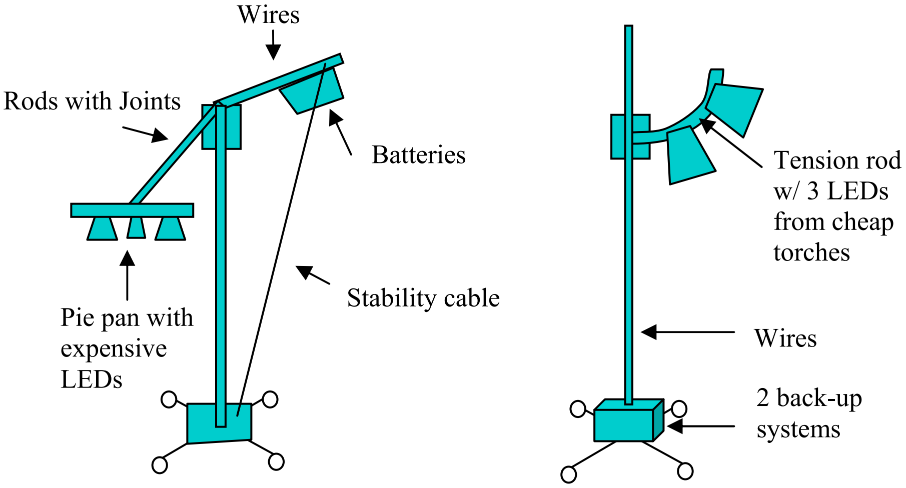

**Figure 57: Juxtaposing University of Michigan biomedical engineers' surgical lamp design to St. Joseph Technical Institute technicians' surgical lamp design.**

The cost of the UM engineers' lamp was approximate $300 for the alpha prototype (with dry cell batteries). The cost of the technicians' lamp was approximate $150 to build. The technicians design included an inverter to charge from the grid (incorporated from the Ugandan available Taigeer[28] torches which charge batteries from the grid) and a hand-

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[28] Please visit http://en.taigeer.com/ for more information about these torches which are available in many parts of Uganda.

crank generator (to be used during energy crisis events when the grid has been off for a long time). The hand crank generator is geared-up three times.

05 08 2009

**Figure 58: St. Joseph Technical Institute technicians' hand crank generator with bicycle DC permanent magnet motor used as generator (left) and with car alternator (right).**

The hope is that two things are learned from juxtaposing outsider's designs to insider's designs: (1) that outside organizations value how to co-design and build with local expertise and equipment and (2) that locally manufactured energy devices can meet local needs better than an imported design because the assumptions going into the design are known. One example is the double back-up electrical energy system the technicians included versus the dry cell batteries the outsiders included.

Transitioning back to the social benefit issues, there are five terms to consider. The first two terms deal with the same empowerment and pays for itself terms discussed in the previous section, but now there are three new terms.

$$\text{System Benefits} = benefit_{1-\text{decrease health crisis hours}} + benefit_{2-\text{decrease loss of life/year}} + benefit_{3-LEDs\text{ end of life}}$$

The first term deals with the decrease number of health crisis hours. There were 518 services hours where both the electric grid and diesel generator failed and no electrical lighting was available. With this back-up surgical lighting system, lighting energy crisis events are decreased during surgery. The second term deals with the decrease in risk associated with the patient dieing. This means that the hand-crank generator could be used for the oxygen concentrations and/or anesthesia machine when the batteries are charged to run the lights. The final term deals with the benefits of using LEDs over CFLs.

### 4.3D Vertical Wind Generator

Due to the topography of Fort Portal, Uganda, there is potential for low to high height, high wind speed vertical wind generators. There are key areas mountainous areas which offer wonderful opportunities for wind generation.

**Figure 59: St. Joseph Technical Institute technicians' designing and building the wind turbine in five days**

There have already been text messages to me and visitors to the Institute with interest in this vertical wind turbine design. The problem currently is that the car alternator is not matched well with the wind turbine. Consequently, I worked on co-designing generators with the rewinders. The following are their designs:

Figure 60: St. Joseph Technical Institute rewinders' designing and building their winded coils that were used with permanent magnets to light LEDs

Another issue is the wind resource in the area. I installed a Hobo weather station at Virika Hospital to measure the wind speed (m/s) and direction as well as the solar radiance (W/m2) and rainfall.

Figure 61: Hobo weather station being installed by me at Virika Hospital

This Hobo weather station is connected with a satellite antenna system such that it transmits the data to me while I am in the United States. The following are the results from the weather station:

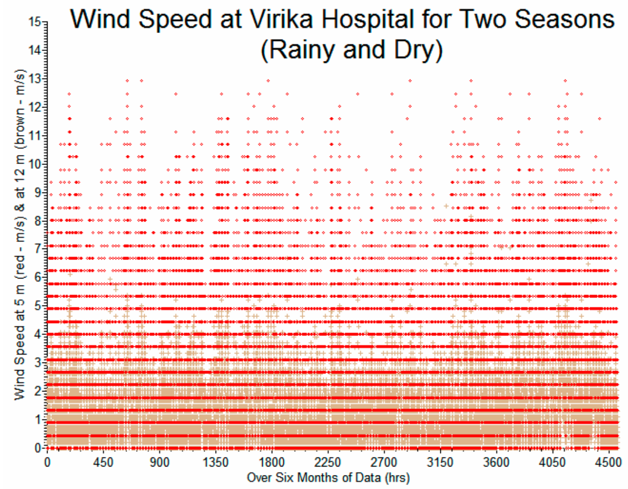

Figure 62: Wind speed data at 5 meters and extrapolated to 12 meters

As can be seen, there is not enough wind resources at the hospital to justify a low height wind turbine. However, in the background of Figure 61, one can see the mountainous regions. These mountains in theory would have wind resources available. Also, in the future, I might install the weather station higher and see what the wind speed would be at a higher height. I did extrapolate wind speed values from my measurements, but since the weather station was place between buildings, this would not be accurate and needs to be verified before building a 12 meter tower for the wind turbine (a tower would be expensive).

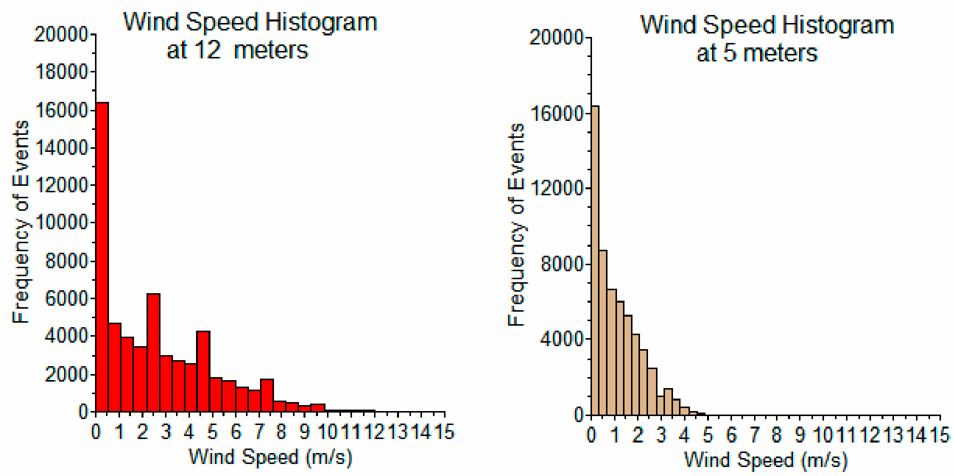

**Figure 63: Wind speed data frequency at 5 meters and extrapolated to 12 meters**

Based on the data which was extrapolated, wind energy would not be significant at the hospital for most projects. However, if one compares the histogram of wind energy and solar radiance, then there is a potential which needs more exploration in future work.

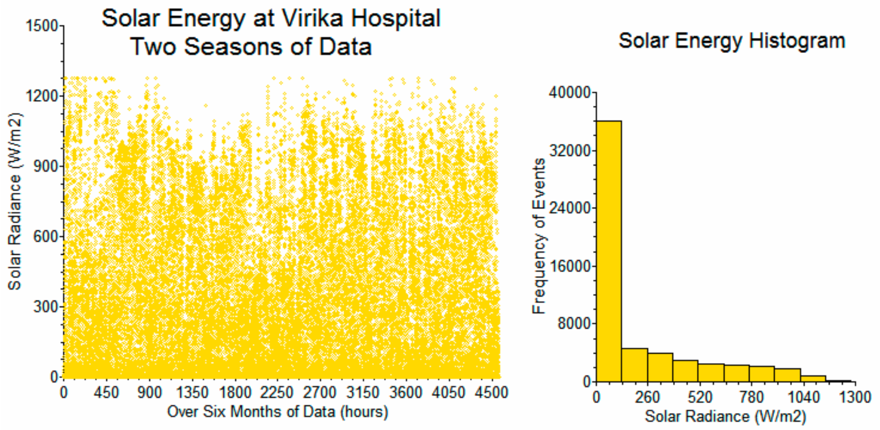

**Figure 64: Wind speed data frequency at 5 meters and extrapolated to 12 meters**

In Figure 64, the solar radiance of 1.0 $kW/m^2$ is found for the two to four peak hours when the sun is at its highest position in the sky. This is the typical result which suggests that solar energy is a great resource for any country in Africa. However, the frequency of events at this radiance is small which is similar to the wind energy data. This suggests to me that there could be the same number of wind events (say 2 to 4 hours) which is at 8 to 10 m/s. This is a strong enough wind speed to generate electricity with a correctly matched wind turbine.

### 4.3E Micro-Hydroelectric Generator

Due to the many rivers in Fort Portal and throughout Uganda, there is potential for low head, high water speed micro-hydroelectric generators.

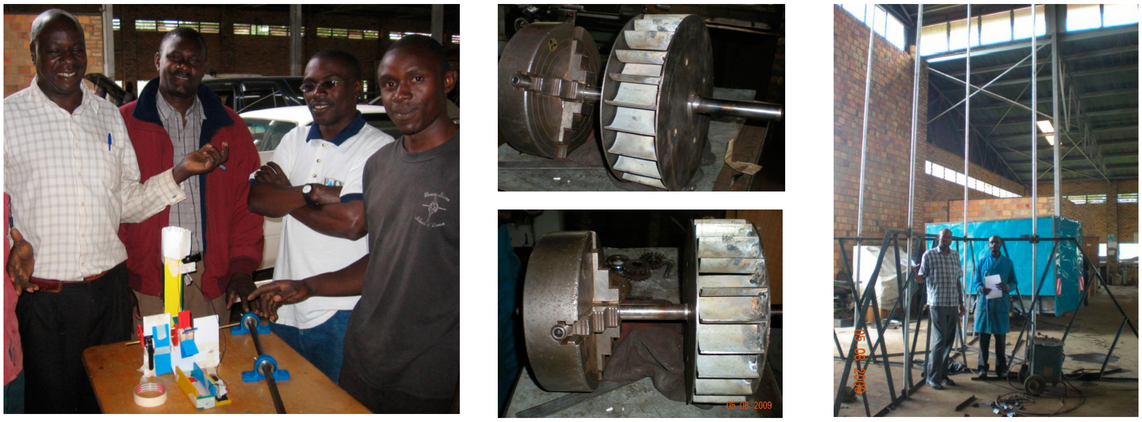

Figure 65: Trade show built micro-hydroelectric generator model, turbine, and 12 m stand

There are many rivers and streams which run between the three main lakes and Lake Victoria as seen in Figure 65.

**Figure 66: Map of Uganda from UNESCO illustrates the vast amounts of lakes and the major rivers which run between lakes to the main lake: Lake Victoria**

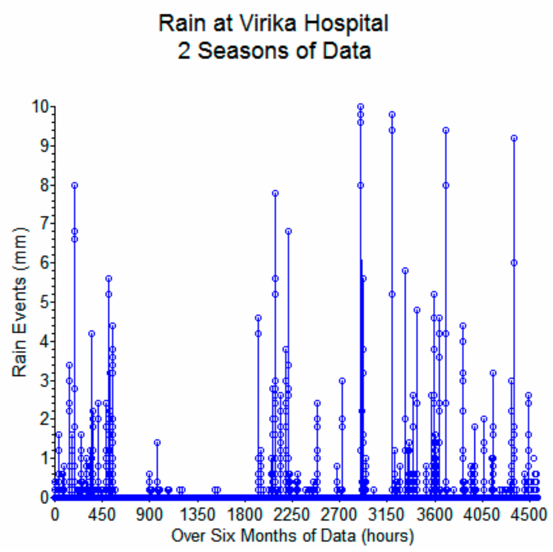

**Figure 67: Rain falling at the Hospital considered to run a hydroelectric generator**

Measurements at the hospital reveal that not enough rain events occur to justify running a hydroelectric generator from the rain (which was expected). The main purpose for the hydroelectric generator designed and built by the technicians was to supply power to off-grid villages who are located near a stream which runs year-round.

### 4.3F Merry-Go-Round Generator

Due to the many schools throughout Uganda without access to electricity and playgrounds, there is potential for children to play and generate electricity at their schools. St. Joseph's Technical Institute and Sts. Peter & Paul's Primary School in Fort Portal, Uganda contacted me to co-create an electricity system for Ugandan student borders and teachers which is better than the kerosene lanterns they are currently using. In Uganda, there are cases of schools burning down due to the use of these lanterns in rooms with large amounts of children. Furthermore, indoor air pollution due to these lanterns has been documented in the World Energy Assessment [23]. Considering Figure 68, the two merry-go-round generators can provide multiple benefits for the community and school.

**Figure 68: Merry-Go-Round generator for this Ugandan school designed by mechanical engineering students juxtaposed with local technicians design[29]**

These designs both use all locally available equipment and recycles automobile tires. Panos Papalambros opened the door for me to create a senior design module for his ADP 555 course at University of Michigan which mechanical engineering students enthusiastically choose. With my encouragement, this student group considered an open

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[29] Images from University of Michigan's student project by Madhav Goel, Rui Mu, Karan Patel, and Po-Chi Wu. Images from technicians work at time of dissertation.

source design methodology (different from the biomedical engineering students). Thus they worked with local technicians, thru me, to create a Bottom of the Pyramid (BoP) social entrepreneurial microeconomic model. Their microeconomic model needs more verification and validation, but in general it appears that there is a great unmet demand for these devices at schools all over Uganda (they claimed $280,000 USD of profit would go to the technicians building this business after five years).

Trying to calculate the energy generation from children's play, I again used the energy consumption rate from kinesiology research. However, here the situation involves using the energy children output when playing football (US soccer) instead to generate electricity. This requires using the Basal Metabolic Rate (BMR) for children as a way of scaling the adult BMR used for the Metabolic Equivalent of Task (MET) given in Table 13. Here the maximum power generated from ten children running around the merry-go-round generator is 600 Watts. This output is easily achievable using a vehicle alternator that has been geared-up from a low rpm from the generator to 1000+ rpms needed for this given output on the alternator. There are currently two designs the local technicians have. One includes using the parts of a typical transmission gearing system from a vehicle. These parts are easily available in Uganda from recycle vehicles. However, the electrical energy will need to be stored and used at the night in the dorms.

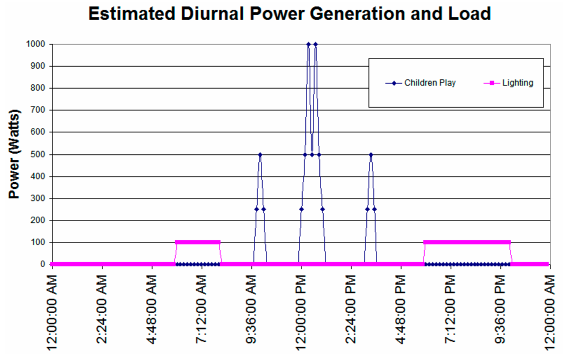

**Figure 69: Merry-Go-Round power generation curve (blue) versus power load curve (pink)**

Figure 69 shows an estimated diurnal power generation (from children's play) and power load curve (from using lights early in the morning and late at night). As one can see, the energy logic system will use a set of batteries to run the LED lighting system. The one drawback from this system is whether or not more energy can be generated from multiple recess groups alternating throughout the day. Currently, very few children are modeled to play on the merry-go-round system. However, in Ghana a similar merry-go-round system was designed and the school used it to run computers as well as charge cell phones. Consequently, the benefit terms are added are two.

$$\text{System Benefit} = benefit_{1-fire.risk} + benefit_{2-indoor.air.pollutione}$$

The first term is the benefit with using electrical lighting instead of kerosene lanterns in terms of decreasing risks to children. The second term is more important because it deals with the indoor air pollution associated with kerosene lanterns.

### 4.3G Conclusion to Section 4.3

The argument should not be capitalism versus socialism, but rather what Nobel Laureate Muhammad Yunus calls a hybrid of both profit maximizing business (PMB) and a social maximizing business (SMB) [74]. In a PMB, a person gains and loses wealth based on the way the business gains and losses revenue. In a SMB, a person gains and loses wealth based on the way the business gains and loses services. So, again how does this relate to electrical energy producing device?

Basically, an electrical energy generating device in Uganda needs to balance the PMB models without sacrificing the SMB benefits. There is no easy way to make this decision and really no rule of thumb to follow. Decreasing the risk to my sons' life, Ambrose, in terms of the public health risks by not having back-up surgical lighting should be worth the same amount as his Ugandan pen pal, David. However, in the United States, if we ever really faced energy crises as Uganda does, our government would spend a considerable amount of money for every hospital surgical room if we knew the unreliability of the grid + back-up diesel generator system was 7%. Of course this level of money is not available in Uganda so the government's policies to address these energy crises issues must be weighed against other crises issues.

So, was the United States 1970’s an energy crisis? No and yes. No, it was not in terms of the energy crises Ugandans face on a daily basis. Yes, it was in terms of unreliability of oil for an energy sector which depended solely on oil. Is the United States in danger of facing another energy crisis for the transportation sector? Yes, because it still primarily depends on oil. The next chapter transitions to diversifying the transportation light-duty vehicle sector such that an energy crisis is less probable even though we do not know what the next energy source will be. This design is a transition design to explore driver options.

# Chapter 5. Two-Fuel Hybrid – US Averting a Future Light-Duty Transportation Sector Energy Crisis

This chapter describes an optimization study for a two-fuel IC engine hybridized with an electric powertrain. It is designed to maximize fuel economy within set performance constraints by optimizing a three-level design and control sequential algorithm: (level 1) engine and motor design for maximum power and speed, (level 2) engine and motor speeds during driving cycle, and (level 3) power switch points during driving cycle. The goal was two fold. First goal was to understand the feasibility of diversifying the engine powertrain fuels which was achieved. The second goal was to discuss and understand the coupling effects between the three levels which was not achieved, but establishes a clear objective for future research.

Scenario: Imagine the 1970s happening this year. What happened? There was an oil shortage. Roads were empty paths of concrete appearing as a relic from an ancient civilization. Long lines waited at gas stations once at least 10 gallons were available/person. Speed limits went down to 55 mph to conserve fuel. An electric vehicle would have gotten people to and from work within a 30 mile range, but they did not exist. Now what would happen? The same thing would happen. Have we learned anything? Yes. Have we done anything about it? No. Why? Because no one knows what the new locked-in energy source for vehicles will be. This is where my transition mode hybrid fits into the picture. It will transition the United States from gasoline to either an alternative fuel or to an all electric vehicle with its' adaptive and robust design. Furthermore, if the United States experiences unreliability in gasoline supply (as Uganda experiences unreliability in electricity generation), then this hybrid could potentially avert this energy crisis in a way that a vehicle without four back-up energy source possibilities cannot do.

I design in this chapter the two-fuel, three driver-choice option, ten mode[30] hybrid electric vehicle to diversify the light-duty transportation sector: designing to avert a future energy crisis. The three driver-choice options include all electric, suburban 1, and suburban 2/highway options set up as a dashboard driver choice. The ten mode expert system power management strategy incorporates two battery charging/discharging cycles (50% HEV versus 20/80% EV/PHEV). Together this transition mode hybrid allows the United States light-duty sector to diverse the powertrain in terms of the potential for plug-in electricity, traditional fossil fuel and three upcoming alternative fuels. However, knowing that the on-the-road fuel economy of the United States takes years to reflect the Reformed CAFE regulation, I propose in the conclusion a new policy to empower technicians to modify vehicles to run off a new energy source (sustainable spark-ignited fuel and/or plug-in hybrid capabilities) similar to what was accomplished in Chapter 4.

The advanced technology simulated includes cylinder-deactivation with two direct-injection fuel lines incorporating gasoline in one line and an alternative fuel in the other: Gasoline Electric Motor/Generator Alternative Fuel Hybrid (GEM-AFH). Optimization was accomplished over four driving cycles and includes the gasoline and alternative fuel IC engine speed along with the two electric motors/generators combined into one combined speed [88-91]. Analytical models are used to simulate the two engines and electric motors/generators [92, 88-91]. To validate the model, I ran three baseline simulations comparing fuel economy gains versus those reported in the literature: V6 gasoline ICE (23 mpg), V3/V6 cylinder deactivation gasoline ICE (25 mpg), V3/V6 cylinder deactivation electric motor hybrid (32 mpg), and GEM-AFH (35 mpg). The two fuels option with cylinder deactivation was conceived to consider an alternative approach to the flex fuel vehicle and plug-in hybrid and the future possibility of incorporating an engine which has one set of cylinders running in a HCCI/PCCI mode while the others running in traditional SI mode potentially with an alternative fuel. The three alternative fuels modeled were methane, ethanol, and hydrogen.

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[30] A mode here refers to a specific power management choice. There are 27 possible modes in this hybrid powertrain explained later on in this chapter.

## INTRODUCTION

Motivated by increased demand and price in fossil fuels coupled with the hope of near economic feasibility of renewable or sustainable energy sources, the automobile industry and fueling industry has shown increased research and development programs for alternative fuels. The vehicles range between a wide spectrum: dependence on enormous fueling infrastructure to minimal fueling infrastructure needed. Since the GEM-AFH can use any one of the spark-ignited alternative fuels in a cylinder-deactivation mode, it will be up to automotive companies or consumers (as well as future simulations) to decide which alternative fuel to use. Furthermore, as new alternative fueling infrastructures expand and economies of scale drive down prices, the GEM-AFH engine can serve as an adaptive medium, transitioning us away from our current reliance on gasoline. Currently, the flex fuel vehicle offers this for some liquid fuels mixture; however being able to run two sets of cylinders in different modes of operation (given the same speed) open new doors of power management for high power regions and should be explored.

## DEVELOPMENTAL GOAL

The first goal is to design a virtual analytical optimization model for the adaptive GEM-AFH engine which can offer a gradual transition from gasoline to any alternate fuel while using the benefits of cylinder deactivation and electric motor hybridization as well as explore the high power hybridization regime. The second goal was to explore the coupling effects between design with control sequential optimization algorithms.

## 5.1 Literature and in–production review of Hybrids

Fuel economy and fuel intensity are discussed in general in the literature with fuel economy given more attention in the United States than fuel intensity. Both arguments will be presented with a slight emphasis on fuel intensity. A brief discussion of the benefits of cylinder deactivation and electric motor hybridization are discussed as well as a literature review of typical fuel economy gains.

### 5.1A Fuel Economy of Manufactured Hybrids

Comparing this vehicle to US manufactured hybrids is based on available published data. The data was used to create the bounds of the optimization inputs and to check the final results. For example, the V6 gasoline ICE with electric motor hybridization optimization result for this analytical model calculated a fuel economy of 32 mpg for the combine driving cycle. Table 17 gives the vehicles characteristics for the Ford Escape, Honda Accord, and Toyota Highlander:

| **Hybrid** | **Ford Escape** | **Honda Accord** | **Toyota Highlander** |
|---|---|---|---|
| Engine | 2.3 L I4 | 3.0 L V6 | 3.3 L V6 |
| Bore | 87.5 mm | 86.0 mm | 92 mm |
| Stroke | 94 mm | 86.0 mm | 83.1 mm |
| Comp. Ratio | 9.4 | 10.5 | 10.8 |
| Power | 114 kW | 178 kW | 155 kW |
| Electric Motor | Permanent AC Synchronous | Interior Permanent Motor | Permanent Magnet Motor |
| Power | 94 hp (70 kW) @3000 -5000 rpm | 16 hp (12 kW) @ 983 - 6500 rpm | 68 hp (50 kW) @ 4610 -5120 rpm |
| Battery | Ni-MH | Ni-MH | Ni-MH |
| Voltage | 330 V | 144 V | 288 V |
| EPA highway | 29 mpg | 37 | 28 mpg |
| EPA city | 24 mpg | 29 | 33 mpg |
| Weight (curb) | 1443 kg | 1591 kg | 1850 kg |
| Transmission | Electronic CVT | 5-spd auto VCM | Electronic CVT |

**Table 17: 2006 Model year manufactured hybrids.**

The GEM-AFH vehicle does not differ significantly from these with respect to weight, 1600 kg, engine size, 2.4 L, and engine power, 115 kW. However, it differs slightly in fuel intensity from the Toyota Prius and potentially will improve fuel economy for many mid-size vehicles and small SUVs. For example, consider Figure 70 reprinted with the permission of Feng An [14].

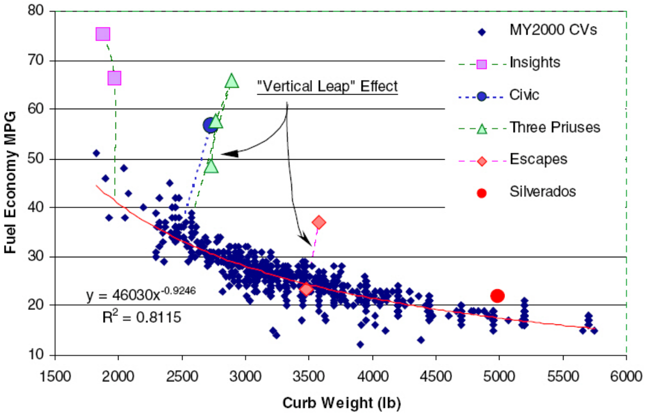

**Figure 70: Mass versus MPG relationship for conventional vehicles and "Verticle Leap Effects" for hybrid vehicles.**

In Figure 70, each hybrid is presented as having a "Vertical Leap" effect with respect to fuel economy. The GEM-AFH is no different. Moreover, when comparing it with the Toyota Prius, which won the 2004 Motor Trend Car of the Year award for its improved fuel economy as well as other impressive attributes, the GEM-AFH has greater fuel intensity benefits to its market replacements as can be seen in the table below:

| **Vehicle** | **Toyota Prius** | **GEM-AFH** |
|---|---|---|
| Conventional | 35 mi/gal<br>0.029 gal/mi | 23 mi/gal<br>0.043 gal/mi |
| Improved | 60 mi/gal<br>0.017 gal/mi | 35 mi/gal<br>0.029gal/mi |
| Difference | 0.012 gal/mi | 0.014 gal/mi |

**Table 18: Conventional and improved vehicle differences in fuel economy.**

As can be seen in Table 18, the GEM-AFH has the potential to save more fuel than the Toyota Prius due to the nature of the US's current fleet. In other words, it is more effective and important to change vehicle powertrain designs from 23 mpg to 35 mpg than from 35 mpg to 60 mpg. Considering the popularity of SUVs and large trucks, it is no wonder that many automotive companies in the US have plans to hybridize these vehicles first.

### 5.1B Fuel Economy – V3/V6 Cylinder Deactivation

Cylinder deactivation has been widely demonstrated as a potential method to improve fuel economy by reducing the pumping losses of an engine [27, 51]. Traditional operation of a spark-ignition engine at light loads involves throttling the airflow in order to maintain stoichiometric conditions in each cylinder. By reducing the number of cylinders, the remaining cylinders in operation require less throttling in order to maintain the same power output. In addition, combustion performance and thermal efficiency may also be improved because the active cylinders running at higher load have an increased effective compression ratio, faster burn rate (partially due to reduced residual gas fractions) and lower relative heat losses [38, 40]. There may also be a positive gain from the balance of reduced friction in the inactive cylinders versus additional friction in the more heavily loaded active cylinders [40].

One possible drawback of cylinder deactivation stems from the step change in output of the engine from turning the cylinders on and off. This reduces the frequency of the torque pulsations from the spacing of the firing but can increase the amplitude of these pulsations at the crankshaft. This leads to a constraint of noise, vibration and harshness (NVH) on the operating limits of cylinder deactivation. In addition, the complexity of the controls needed along with their resulting costs can limit the practicality of the method. However, past use of cylinder deactivation illustrates that researchers believe enough in the positive benefits to put this technology into production automobiles:

- 1916 - Enger “Twin-Unit Twelve” V12-6 [23]
- 1981 - Cadillac Eldorado V8-6-4
- 1983 - Mitsubishi ORION-MD I4-2 [8]
- 1993 - Mitsubishi MIVEC I4-2 [10]

- 1998 - Mercedes 5.0L V8-4 and 6.0L V12-6 S-Class [7]
- 2004 - DaimlerChrysler 5.7L V8-4 HEMI® [6]
- 2005 - Honda Accord 3.0 L V6-3 [2005-01-0274]

A common guideline for technologies that eliminate pumping losses is that the heavier vehicles that have a higher ratio of engine size to vehicle mass are the type that respond best to its usage [40]. This combination of vehicle weight and engine size along with the gear ratio of the transmission has a major influence on the engine operating during cylinder deactivated mode [38]. In 2002, a National Research Council report suggested that fuel consumption can be reduced from 3-6% by using cylinder deactivation [30]. The researchers in [40] calculated that 2.4-5.0% of fuel energy used in the EPA combined cycle test goes to pumping losses. They determined that by using an indicated efficiency of 37%, this gives a range of 6.5-13.5% reduction of fuel consumption that can come from the elimination of pumping losses. Other transient test cycle improvements using cylinder deactivation were found in [43] where a 7-14% improvement is found based on driving cycle, and in [35] where a 23% increase in fuel economy was seen over a conventional gasoline engine for a 4.3 L Turbo Lean-Burn CNG engine operating with a skip fire cylinder deactivation.

### 5.1C Fuel Economy – Electric Motor Hybridization

Hybridization has been widely demonstrated as a method to improve fuel economy by reducing idling loses, recapturing braking energy, and reducing transient loses [14, 18, 24, 55, 79, 82-85, 88-91]. Traditional operation of a spark-ignition engine at light loads involves higher levels of friction. However, the electric motor is more efficient at light loads. In addition, prior to adding an electric motor into the powertrain, braking energy was lost to heat, but now the electric motor can operate to charge the battery. Finally, some drivers tend to accelerate and decelerate often and for mild acceleration, the electric motor can operate for coasting speeds on the highway and mild transients; thereby, leaving the engine either off or in its efficient operating point.

Some drawbacks of hybridization stems from the advance controls needed, the addition of weight, and their interdependence on driving cycles (or how fuel economy depends on user). However, current use of hybridization illustrates that researchers and manufactures believe enough and have proven in recent years in the positive benefits to put this technology into production automobiles as well as future plans. In addition to these, combining cylinder deactivation with electric motor hybridization has also been manufactured in the Honda Accord 3.0 L V3-6 [82]. Adding two fuels lines into a cylinder deactivation electric hybrid engine offers an additional degree of freedom.

## 5.2. Two-Fuel Hybrid Baseline Comparisons

As a model validation check, it is important to compare our simulation efforts with previous observations in the literature. As a result, three baseline simulations were run to examine the effects of cylinder deactivation, hybridization and alternative fuel incorporation. All baselines utilized the same power management strategy incorporating different rules depending on the number of components included in the propulsion system (see Power Domain section). Optimization for each baseline was based on minimizing inefficiencies with respect to engine and electric motor speeds.

### 5.2A V6 Gasoline.

The simulation of the baseline V6 gasoline engine calculated a final fuel economy of 23 MPG over the urban driving cycle (although, four driving cycles were completed). Based on the size of the engine and the weight of the vehicle, we find that this average slightly higher than other vehicles currently in production (see Table 19) due to the wide-open-throttle (WOT) operation of the analytic model[31]:

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[31] Due to the WOT throttle requirements of the analytic model, power requirements are not met in the optimization (i.e. idling conditions are not met). The fuel economy is calculated using the lowest power at WOT even though this power is more than required by the driving cycle.

| 2005 Vehicles | MPG (city) | Engine | Weight (kg) |
|---|---|---|---|
| Ford Free Style | 18 | 3.0 L V6 | 1869 |
| Dodge Caravan | 19 | 3.3 L V6 | 1885 |
| Mercury Mariner | 18 | 3.0 L V6 | 1600 |
| Hyundai Santa Fe | 17 | 3.5 L V6 | 1705 |
| Honda Pilot | 17 | 3.5 L V6 | 2006 |

**Table 19: 2005 model year vehicles of the same size as GEM-AFH.**

### 5.2B V3/V6 Gasoline.

When optimizing the system for cylinder deactivation, the simulation calculates an improved fuel economy of 25 MPG. This ends up being an improvement of 8% in the fuel economy over the urban driving cycle calculated as follows:

$$\text{improvement} = \frac{\text{MPG}_{\text{V3/V6}} - \text{MPG}_{\text{V6}}}{\text{MPG}_{\text{V6}}}$$

Based on my literature search, I anticipate around a 6 to 10% improvement as shown in Appendix C. This is within the range because the analytical model meets all power requirements with cylinder deactivation.

### 5.2C V3/V6 Hybrid Gasoline.

Hybridizing the engine increases the fuel economy up to 32 MPG which is an improvement of 28% over the cylinder deactivated version and 39% over the baseline V6 gasoline model. Compared to 2006 models in Table 20, I find that the simulation predicts within the Ford Escape and Toyota Highlander values:

| Vehicle | MPG (city) | Engine | Transmission |
|---|---|---|---|
| Escape HEV | 36 | 2.3L I4 | Electronic CVT |
| Escape | 22 | 2.3L I4 | 4-spd auto |
| Highlander HEV | 31 | 3.3L V6 | Electronic CVT |
| Highlander | 18 | 3.3L V6 | 5-spd auto |

**Table 20: 2006 model year improvements due to hybridization over conventional model (all 4WD vehicles)**

### 5.2D V3/V6 Hybrid Gasoline+Alternative Fuel.

Finally, when I utilize alternative fuels, I get different results depending on which fuel is chosen. For the best alternative fuel, I achieve a fuel economy of 35 mpg which is an improvement of 9% over the hybridized/cylinder deactivated version, 40% over the cylinder deactivated version, 59% over the baseline.

Given these results, I make the conclusion here that this engine design is feasible and compelling and that the power management strategy can be employed within this design, but that I need a complete dynamic vehicle model in future iterations. However, it is suggestive that this configuration uniquely optimizes the additional low-to-medium and medium-to-high power domain offering greater flexibility for the power management. Moreover, this power management conceptualization allowed me to optimize the switching power modes ($P_{LM}$=29 kW and $P_{MH}$=30 kW). This result must be explored further because it is not at all expected, but before explaining this result, I must explain how the power management strategy was set-up.

## 5.3. Power Management Domains & Three Level Design/Control Optimization

Driving cycles directly effect the optimization of all HEVs. The effect of various driving cycles on HEVs performance has been investigated in depth by An. [83]. Moreover, it has also been measured in customer driving by Yaegashi at el [84] that EPA's fuel economy measurements for hybrids do not correlate with user fuel economy. Overall, this section will discuss our presentation of US EPA's city driving and how this lead to a mainstreaming of the power management rules for efficient calculations as well as a projected future ability to specifically optimize the power management rules instead of choosing them based on engineering intuition[32]. In addition to this, I note a significant power domain hole within the US EPA city driving cycle.

$$P = Fv = mva$$

$$\frac{P}{m} = va$$

The first two equations simply show the relationship between power, force, velocity, mass, and acceleration. Bringing mass over with power allows velocity versus acceleration to be independent of mass. The purpose of this is to argue that the driving cycle, created in terms of velocity and time, has an underlining fundamental role with the power management strategy. As seen in the Figure 71, the power domain hole means that any static power management strategy based on this driving cycle does not consider the state points of operation. Thus, drivers driving in these regimes will potentially have less than optimal results.

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[32] This research used engineering intuition first for choosing our power management rules, but then optimized for the power switch points.

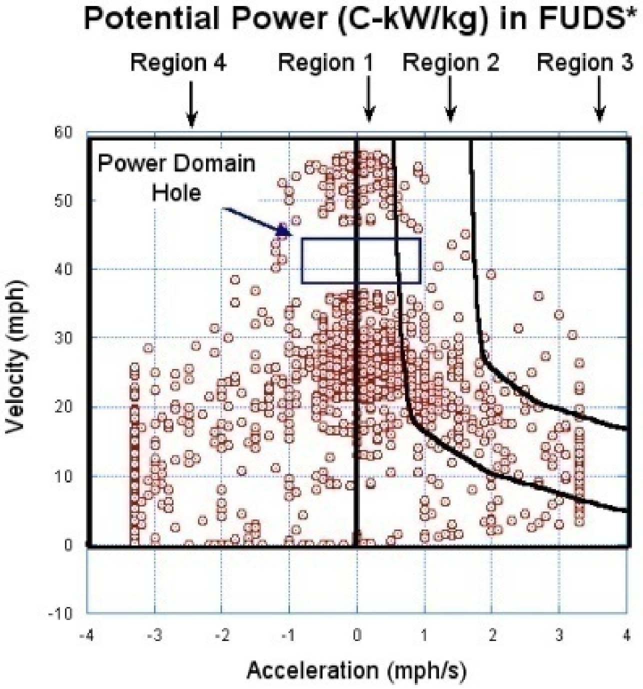
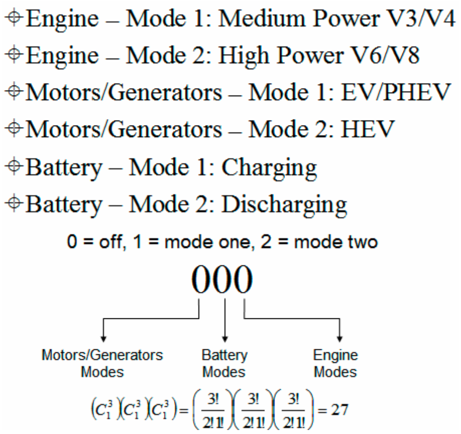


**Figure 71: Potential power demand.**

The two axes are velocity and acceleration instead of power and velocity or velocity and time. The two curves are drawn as approximate constant power curves. Region one represents low operating regimes. Typically, the motor/generator/battery system can handle all the loads except when the state of charge of the battery runs too low and then the gasoline engine will charge the battery. Region two handles medium loads where the gasoline ICE operates alone (i.e. three of the cylinders) or with the electric motors/generators to charge the battery. Region three operates in high areas where all three components run: gasoline ICE with alternative fuel ICE (six cylinders modeled as two three-cylinder engines running at the same speed), and electric motors/generators. The final region is the regenerative braking regime or negative acceleration. The amount of energy which can be generated depends on the size and configuration of the electric motors/generators.

Due to our focus on the power management strategy for hybridizations, the potential power domain was used to simplify the power management strategies. However, first a general strategy was created to formalize the number of possible combinations for this hybrid.

Figure 72 was created as a general methodology to figure out all the permutations possible in creating a hybrid energy system.



$$\left(C_1^3\right)\left(C_1^3\right)\left(C_1^3\right)=\left(\frac{3!}{2!1!}\right)\left(\frac{3!}{2!1!}\right)\left(\frac{3!}{2!1!}\right)=27$$

**Figure 72: Repeatable Combinations of sub-systems with two modes in this hybrid.**

Some of these combinations are physically possible, but some of the 27 sub-system combinations are not. The most interesting thing is to consider all the ways the engine can be operating in medium power versus high power modes. Table 21 illustrates the two mode options available currently in manufactured vehicles, but not discussed in this way.

- Cylinder Options:
  - Mode 1 – Fossil Fuel in 3 cylinders activated and with 3 deactivated
  - Mode 2 – Fossil Fuel in 3 cylinders and 3 cylinders with Sustainable Fuel
  - Mode 1 – Sustainable Fuel in 3 cylinders activated with 3 deactivated
  - Mode 2 – Sustainable Fuel in 3 cylinders and 3 cylinders with Fossil Fuel
- Pressure Options:
  - Mode 1 - downsized engine not engaging turbo-charge
  - Mode 2 - downsized engine engaging turbo- charge
- Thermodynamic Cycle Options:
  - Mode 1 - gasoline engine using Atkinson cycle
  - Mode 2 – gasoline engine using Otto cycle

**Table 21: Various engine modes for medium and high power operations.**

In Table 22, there are many possible choices for the power management strategy which are written as zeros for off, ones in the first mode, and twos in the second mode. However, it is best to first consider the driver options in this powertrain design. For the all electric and suburban 1 dashboard options, the choices boil down to the following.

| **Low Power** | **Motor** | **Battery** | **ICE** |
|---|---|---|---|
| 000 | Off | Off | Off |
| 110 | Mode 1 | Charge | Off |
| 120 | Mode 1 | Discharge | Off |
| **Med Power** | **Motor** | **Battery** | **ICE** |
| 001 | Off | Off | Mode 1 |
| 111 | Mode 1 | Charge | Mode 1 |
| 121 | Mode 1 | Discharge | Mode 1 |
| **High Power** | **Motor** | **Battery** | **ICE** |
| 002 | Off | Off | Mode 2 |
| 112 | Mode 1 | Charge | Mode 2 |
| 122 | Mode 1 | Discharge | Mode 2 |

**Table 22: Power Management Options for urban (electric plug-in) and suburban 1 (plug-in) driver options (20/80% SOC cycle).**

In the low power regime, the powertrain operates as an all electric vehicle (with a range of 30 miles, but that will be discussed later on). In the medium power regime, the hybrid operates as a traditional plug-in hybrid electric vehicle (PHEV). In the high power regime, the hybrid operates as a new plug-in hybrid electric vehicle (Alt-PHEV). These options appear in the potential power driving cycle as the following:

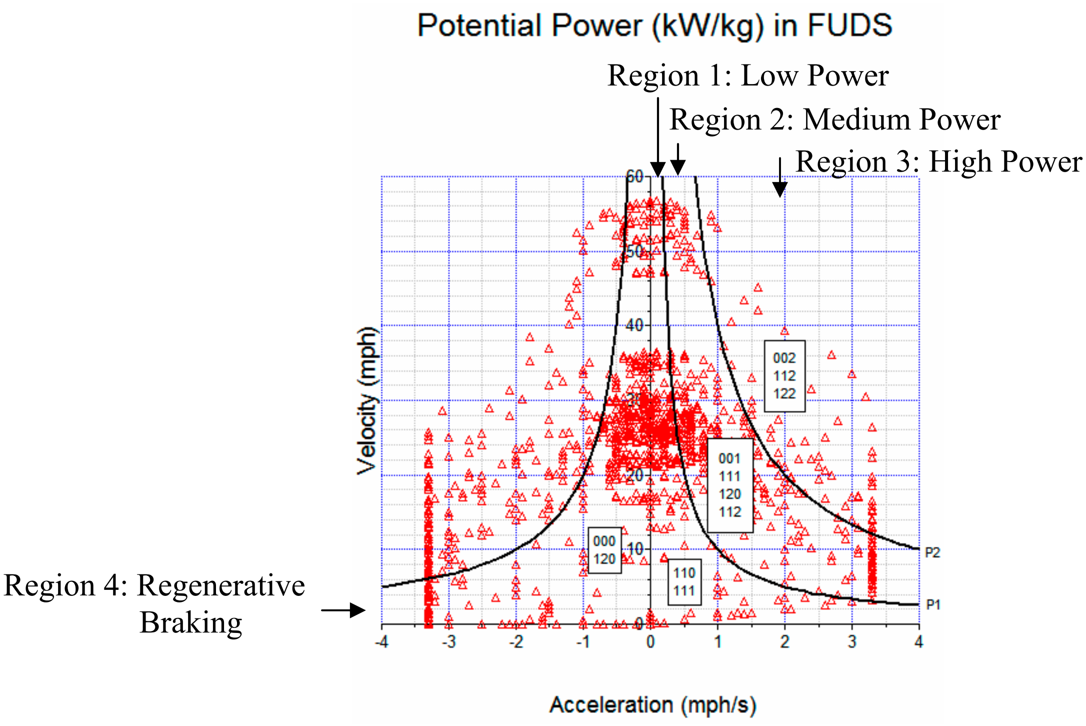


**Figure 73: Power management strategy for suburban 1 option.**

There are only two values ($P_{low}$ = P1 and $P_{high}$ = P2) which dictate all the choices except the regenerative braking region. For example, in regime one the power management choices are two: 110 and 111. Consequently, depending on the power demand and state-of-charge of the battery (SOC), there is a smaller subset of choices and the controls logic simplifies. However, this driving cycle is too powerful for the all electric mode. In fact, the two driving cycles which can be used in the all electric mode are the Japan 10*15 and NDEC driving cycles.

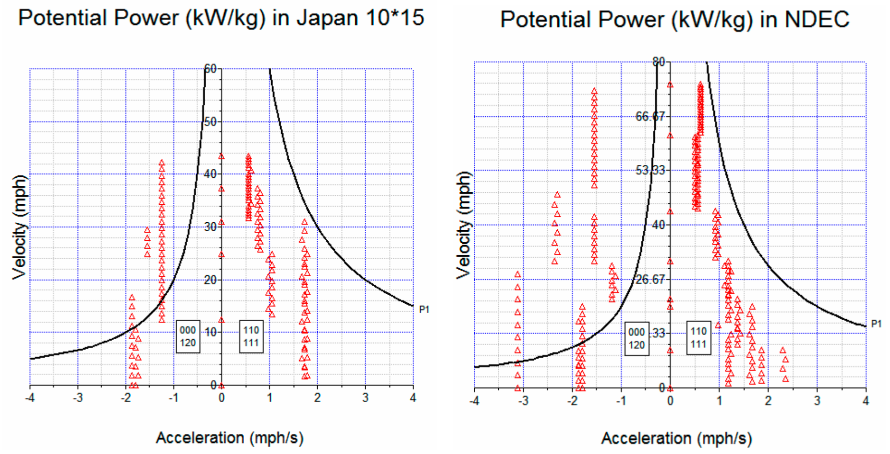


**Figure 74: Power management strategy for all electric options.**

In Figure 74, the constant power line, P1, illustrates that the vehicle can be in an all electric mode and meet all the power demands. However, in the US driving cycles, there are high power points which cannot be met by an all electric mode. If these points were scaled down (see yellow shade in Figure 75), then they could be met.

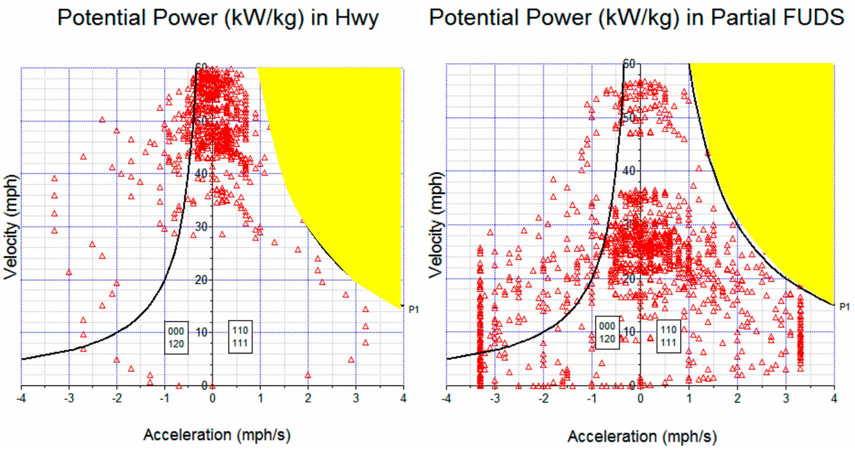


**Figure 75: Power management strategy for all electric options. Yellow data points power demand cannot be met.**

One interesting observation made about this driving cycle representation compared to the traditional representation of the velocity versus time or power versus velocity is that there are big holes where the driving cycle does not cover the power and/or energy domain. For example, this power domain hole shown in Figure 71 may explain why the Toyota Prius measures 60 mpg on the US Environmental Protection Agency (EPA) dynamometer test, but users measure 44.8 average mpg in real-world driving [84]. This difference is significantly greater than any other vehicle. Consequently, the third level optimization will change based on various driving cycles (i.e. expert system algorithm). The motivation is that the Hybrid Human Interface (HHI) concept allows users to manually shift between different power management strategies and have resulted in higher fuel economies for the Honda Insight[33].

---

[33] Some reported on Insight Central that on a 1,000 miles trip to Washington, DC, the MIMA Insight average 100.5 mpg, including driving in the city. Highway speeds ranged between 50-65 mpg.

In Table 23, there are many possible choices for the power management strategy which are written as zeros for off, ones in the first mode, and twos in the second mode. However, it is best to first consider the driver options in this powertrain design. For the suburban 2/highway dashboard option, the choices boil down to the following:

| **Low Power** | **Motor** | **Battery** | **ICE** |
|---|---|---|---|
| 000 | Off | Off | Off |
| 210 | Mode 2 | Charge | Off |
| 220 | Mode 2 | Discharge | Off |
| **Med Power** | **Motor** | **Battery** | **ICE** |
| 001 | Off | Off | Mode 1 |
| 211 | Mode 2 | Charge | Mode 1 |
| 221 | Mode 2 | Discharge | Mode 1 |
| **High Power** | **Motor** | **Battery** | **ICE** |
| 002 | Off | Off | Mode 2 |
| 212 | Mode 2 | Charge | Mode 2 |
| 222 | Mode 2 | Discharge | Mode 2 |

**Table 23: Power Management Options for suburban 2 and highway (HEV) driver options (50% SOC cycle).**

In the low and medium power regime, the powertrain operates as a tradition HEV (with a 300 mile range). In the high power regime, the hybrid operates as a new plug-in hybrid electric vehicle (Alt-PHEV). These options appear in the potential power driving cycle as the following:

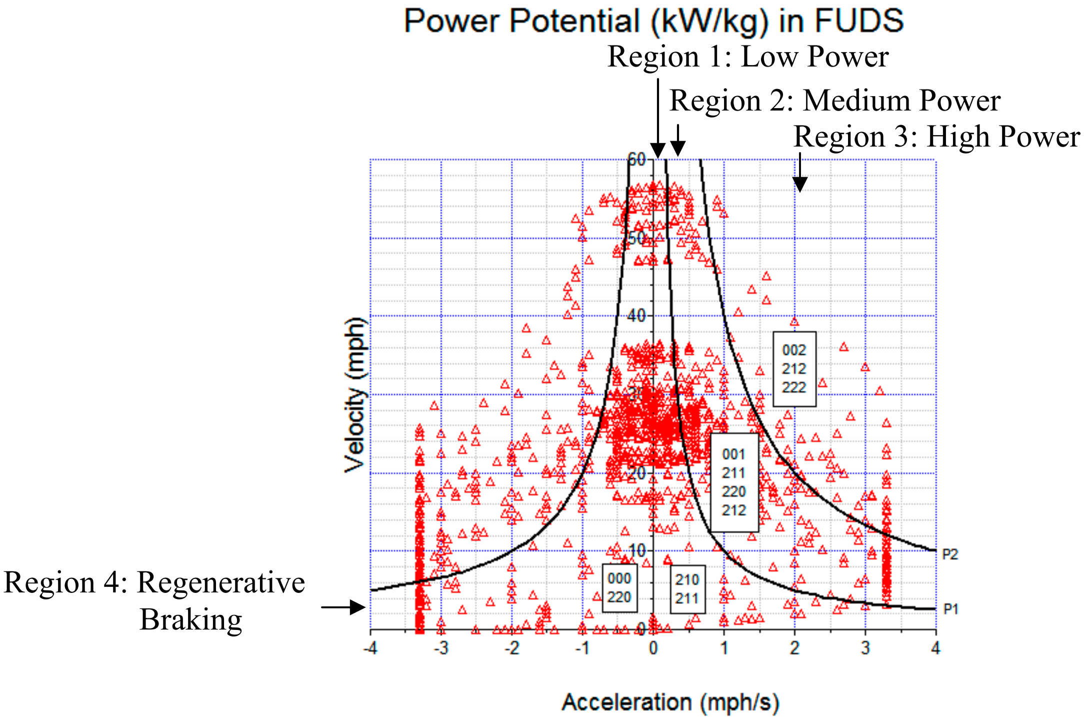


**Figure 76: Power management strategy for suburban 2/highway option.**

There are only two values ($P_{low}$ = P1 and $P_{high}$ = P2) which dictate all the choices except the regenerative braking region. For example, in regime one the power management choices are two: 210 and 211. Consequently, depending on the power demand and state-of-charge of the battery (SOC), there is a smaller subset of choices and the controls logic simplifies.

Using the power management logic set-up in this section, Section 5.3 will describe the following three level optimization structures and Section 5.4 will describe the results from each sequential optimization level.

### 5.3A Two Fuel Hybrid Concept

This two-fuel hybrid plug-in hybrid electric vehicle which will allow the United States to transition to a new sustainable energy fuel while (1) making the most of the electric grid for small in-town or in-city traveling trips (urban option) and (2) creating an electric vehicle for crisis events where a driver can at least drive 30 miles.

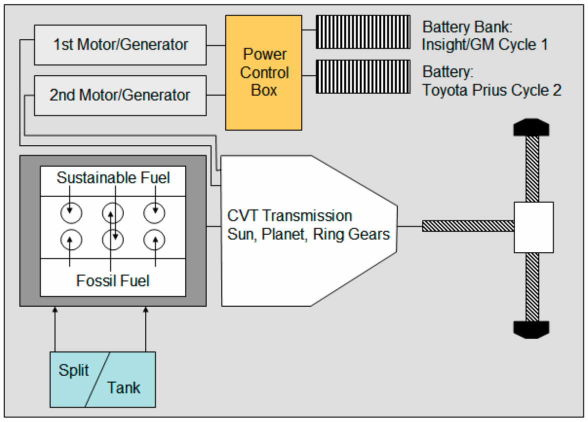


**Figure 77: Powertrain design for this two fuel cylinder deactivation hybrid electric vehicle.**

Unlike most new designs, this design is not based on new technology. Rather it is based on organizing currently manufactured technology in a new way.

- Cylinder Deactivation
  - First set on Fossil Fuel
  - Second set on Sustainable Fuel
- Continuous Variable Transmission
  - Sun, Ring, Planet Gears
  - Two Motors – GM Two-Mode
- Two Battery Banks
  - 50% - Prius charging/discharging cycle
  - 20/80% - Insight charging/discharging cycle
- Split tank with two fuel lines
- Dual fuel (sensors)
  - Tetra fuel vehicle in Brazil

**Table 24: Manufactured designs already existing in today's vehicles.**

Moreover, this design uses the drivers' knowledge to choose an all electric option (called urban option). This means that only part of the powertrain will be consider in the power management algorithm. Also, it means that the driver has to know that the vehicle range is only 30 miles and therefore must be prepared to plug-in to an electrical outlet to recharge the batteries (or switch to another driving option).

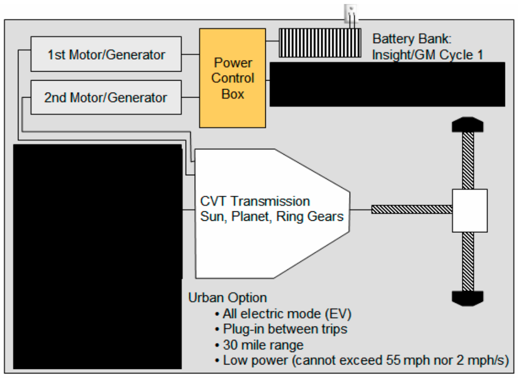


**Figure 78: The urban option – pure electric, 30 mile range, low power, and plug-in capability.**

The urban option is an all electric mode driver-chosen option. As can be seen in previous figures relating to the potential power, many of the points in the urban driving cycle cannot be met. The Japan 10*15 mode and the NDEC driving cycle can be used. However, the yellow box for the US city and highway driving cycles illustrate that there are operating points that an urban driving cycle option could not be used because this option is limited by 55 mpg maximum speed, 2 mph/s maximum acceleration, and a maximum power depending on the power switch point optimization at level three and motor/generator design at level one.

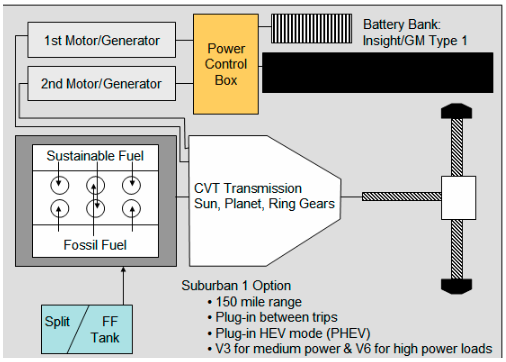


**Figure 79: Suburban 1 option – with a 150 mile range using plug-in capability.**

The suburban 1 option is the second driver choice on the dashboard. This option again uses a 20/80% battery charging/discharging SOC cycle, but allows the driver to have a longer HEV range (150 miles until switch to suburban 2/highway option). Moreover, medium and high power loads will be met. In the suburban 1 mode which uses the city driving cycle, the vehicle will have to fill up with the alternative fuel infrequently and fill up the fossil fuel on a normal routine scheduled (depends on driver's daily commute).

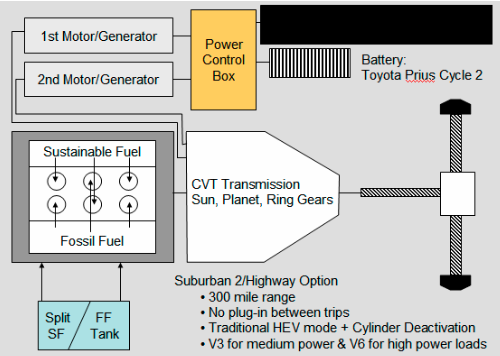
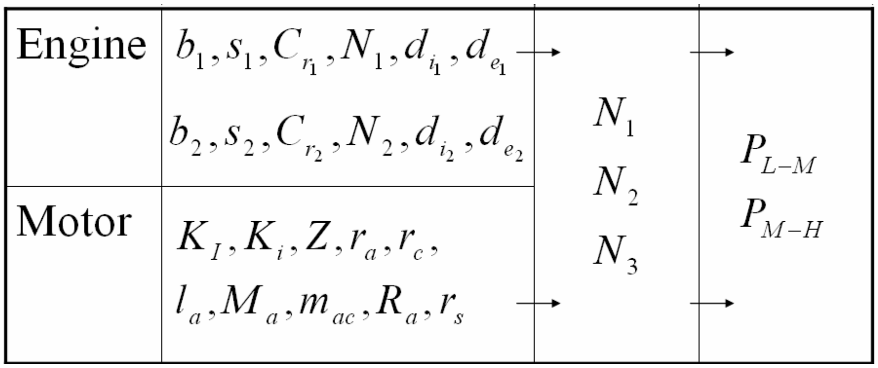


**Figure 80: Suburban2/Highway option – with no need for plugging in and a 300 mile range**

The suburban 2/highway option is the final driver choice on the dashboard. This option uses a 50% battery charging/discharging SOC cycle (300 mile range). During low and medium loads, this is a typical traditional HEV option. For high load, the alternative fuel will be used in three cylinders. In the suburban 2 mode which uses the city driving cycle, the vehicle will have to fill up with the alternative fuel infrequently and fill up the fossil fuel on a normal routine scheduled (depends on driver's daily commute).

### 5.3B Three Level Sequential Optimization Modeling

There are three levels to this optimization algorithm because there is a design phase, control phase 1, and control phase 2. In general, the three level looks like the following:



| | | | |
|---|---|---|---|
| Engine | $b_1, s_1, C_{r_1}, N_1, d_{i_1}, d_{e_1}$ $\rightarrow$ | $N_1$<br>$N_2$<br>$N_3$ | $\rightarrow$<br>$P_{L-M}$<br>$P_{M-H}$ |
| | $b_2, s_2, C_{r_2}, N_2, d_{i_2}, d_{e_2}$ | | |
| Motor | $K_I, K_i, Z, r_a, r_c,$<br>$l_a, M_a, m_{ac}, R_a, r_s$ $\rightarrow$ | | $\rightarrow$ |

**Figure 81: The three levels of optimization algorithms for these four sets of hybrid powertrain design variables.**

In the first level, there were five different sub-systems: one for the fossil fuel (gasoline) internal combustion engine, one for each of the sustainable fuels (hydrogen, methane, and ethanol), and one for the motors/generators/battery systems.

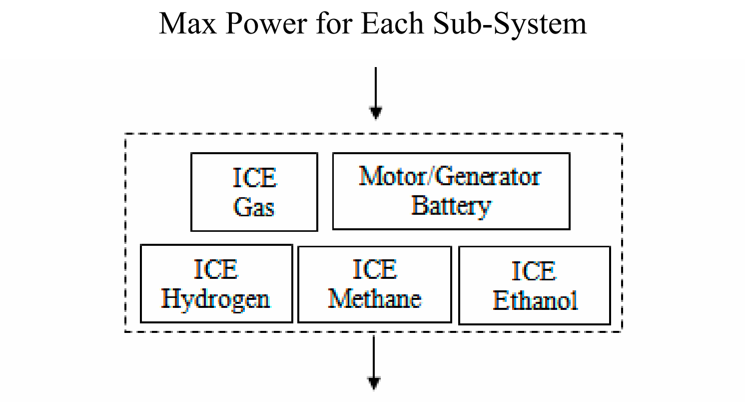
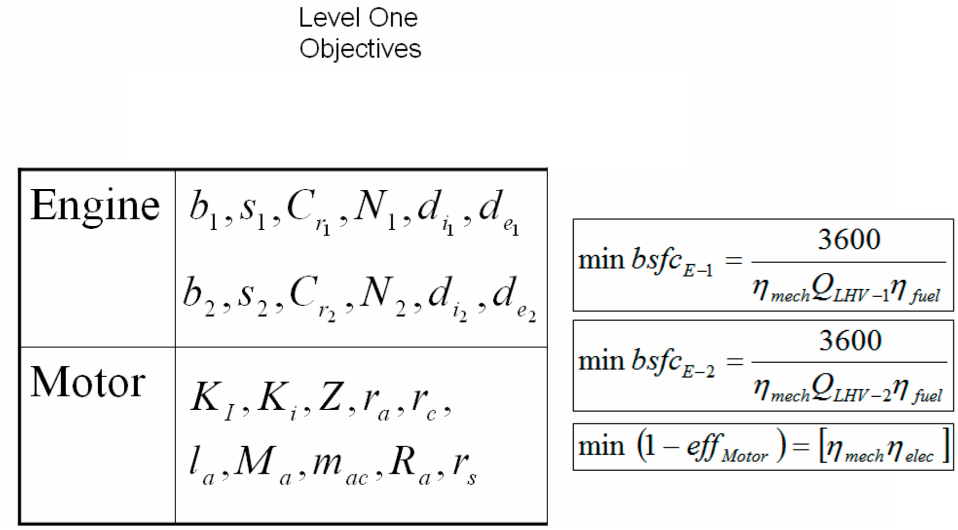


**Figure 82: Level One - Individual Sub-System Design- based on Static Optimizations**

The following states the objectives for each of these sub-systems.


Level One Objectives

| | |
|---|---|
| Engine | $b_1, s_1, C_{r_1}, N_1, d_{i_1}, d_{e_1}$<br>$b_2, s_2, C_{r_2}, N_2, d_{i_2}, d_{e_2}$ |
| Motor | $K_I, K_i, Z, r_a, r_c,$<br>$l_a, M_a, m_{ac}, R_a, r_s$ |

$$\min bsfc_{E-1} = \frac{3600}{\eta_{mech} Q_{LHV-1} \eta_{fuel}}$$

$$\min bsfc_{E-2} = \frac{3600}{\eta_{mech} Q_{LHV-2} \eta_{fuel}}$$

$$\min \left(1 - eff_{Motor}\right) = \left[\eta_{mech} \eta_{elec}\right]$$

**Figure 83: In the first level, there were three main objectives. The E-2 objective was run for three different alternative fuel possibilities.**

Once level one is completed, then the sub-systems are situated together in various combinations to build the baseline comparisons and the different hybrid options.

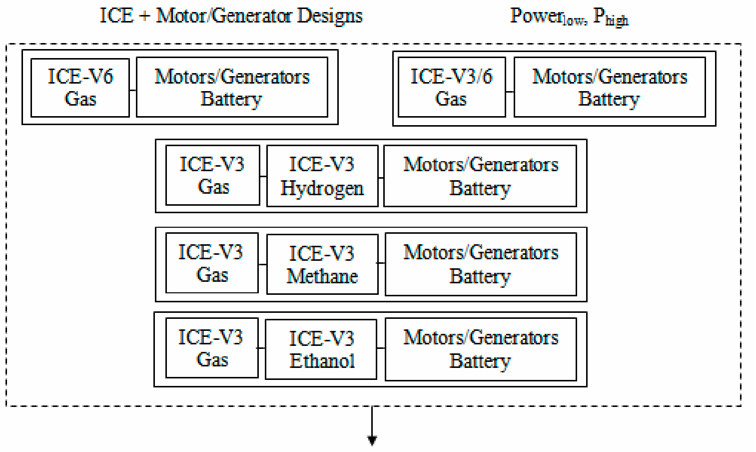
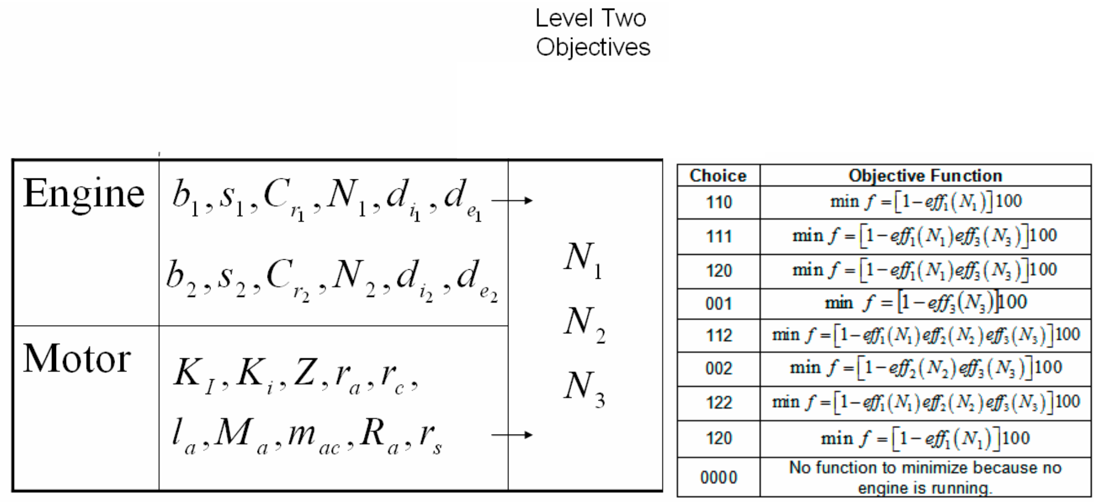


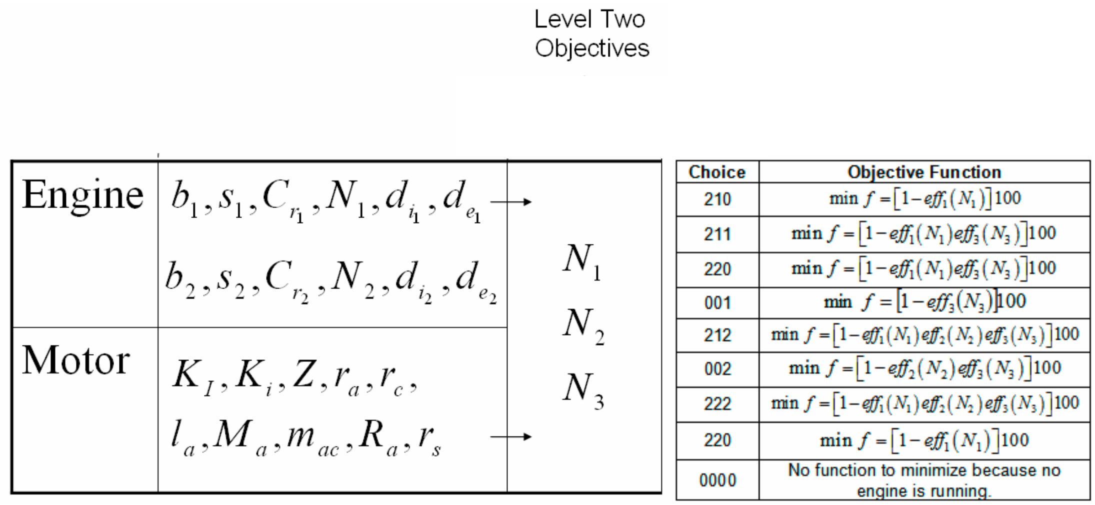
**Figure 84: Level Two – Sub-System Combinations Quasi Static Optimizations of Controls**

There are five optimization systems which were generated for each driving cycle data point and results are in the next section. Each driving cycle data point is a quasi-static optimization result. Figure 85 and 86 illustrate the various objectives which the power management strategy uses depending on the driving cycle data point.



| Choice | Objective Function |
|---|---|
| 110 | $\min f = [1 - eff_1(N_1)]100$ |
| 111 | $\min f = [1 - eff_1(N_1) eff_3(N_3)]100$ |
| 120 | $\min f = [1 - eff_1(N_1) eff_3(N_3)]100$ |
| 001 | $\min f = [1 - eff_3(N_3)]100$ |
| 112 | $\min f = [1 - eff_1(N_1) eff_2(N_2) eff_3(N_3)]100$ |
| 002 | $\min f = [1 - eff_2(N_2) eff_3(N_3)]100$ |
| 122 | $\min f = [1 - eff_1(N_1) eff_2(N_2) eff_3(N_3)]100$ |
| 120 | $\min f = [1 - eff_1(N_1)]100$ |
| 0000 | No function to minimize because no engine is running. |

**Figure 85: Level two was run as a Quasi-Static optimization algorithm for the urban and suburban 1 driver option. The results are very dependent on the power switch points.**



| Choice | Objective Function |
|---|---|
| 210 | $\min f = [1 - eff_1(N_1)]100$ |
| 211 | $\min f = [1 - eff_1(N_1) eff_3(N_3)]100$ |
| 220 | $\min f = [1 - eff_1(N_1) eff_3(N_3)]100$ |
| 001 | $\min f = [1 - eff_3(N_3)]100$ |
| 212 | $\min f = [1 - eff_1(N_1) eff_2(N_2) eff_3(N_3)]100$ |
| 002 | $\min f = [1 - eff_2(N_2) eff_3(N_3)]100$ |
| 222 | $\min f = [1 - eff_1(N_1) eff_2(N_2) eff_3(N_3)]100$ |
| 220 | $\min f = [1 - eff_1(N_1)]100$ |
| 0000 | No function to minimize because no engine is running. |

**Figure 86: Level two was run as a Quasi-Static optimization algorithm for the suburban 2/highway driver option. The results are very dependent on the power switch points.**

One the previous two levels were completed, then the third level was developed and optimized, but this time over the entire driving cycle. This means that a discrete optimization algorithm was used (direct algorithm in MatLab).

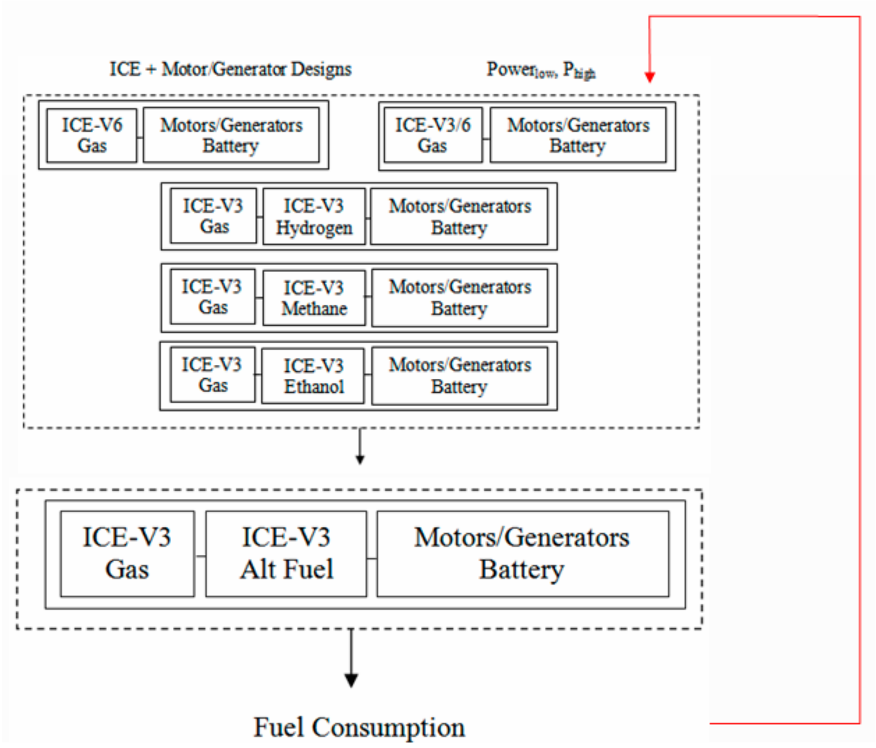


**Figure 87: Level Three – Power Switch Points Discrete Optimization**

The goal was to actually design the individual components first based on the power switch points and then to optimize the power switch points based on different driving cycles (set up expert system).

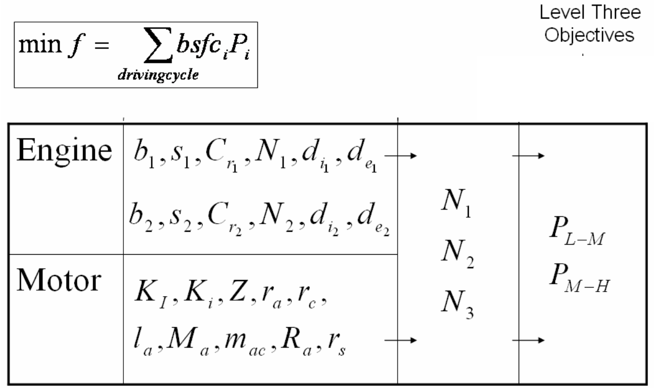


**Figure 88: This analysis generated three results depending on which alternative fuel was chosen.**

Here the objective was to minimize the total grams of gasoline fuel used. This power management optimized the switching power modes at $P_{LM}$=29 kW for the low-to-medium switch point and $P_{MH}$=30 kW for the medium-to-high switch point for the city driving cycle. Actually, whenever I set-up the direct algorithm to optimize these switch points it converged to the point at which they are the same. This means that it got rid of the middle power management strategy for the medium power regime for all the driving cycles. This result must be explored further because it is not at all expected.

In conclusion, level one optimization designed each one of the sub-systems separately using a completely static control point (maximum power and speed). Level two optimized the controls (for example, engine speeds) for a set of power switch points (low-power and high-power). Level three optimized the power switch points specifically and ended with a non-intuitive and yet acceptable and explainable result due to the objective chosen (minimize grams of gasoline).

# 5.4 Optimization Analysis

This study was created to determine whether to develop a three component engine vehicle and expand on the earlier three components Dual-Use Medium Truck with Hydraulic-Hybrid Powertrain and Fuel Cell auxiliary power engine within University of Michigan's ARC [85] model. In the first part of this section (5.4A), the four internal combustion engines (gasoline, ethanol, methane, and gasoline) sub-system results are given. Subsequently, in section 5.4B formalizes the system model and discusses the results for the GEM-AFH.

## 5.4A ICE Component Sub-systems Design Results

Before the system optimization was performed, each individual engine was optimized separately. These results were then used as inputs into the system optimization. The following four graphs in Figure 89 show the results from the four individual ICE optimizations subsystems:

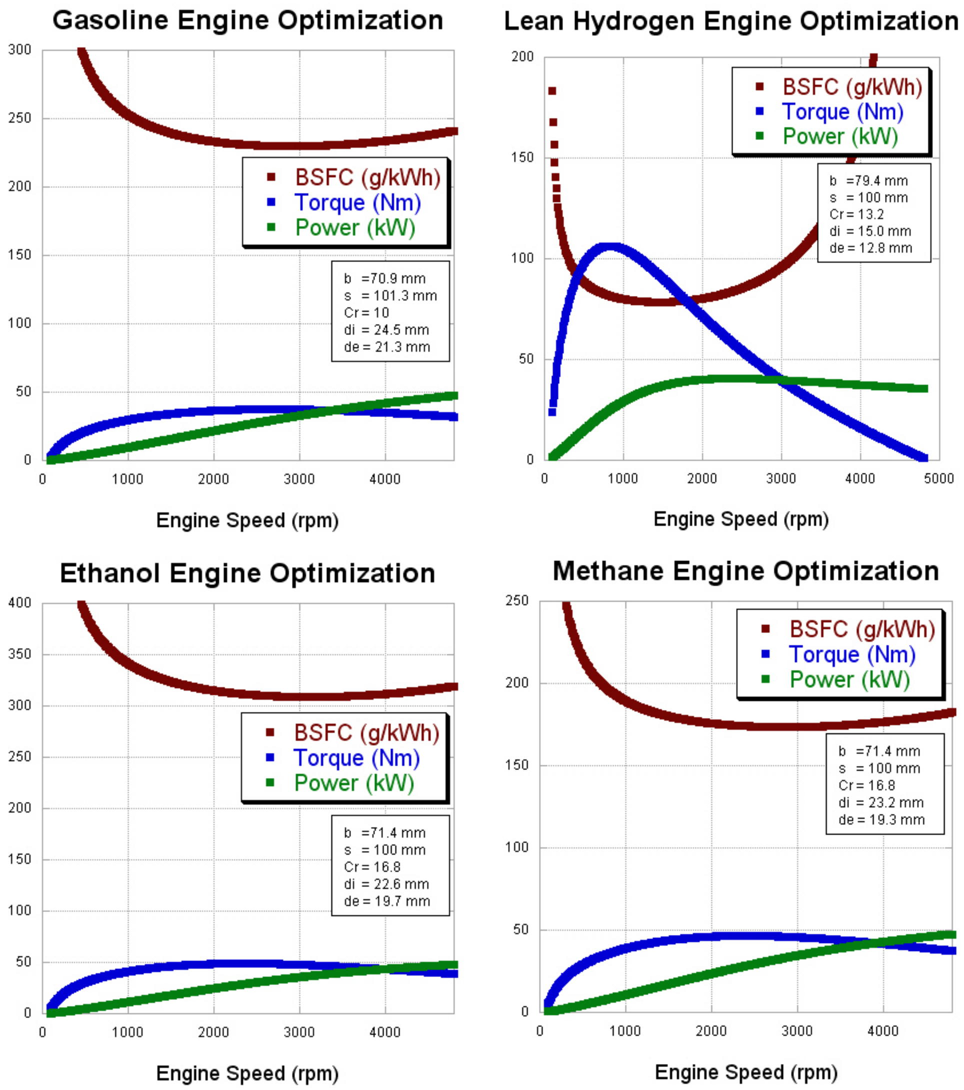


**Figure 89: Subsystem ICE optimization design results.**

Together the cylinder deactivation, direct injection, spark-ignited V3/V6 engine would range in power from 100 kW (hydrogen which is low power in nature) to 125 kW (ethanol, methane, and gasoline). The main drawback of this study is that each engine was optimized separately in this study and the design variables are not matched which could prove to be very hard to deal with vibrations when cylinders are not the same size. However, in future research, it could be shown that the engines' design variables can be more closely matched or choose between the trade-offs. Also, considering the success of cylinder deactivation and the ability of the crankshafts to adapt to different levels of torque coming from one set of cylinders versus a different set of cylinders, the belief is that this would require additional calculations, but be straight forward.

### 5.4B Control System Optimization Results

The following design problem is formulated and solved:

**Maximize** engine efficiencies
**with respect to** powertrain design variables
**subject to** power and engine speed constraints

<u>System Global Objective</u>:

This optimization process minimized the three component propulsion system inefficiencies using the following objective function for each point in the driving cycle:

$$\min f = \left[1 - eff_1\left(N_1\right) eff_2\left(N_2\right) eff_3\left(N_3\right)\right]100$$

After the sub-system optimization was performed, the efficiency of the motors/generators was calculated from the performance map of the motors/generators at different engine speeds: $N_1$ [88-91]. First a look-up table was constructed to find the approximate value of the motors/generators' power, engine speed, torque, and efficiency needed to meet overall power requirement from the driving cycle. However, the constraints took so long to calculate with a large set of look-up tables to satisfy during the optimization so a quadratic function was fitted using Excel's regression algorithm along the most efficient path of the motors/generators.

$$P_1 = 0.0003\omega^2 + 0.0233\omega$$

$$T_1 = -0.0175P_1 + 3.2869P_1$$

$$eff_1 = 0.7997 - 0.0008P_1 + 3\left(10^{-5}\right)P_1^2$$

The efficiency of the gasoline and hydrogen ICE was calculated from the brake specific fuel consumption equation using the analytical model (see Appendix D).

$$bsfc_{ICE} = \frac{3600}{n_{fuel} Q_{LHV} n_{mech}} \rightarrow eff_{ICE} = \frac{3600}{bsfc_{ICE} Q_{LHV}}$$

With these three efficiencies, motor efficiency, hydrogen internal combustion efficiency, and gasoline internal combustion efficiency, the specific objective can be calculated.

Specific Objective:

Since Matlab's SQP fmincon command cannot effectively handle discrete variables, a generic power management strategy was designed to choose which engine would be running depending on the state of the vehicle at a specific point along the urban driving cycle. First the driving cycle (velocity versus time) was converted to a velocity versus acceleration graph. (Table 25) that shows the potential power (C-kW/kg) required by the driving cycle. That is, each point is a unique power requirement point (P/m = va) as described in the earlier section: Power Management Domains. Consequently, there were now eight unique objective functions.

| Choice | Objective Functions<br>Urban and Suburban 1 Driving Option | Choice | Objective Functions<br>Suburban 2/Highway Driving Options |
|---|---|---|---|
| 110 | $\min f = \left[1-\mathit{eff}_1\left(N_1\right)\right]100$ | 210 | $\min f = \left[1-\mathit{eff}_1\left(N_1\right)\right]100$ |
| 111 | $\min f = \left[1-\mathit{eff}_1\left(N_1\right)\mathit{eff}_3\left(N_3\right)\right]100$ | 211 | $\min f = \left[1-\mathit{eff}_1\left(N_1\right)\mathit{eff}_3\left(N_3\right)\right]100$ |
| 120 | $\min f = \left[1-\mathit{eff}_1\left(N_1\right)\mathit{eff}_3\left(N_3\right)\right]100$ | 220 | $\min f = \left[1-\mathit{eff}_1\left(N_1\right)\mathit{eff}_3\left(N_3\right)\right]100$ |
| 001 | $\min f = \left[1-\mathit{eff}_3\left(N_3\right)\right]100$ | 001 | $\min f = \left[1-\mathit{eff}_3\left(N_3\right)\right]100$ |
| 112 | $\min f = \left[1-\mathit{eff}_1\left(N_1\right)\mathit{eff}_2\left(N_2\right)\mathit{eff}_3\left(N_3\right)\right]100$ | 212 | $\min f = \left[1-\mathit{eff}_1\left(N_1\right)\mathit{eff}_2\left(N_2\right)\mathit{eff}_3\left(N_3\right)\right]100$ |
| 002 | $\min f = \left[1-\mathit{eff}_2\left(N_2\right)\mathit{eff}_3\left(N_3\right)\right]100$ | 002 | $\min f = \left[1-\mathit{eff}_2\left(N_2\right)\mathit{eff}_3\left(N_3\right)\right]100$ |
| 122 | $\min f = \left[1-\mathit{eff}_1\left(N_1\right)\mathit{eff}_2\left(N_2\right)\mathit{eff}_3\left(N_3\right)\right]100$ | 222 | $\min f = \left[1-\mathit{eff}_1\left(N_1\right)\mathit{eff}_2\left(N_2\right)\mathit{eff}_3\left(N_3\right)\right]100$ |
| 120 | $\min f = \left[1-\mathit{eff}_1\left(N_1\right)\right]100$ | 220 | $\min f = \left[1-\mathit{eff}_1\left(N_1\right)\right]100$ |
| 0000 | No function to minimize because no engine is running. | 0000 | No function to minimize because no engine is running. |

**Table 25: Objective Function based on Power Management Choice and Driving Options.**

Control Variables:

Each engine speed will be optimized for each point along the driving cycle:

$$\text{Speed of Motors/Generators} = N_1$$

$$\text{Engine Speed of } \mathrm{H}_2 \text{ ICE} = N_2$$

$$\text{Engine Speed of Gas ICE} = N_3$$

The urban driving cycle is reconfigured to calculate the power required to meet each point in the driving cycle. For example, if the first set of points are (0s, 0m/s); (1s, 10m/s); (2s, 10m/s), then the acceleration points from one point to another are (1s, 10m/s/s) and (2s, 10m/s/s). The power for each point is the mass times the velocity times the average acceleration to go to the next point plus the power required to overcome rolling and air drag resistance and the power for the accessories as can be seen below:

$$P_i = \begin{bmatrix} m v_i a_i + C_r m g v_i + \dfrac{C_r}{100} m g v_i^2 + \dfrac{1}{2}\rho C_d A v_i^3 \\ + P_{\text{accessories}} + P_{\text{tranmission}} + P_{\text{cooling system}} + P_{\text{controls}} \end{bmatrix}$$

For simplicity, we are neglecting the extra power needed to overcome friction from the transmission. Consider the following energy flow/loss diagram in a combined urban and city driving cycle:

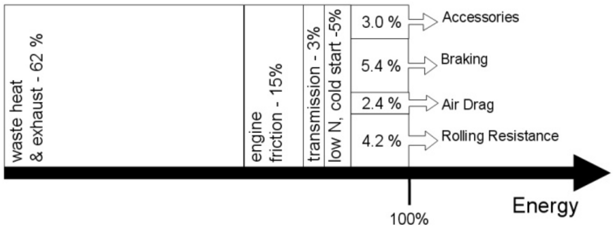


**Figure 90: Energy losses during urban driving cycle.**

In Figure 90, the losses associate with the transmission and accessories are small. To take this into consideration, we added a constant power term.

So, for each point on the driving cycle the engine speed variables are found such that the objective function is minimized. Moreover, optimizing along the driving cycle was considered as a parametric study of the power space of the driving cycle. Each point on the driving cycle is a completely different and independent system optimization except for the constraint dealing with the state of charge of the battery (SOC) which depends on the previous point and upon which driver option is being calculated.

<u>Constraints</u>:

The optimum engine variables were evaluated for maximum power at WOT while satisfying the following constraints for the seven optimization algorithms along the urban driving cycle as explained earlier. For each point along the driving cycle, MatLab's SQP fmincon calculated the constraints based on the power management choices discussed earlier and optimizes the three engine speeds by minimizing the inefficiencies. Each constraint was programmed with a "choice" variable and these choice variables are either one (on) or zero (off).

## Motors/Generators (Discharging Battery)

$$g_1 \rightarrow (N_1 - 5500)\text{choice}_1 \leq 0$$

$$g_2 \rightarrow (-N_1)\text{choice}_1 \leq 0$$

$$g_3 \rightarrow (P_1 - 50)\text{choice}_1 \leq 0$$

## Motor/Generators (Charging Battery)

$$g_1 \rightarrow (N_1 - 5500)\text{choice}_4 \leq 0$$

$$g_2 \rightarrow (-N_1)\text{choice}_4 \leq 0$$

$$g_3 \rightarrow (P_4 - 50)\text{choice}_4 \leq 0$$

## Alternative Fuel ICE

$$g_4 \rightarrow (N_2 - 5500)\text{choice}_2 \leq 0$$

$$g_5 \rightarrow (-N_2)\text{choice}_2 \leq 0$$

$$g_6 \rightarrow (P_2 - 55)\text{choice}_2 \leq 0$$

$$g_7 \rightarrow \left[ 9.428x10^{-8} N_3 s_2 \left( \frac{b_2}{d_{i2}} \right)^2 - 0.6C_{s2} \right] \text{choice}_2 \leq 0$$

## Gasoline ICE

$$g_8 \rightarrow (N_2 - 5500)\text{choice}_3 \leq 0$$

$$g_9 \rightarrow (-N_2)\text{choice}_3 \leq 0$$

$$g_{10} \rightarrow (P_2 - 55)\text{choice}_3 \leq 0$$

$$g_{11} \rightarrow \left[ 9.428x10^{-8} N_3 s_2 \left( \frac{b_2}{d_{i2}} \right)^2 - 0.6C_{s2} \right] \text{choice}_3 \leq 0$$

## Battery

$$g_{12} \rightarrow SOC_i + \left( \varepsilon_c \frac{T}{K_i} \right) \text{choice4} - \left( \frac{T}{K_i} \right) \text{choice1} - SOC_{MAX} \leq 0$$

**System**

$$h_1 \rightarrow (P_1)\text{choice}_1 + (P_2)\text{choice}_2 + (P_3)\text{choice}_3 - (P_4)\text{choice}_4 - P_{TOTAL} = 0$$

For example, in region one, the power management choice 1000 would have $\text{choice}_1 = 1$, $\text{choice}_2 = 0$, $\text{choice}_3 = 0$, and $\text{choice}_4 = 0$. Consequently, the constraints would simplify to the following:

**Motors/Generators (Discharging Battery)**

$$g_1 \rightarrow (N_1 - 5500) \le 0$$

$$g_2 \rightarrow (-N_1) \le 0$$

$$g_3 \rightarrow (P_1 - 50) \le 0$$

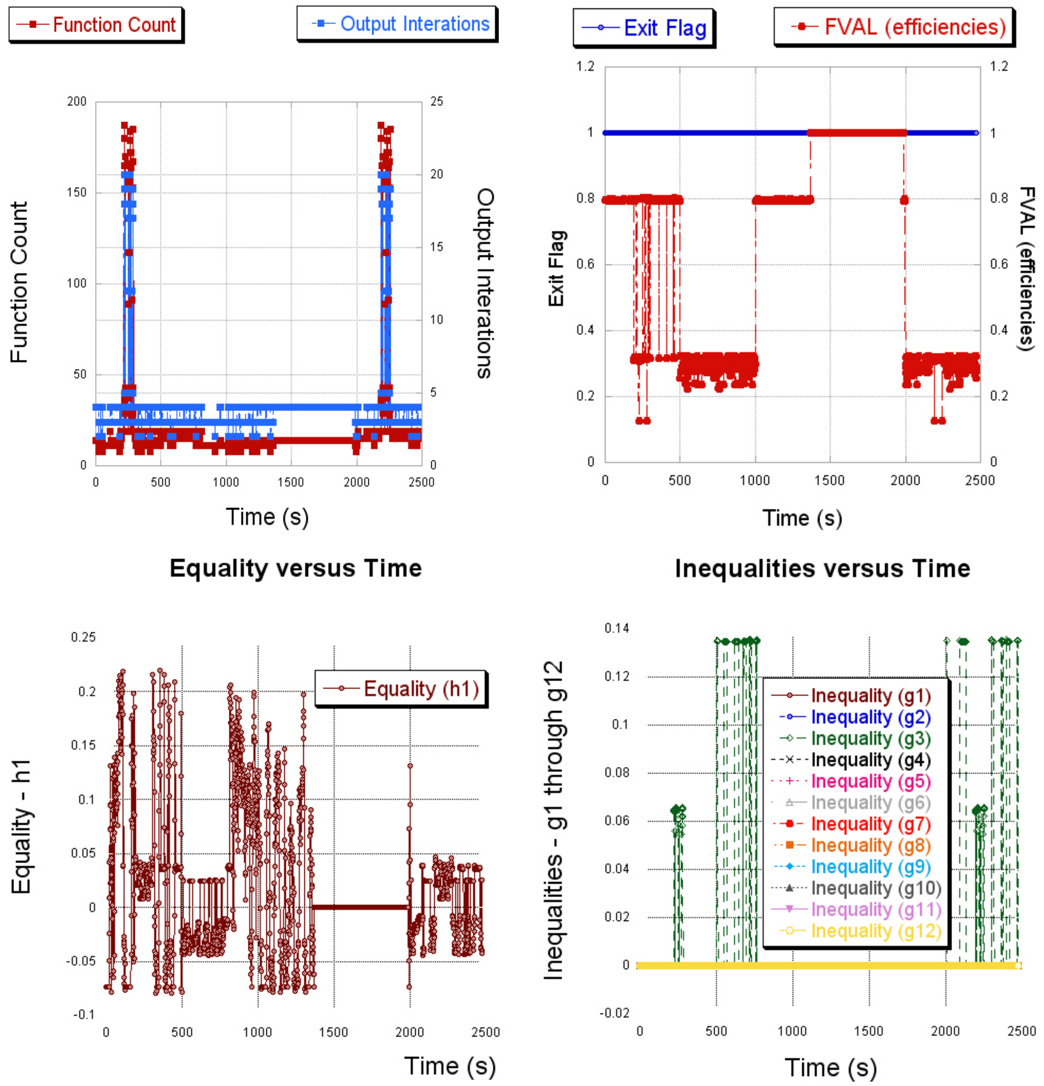
**Battery**

$$g_{12} \rightarrow SOC_i - \frac{T}{K_i} - SOC_{MAX} \le 0$$

**System**

$$h_1 \rightarrow (P_1) - P_{TOTAL} = 0$$

Given the system description, the first goal was to reach first order optimality as defined by KKT conditions and seen by Matlab's Sequential Quadratic Programming algorithm results.



Equality versus Time

Inequalities versus Time

**Figure 91: First order optimality reached based on Exit Flag and evaluations of LaGrange Multipliers.**

As can be seen in Figure 91, for all deterministic optimization runs, the exit flag was one meaning that first order optimality was reached or KKT conditions are satisfied. In addition, almost all the equality constraints results yielded $\lambda \neq 0$ and this was verified by making sure the power provided by the three component propulsion system equaled the total power required by the urban driving cycle. Finally, the only two inequality constraints which became active, $\lambda = 0$, were due to mach speed constraint when an ICE engine was producing maximum power or when the total power was zero (during idling).

After reaching first order optimality, iterations were performed for various transmission loses, vehicle mass loads, and other frictional losses not included within the feasibility study. The majority of results yielded that the high region engine (ethanol, methane, or hydrogen ICE) would only be required twice during the urban driving cycle. Furthermore, due to the similarity in brake specific fuel consumption equations, the actual engine speed was found not to be close enough to each other so that future constraints should be created so that cylinder deactivation would more easily apply. That is, when the high engine turned on, it would have the same engine speed as the medium engine (as not seen here in Figure 92 – although will be in the future journal article).

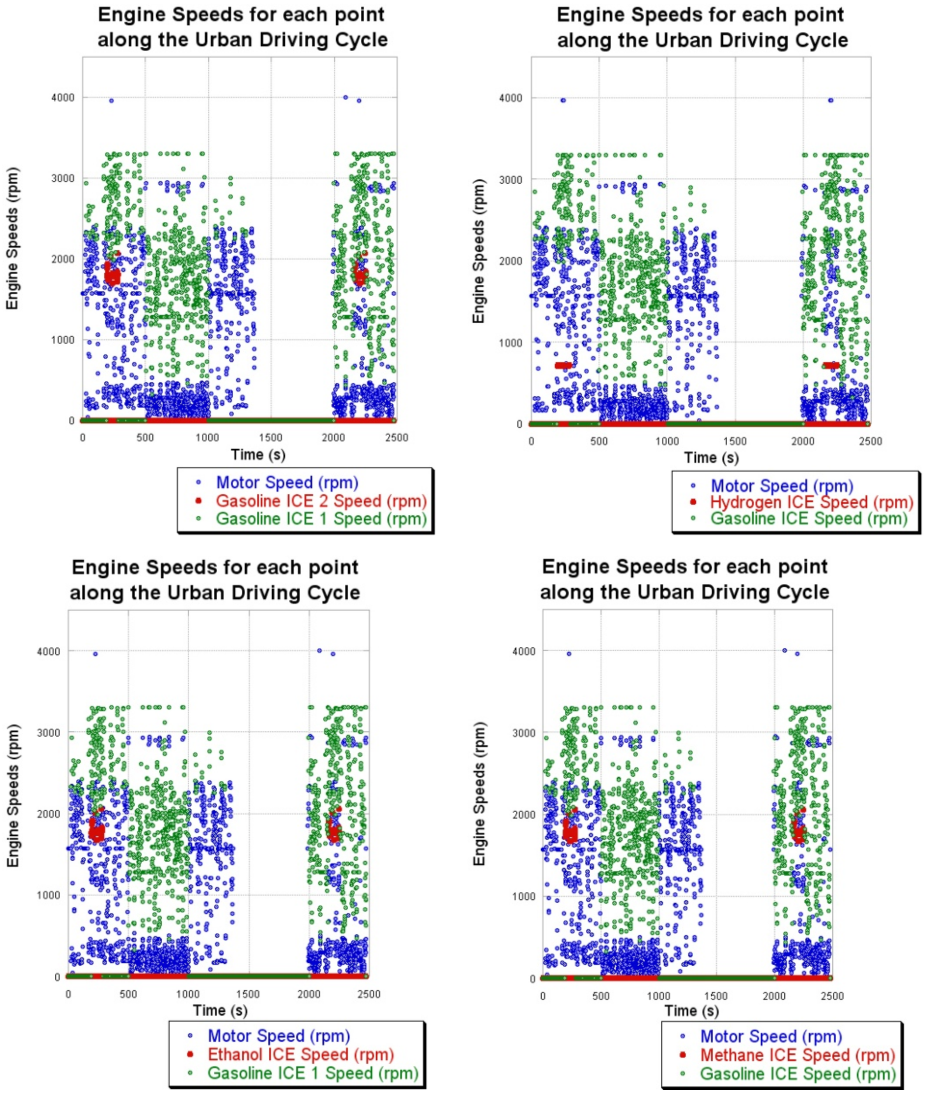


**Figure 92: System optimization results.**

These graphs illustrate the results from four different iterations: gasoline electric motor - gasoline hybrid (GEM-GH), gasoline electric motor - hydrogen hybrid (GEM-HH), gasoline electric motor - ethanol hybrid (GEM-EH), gasoline electric motor - methane hybrid (GEM-MH). The three colors (blue, red, and green) represent the optimal engine speed for each component. Again for times when the all cylinders are on, the speeds of the gasoline ICE and the alternative fuel ICE are equal.

In conclusion, an optimization algorithm was designed and solved for the GEM-AFH feasibility study such that first order optimality was reach (KKT conditions). The most appealing aspect to the results besides meeting performance requirements and achieving better fuel economy is that the high power engine is only need twice during the urban driving cycle.

### 5.4C Power Switch Points

The optimization system was written to minimize grams of gasoline fuel by varying power switch points subject to tank requirements and meeting power requirements for each driving cycle power domain point. Surprisingly, optimality converged over and over again as described earlier.

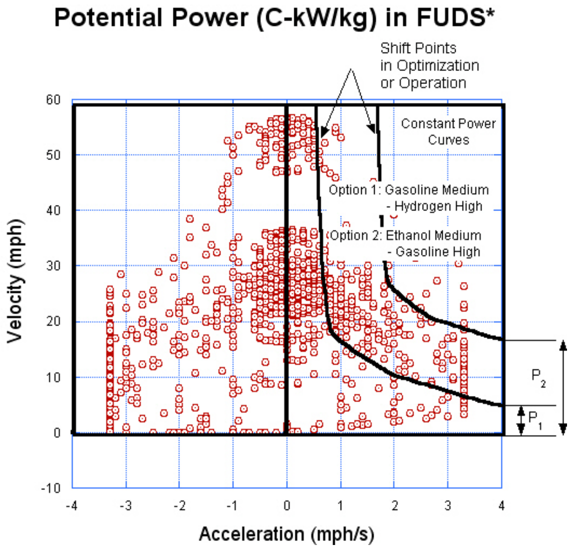


**Figure 93: Adaptive Design with respect to power region options and with respect to shifting curves.**

Figure 93 helps develop and describe the concept of the adaptive engine design and what this hybrid able to be called the transition mode hybrid. Here the consumer could choose which fuel would be for low and medium power and which would be for high power exclusively. In Figure 93, option 1 would choose gasoline for low and medium power demands of the driver and would only use hydrogen once during the urban driving cycle. In the highway driving cycle, it is conceivable that the driver would quickly learn that 55 mph speed could only use gasoline, but 75 mph would require gasoline and hydrogen. However, option 2 would choose ethanol for low and medium power and gasoline for the high power regime. As hybrid drivers learned how to drive to maximize fuel economy with traditional hybrids in city driving, so the hybrid driver here would learn how to drive to maximize fuel economy in high power driving.

## 5.5 Discussion of Results & Future Work: Coupling between Design and Controls

At each point along the driving cycle, the brake specific fuel consumption, power, torque, speeds, etc. are calculated and recorded. Given brake specific fuel consumption, power, and time at each point along the driving cycle, the grams of fuel used during the entire driving cycle are computed by summing the following:

$$\mathrm{bsfc}(\mathrm{g/kWh})\mathrm{P}(\mathrm{kW})\mathrm{t}(\mathrm{h}) = \text{grams of fuel}$$

With the grams of fuel used and distance traveled during the driving cycle, the fuel economy and gasoline equivalent fuel economy is calculated for each alternative fuel.

**Hydrogen**

$$f_{\mathrm{H_2}} = 6.21\,grams\text{ , } \mathrm{FE_{gas}} \;=\; 30.2\text{ mi/gal}$$

$$f_{\text{Gas Equivalent}} = 1110 g_{gas} + 6.21\, g_{\mathrm{H_2}} \frac{g_{gas}}{44kJ}\frac{120kJ}{g_{\mathrm{H_2}}} = 1130\, g_{\mathrm{gas}}$$

$$\mathrm{FE_{joint}} = 29.7\text{ mi/gal}$$

**Methane**

$$f_{\text{methane}} = 17.58\,grams\text{ , } \mathrm{FE_{gas}} \;=\; 30.2\text{ mi/gal}$$

$$f_{\text{Gas Equivalent}} = 1110 g_{gas} + 17.58\, g_{\mathrm{CH_4}} \frac{g_{gas}}{44kJ}\frac{50kJ}{g_{\mathrm{CH_4}}} = 1130\, g_{\mathrm{gas}}$$

$$\mathrm{FE_{joint}} = 29.7\text{ mi/gal}$$

**Ethanol**

$$f_{\text{ethanol}} = 17.58\,grams\text{ , } \mathrm{FE_{gas}} \;=\; 32.0\text{ mi/gal}$$

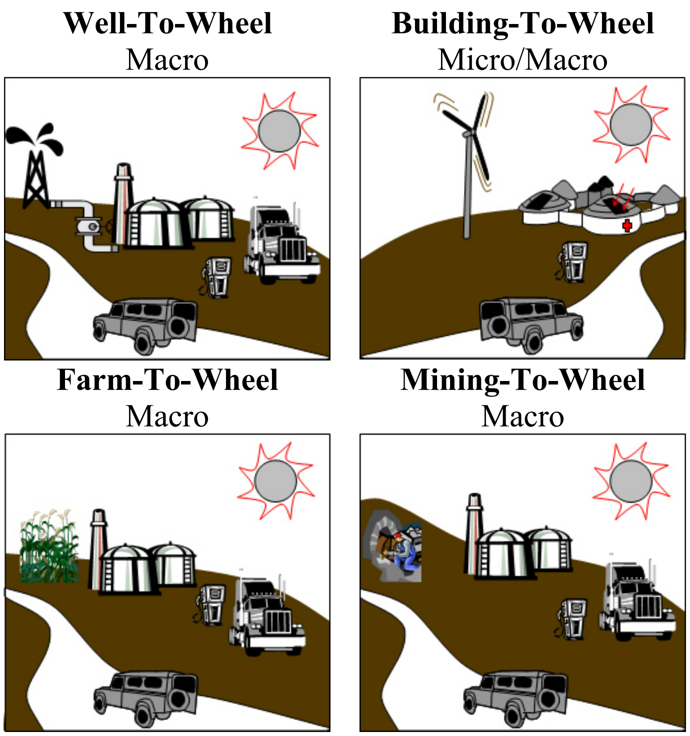
$$f_{\text{Gas Equivalent}} = 1110 g_{gas} + 17.58\, g_{\mathrm{C_2H_5OH}} \frac{g_{gas}}{44kJ}\frac{27.7kJ}{g_{\mathrm{C_2H_5OH}}} = 1120\, g_{\mathrm{gas}}$$

$$\mathrm{FE_{joint}} = 30.0\text{ mi/gal}$$

**Table 26: Gasoline equivalent fuel economy sample calculations for alternative fuel used for the GEM-AFH during one of the runs.**

According to Table 26, the fuel with the best fuel economy is ethanol; although not by much and may not be a significant difference. Consequently, this chapter is concluding that the fuels are all resulting in similar fuel economy results. However, the complete cradle-to-wheel (typical called well-to-wheel) analysis would yield energy consumptions based on how the fuel is created.

Figure 94 shows pictorially the life cycle analysis of the hybrid vehicle's fuel economy from four pathways: farm-to-wheel, building-to-wheel, mining-to-wheel, and typical well-to-wheel.


**Well-To-Wheel**
Macro

**Building-To-Wheel**
Micro/Macro

**Farm-To-Wheel**
Macro

**Mining-To-Wheel**
Macro

**Figure 94: Four Life Cycle Analysis Pathway Possibilities.**

It is imperative to know where any fuel is coming from to calculate total energy consumed. Table 27 illustrates four net energy ratios for hydrogen produced from wind turbine (13.2), methane pumped from a well (0.86), ethanol produced from sugar cane (1.21), and gasoline pumped from a well (0.86).

<table>
<tr>
<td>$$\begin{aligned} f_{\mathrm{H_2}} &= 6.21\ g\text{-}H_2 \left[\frac{120kJ}{g\text{-}H_2}\right]\left[\frac{1.00kJ}{13.2kJ}\right] \\ &= 56.45\ kJ \\ f_{\mathrm{gasoline}} &= 1110 g\text{-}gas \left[\frac{44kJ}{g\text{-}gas}\right]\left[\frac{1.00kJ}{0.890kJ}\right] \\ &= 54,880\ kJ \\ \mathrm{E_{Total}} &= 55,940\ kJ \end{aligned}$$</td>
<td>$$\begin{aligned} f_{\mathrm{methane}} &= 17.58\ g\text{-}CH_4 \left[\frac{50kJ}{g\text{-}CH_4}\right]\left[\frac{1.00kJ}{0.86kJ}\right] \\ &= 1022\ kJ \\ f_{\mathrm{gasoline}} &= 1110 g\text{-}gas \left[\frac{44kJ}{g\text{-}gas}\right]\left[\frac{1.00kJ}{0.890kJ}\right] \\ &= 54,880\ kJ \\ \mathrm{E_{Total}} &= 55,900\ kJ \end{aligned}$$</td>
</tr>
<tr>
<td colspan="2">$$\begin{aligned} f_{\mathrm{ethanol}} &= 17.58\ g\text{-}\mathrm{C}_2H_5OH \frac{27.7kJ}{g\text{-}\mathrm{C}_2H_5OH} \frac{1.00kJ}{1.21kJ} \\ &= 402.5\ kJ \\ f_{\mathrm{gasoline}} &= 1110 g\text{-}gas \frac{44kJ}{g\text{-}gas} \frac{1.00kJ}{0.890kJ} \\ &= 54,880\ kJ \\ \mathrm{E_{Total}} &= 55,280\ kJ \end{aligned}$$</td>
</tr>
</table>

**Table 27: Total Energy of Three Life Cycle Analysis Pathway Possibilities.**

Due to the choice that gasoline is the primary energy source, there is little difference between the choices for the original power switch points.

## 5.6 Two-Fuel Hybrid Conclusion

I designed the two-fuel, three option, ten mode hybrid electric vehicle to diversify the light-duty transportation sector –designing to avert a future energy crisis. The three options include all electric, suburban 1, and suburban 2/highway options set up as a dashboard driver choice. The ten mode expert system power management strategy incorporates two battery charging/discharging cycles (50% HEV versus 20/80% PHEV). Together this transition mode hybrid allows the United States light-duty sector to diverse the powertrain in terms of the potential for plug-in electricity, traditional fossil fuel and three upcoming alternative fuels. The simulations comparing fuel economy gains were similar to those reported in the literature - V6 gasoline ICE (23 mpg), V3/V6 cylinder deactivation gasoline ICE (25 mpg), V3/V6 cylinder deactivation electric motor hybrid (32 mpg) – and greater for the GEM-AFH (35 mpg) design. The two fuels option with cylinder deactivation is an interesting conception as an alternative approach to the flex fuel vehicle and the future possibility of incorporating an engine which has one set of cylinders running in a HCCI/PCCI mode while the others running in traditional SI mode potentially with an alternative fuel. The three alternative fuels modeled (methane, ethanol, and hydrogen) yielded similar fuel consumption and life cycle analysis results due to the initial power switch points chosen.

# Chapter 6. Importance of an Energy Crisis Conclusion

My dissertation begins by defining what the 1970's energy crisis did for the transportation light-duty vehicle sector. Building upon this work, I conclude potentially little will be drastically changed until another energy crisis. Consequently, I progress to understanding what frequent energy crises do in Fort Portal, Uganda to hospitals, schools, and businesses (preventing human development). Developing a methodology to navigate from meeting critical needs to ideal needs, I innovatively work with technicians to co-design and build five electrical energy producing devices for solutions to their energy crises including bicycle generator, wind turbine, micro-hydroelectric generator, merry-go-round generator, and hand-crank generator for back-up surgical lighting. Finally, re-evaluating the potential for an energy crisis in the United States, I move back to the transportation light-duty vehicle sector. Upon returning to this issue, I design the two fuel, three option, ten mode hybrid electric vehicle to diversify this sector – thus designing to avert a future energy crisis. The three options include all electric, suburban 1, and suburban 2/highway options set up as a dashboard driver choice. The ten mode expert system power management strategy incorporates two battery charging/discharging cycles (50% HEV versus 20/80% EV/PHEV). Together this transition mode hybrid allows the United States light-duty sector to diverse the powertrain in terms of the potential for plug-in electricity, traditional fossil fuel and three upcoming alternative fuels. However, knowing that the on-the-road fuel economy of the United States takes years to reflect the Reformed CAFE regulation, I propose a new policy to empower technicians to modify vehicles to run off a new energy source (sustainable spark-ignited fuel and/or plug-in hybrid capabilities).

Together (1) developed countries can avert an energy crisis by learning how developing countries are dealing with the daily, weekly and monthly energy crises while (2) developing countries can learn how to progress from meeting critical to ideal energy needs by learning how developed countries are replacing centralized grid mechanisms with smart grid as well as micro-grid mechanisms.

Tables 28, 29, and 30 lay out the policy implications for each Chapters 3, 4, and 5, respectively.

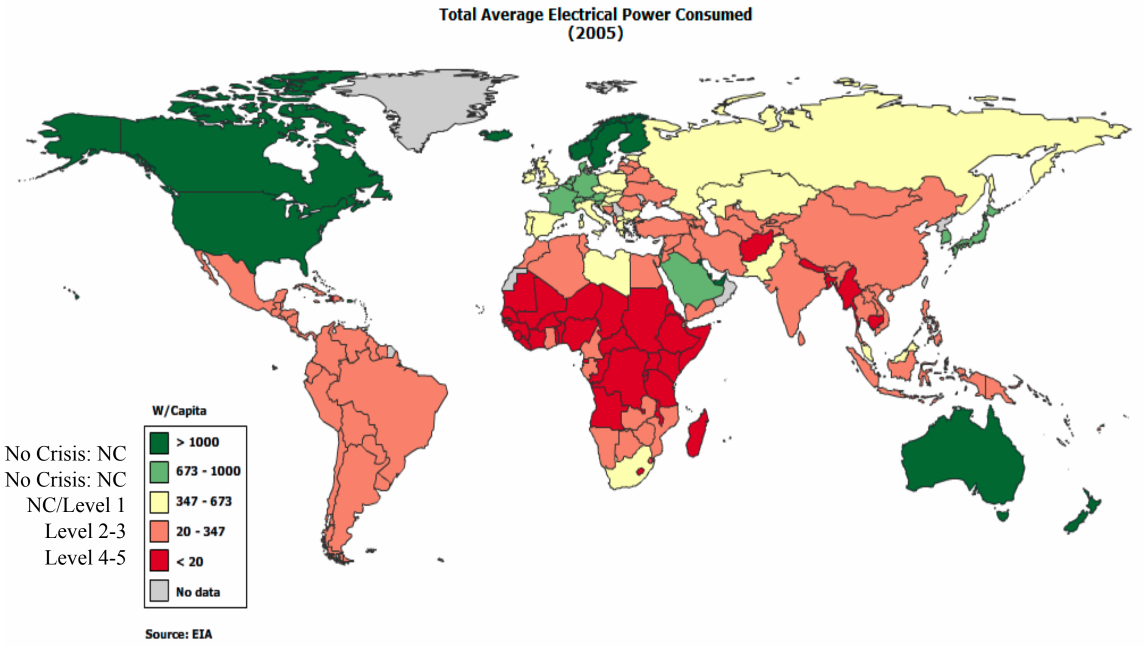
| | |
|---|---|
| (1) | New Niche Technology: The US must be leery of policies which focus solely on new technologies for decreasing motor gasoline consumption. Moreover, high fuel efficient new technology vehicles must be supported to become status-quo quickly (with a hybrid credit). There must be a distinction between technology implementation which yields better-than status-quo FE versus same-as status-quo FE: e.g. mild versus partial/full hybrids. Furthermore, niche technologies which are worse-than status-quo FE should be the first to change to an alternative energy source. |
| (2) | Status-quo Technology: The US should encourage all status-quo vehicles to decrease mass and engine displacement by perhaps 30%. This could be done using status-quo technologies (P/V) without sacrificing performance standards (P/M) when all technological advances from 1986 went into fuel economy in a proposed 2004 scenario. No new technological advancements are needed to reach a 35 mpg target. |
| (3) | Missing Key Offered Vehicle: The US could develop, support, and implement a cousin to the Kei car, van and/or truck with a policy-based support mechanism equivalent to or stronger than what Japan implemented. |
| (4) | Potential for a New Loophole: If the US wants to decrease greenhouse gas emissions and enhance security, then the US is obliged to watch carefully that the Reformed CAFE regulations do not create a new loophole: alternative fuels (e.g. Telsa's 244 mpg CAFE or the flex-fuel credit). In other words, upstream and downstream policy regulations must be implemented with or in conjunction with the Reformed CAFE regulations. |

**Table 28: Policy Implications from Chapter 3.**

| | |
|---|---|
| (1) | Energy Availability: Uganda has an electrification rate of about 10%. Meaning that 90% of the population has no access to the electric grid. Uganda's current average power consumed per capita is 11 W/Capita (well below the human capability on a bicycle or hand-crank generator). Since lack of employment permeates the country, Uganda could seriously consider having the healthy population between the ages of 21 and 65 bike one hour a day in an exercise gym for some monetary value. This would increase Uganda's electricity consumption per capita from about 60 kWh/capita/year to 90 kWh/capita/year or 150%. |
| (2) | Energy Reliability: Uganda's hospitals, businesses and schools which do have access to the electric grid suffer due to load shedding and faults. A systematic policy should be in place to guide the population in how to meet critical, desired, and ideal loads as defined in Chapter 4. For example, the surgical back-up lighting system for hospitals, bicycle/tv or bicycle/speaker systems for businesses, and merry-go-round generator for schools are able to meet crisis electricity needs when the grid is unavailable. If these devices are built locally then they can be operated and maintained and will provide a cheaper option to diesel and gasoline generators as well as solar pv panels. |
| (3) | Physics and Business of Energy Curriculum: Uganda should implement a physics and business of energy curriculum throughout their country. The technical institutes should be actively involved in designing and building electrical energy generation devices to meet various local power loads. The university business departments should be actively involved in creating social entrepreneurial enterprises and market analysis for all the devices. Although it will take another two years to finish the first round of validity for my course at St. Joseph's Technical Institute, the Ugandan Small Scale Industries Association is working with me to bring the beginning steps to other districts. |
| (4) | EIA or UNDP Crisis Level Distinctions: I argue for the EIA or UNDP to create a mechanism for labeling an energy crisis similar to how the World Health Organization labels a health crisis (i.e. swine flu pandemic level). There is great motivation to decrease unnecessary deaths due to lack of health care; however, the majority of health care devices are electrical and therefore dependent on available and reliable electrical energy. Also, there is a tremendous amount of education which could result if and when journalists cover stories that distinguish one energy crisis level from another. Just as the World Health Organization has many mechanisms of crisis events, the EIA might have to create a mechanism for global climate change crisis level which is different from (1) a reliability crisis level and (2) an availability crisis level. |

**Table 29: Policy Implications from Chapter 4.**

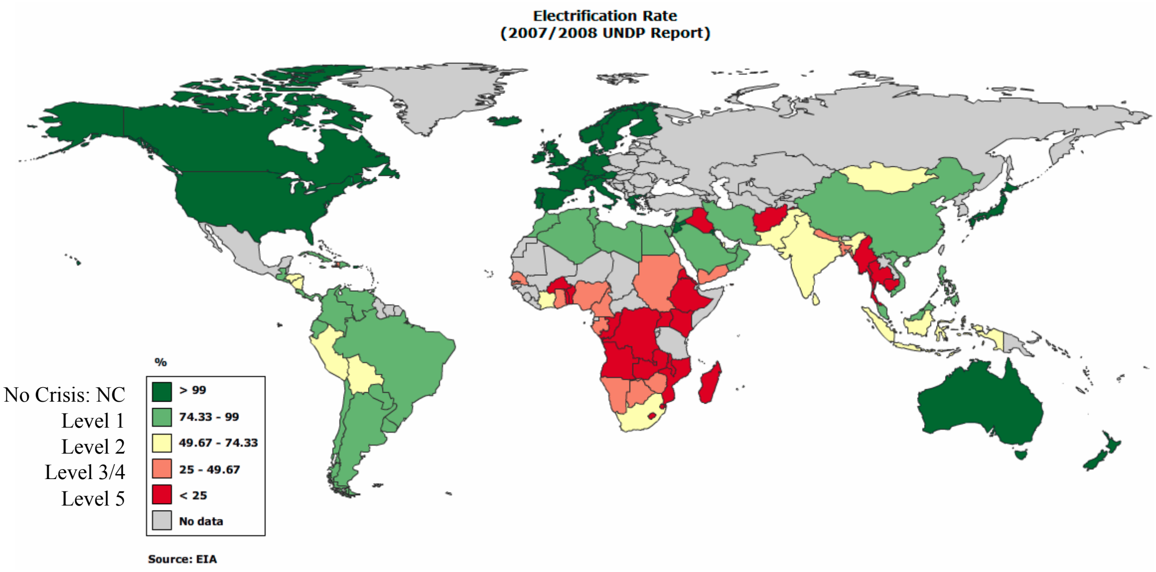
Figure 95 illustrates the countries which would benefit from human power electricity generation to meet critical human development needs (< 20 W/Capita - red).



Source: EIA

Figure 95: 2005 Country-by-Country Total Average Electrical Power Consumed per Capita.

The above figure also illustrates which countries where human power would not be significant. It is suggested in areas where human power could be significant that it be used for energy crises situations. Another more discussed energy crisis condition is electrification rate. Here between 74% and 99% would be defined as a low level energy crisis; whereas, below 25% would be defined as a high level energy crisis.



Source: EIA

Figure 96: Country-by-Country Electrification Rate from 2007/2008 UNDP Report.

| | |
|---|---|
| (1) | Energy Crisis in Light-Duty Transportation Sector: The United States should not only consider increasing fuel economy regulations for personal transportation, but should also design for a potential 1970's energy crisis event due to unreliable gasoline supply. There should be strong political motivation to diversify the vehicle powertrain in terms of the possible new energy sources. Whether electricity is used to charge a plug-in battery or to compress a hydraulic accumulator, the range of all vehicles should have a crisis mode whereby the vehicle can plug-in from electricity and have a minimum range of around 30 miles. |
| (2) | Transition mode: The United States should encourage popular SUV and light trucks to incorporate a similar transition mode hybrid since electrification will not be adequate for them. This two-fuel cylinder deactivation hybrid is just one of many choices (including but not limited to the Fiat TetraFuel vehicle) to transition to another combustible fuel. The United States should remember that liquid fuels offer the best energy and power density available, but complete life cycle analysis from cradle-to-wheel should always be included during the transition. |
| (3) | Physics of Energy Curriculum: The United States should consider implementing a physics of energy curriculum into all technical and/or vocational schools. The hope would be to empower technicians to co-design and build vehicle and building energy systems with a clear understanding of the various life cycle analysis results depending on the upstream energy sources and downstream energy consumption loads. |

**Table 30: Policy Implications from Chapter 5.**

Considering how an energy crisis level mechanism is employed either in the United States or Uganda allows me to distinguish an energy crisis for the transportation sector versus the electrical generation section. Figure 97 illustrates combining the two concepts.

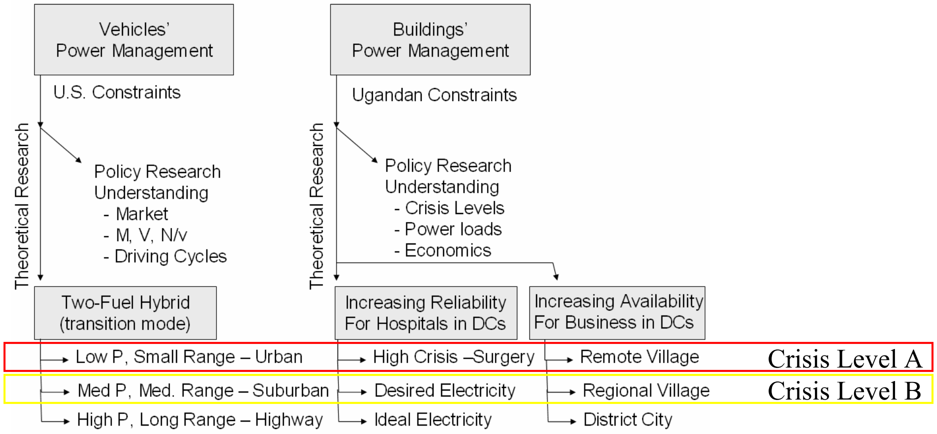


**Figure 97: Two Sample Energy Crisis Levels for Transportation Juxtaposed to Electricity.**

In Figure 97, an energy crisis labeled Level A can occur (1) in the transportation sector when there is a complete gasoline shortage – say due to a political instability, (2) in hospitals when there is unreliability due to the electric grid, and/or (3) in remote villages without access to electricity. The transition mode hybrid would still be able to run in an all electric mode with a range of around 30 miles and a suburban crisis mode (only using the three cylinders with one of the alternative fuels available and with greater range than the all electric mode). The surgical back-up lighting system for hospitals, bicycle/tv or bicycle/speaker systems for businesses, and merry-go-round generator for schools are able to meet crisis electricity needs when the grid is unavailable and/or unreliable.

At this point in my analysis, I illustrate the importance of understanding an energy crisis by juxtaposing (1) the United Station’s past and potential future light-duty vehicle transportation crisis to (2) the Uganda’s current electricity reliability and availability crises. The provocative comparison yields specific policy implications not only for these countries individually, but also for the world as these countries are representative of one of the largest consumers and one of the smallest consumers of gasoline and electricity.

# Appendices

## APPENDIX A. SIMULATION MODEL – ACCURACY LEVEL

Vehicle simulation models discussed here are categorized into three spectrums: (1) static versus dynamic, (2) deterministic versus probabilistic, and (3) analytic versus non-analytic. Regardless of where the models fit on these three spectrum levels, the real issue is what level of accuracy is desired. Four vehicle simulation models are compared in terms of these three spectrums of modeling capabilities as well as the vital feature: accuracy of model.

### Simulation Model Comparisons

| | VehSim | Advisor | EPA | MIN-PAR |
|---|---|---|---|---|
| Number of Parameters Needed | ~400 | ~200 | 20 | 3 |
| (1) Static vs Dynamic<br>Time Step | 0.02 sec | ~0.1 sec | 1 sec | 1 sec |
| (2) Deterministic vs Probabilistic<br>Model Input | Defined Driving Cycle | Defined Driving Cycle | Defined Driving Cycle | Defined Driving Cycle |
| (3) Analytic vs Non-analytic<br>Mathematical Calculations | Both | Both | Both | Both |
| Accuracy Desired | ~0.01mpg | ~0.1 mpg | 1 mpg | 3 mpg |

In above Table, the level of accuracy is dependent on these four issues: number and quality of parameters, the time step between calculations, the type of input driving cycle used (i.e. urban versus highway driving cycle), as well as the type of physics-based calculations done.

*Example of Time Step Issue:* At the University of Michigan Automotive Research Center (ARC), the VESIM model increased the time step from 0.01 to 0.02 seconds in a driving cycle because they gained more computational speed and lost negligible accuracy for what they were calculating and measuring in the lab experiments. There continues to be an argument about what time step is needed to be considered a dynamical simulation. This MIN_PAR model is two orders-of-magnitude less dynamic than the VESIM model; however, considering the deterministic and probabilistic nature of driving cycles VESIM's accuracy level may mean nothing in the policy realm.

*Example of Deterministic versus Probabilistic Issue:* Viewing the accuracy levels estimated in Table 1, one could easily ask why there is such variability in fuel economy for real-world driving. There are two ways to answer this question. First, the vehicle is not under laboratory conditions. Second, the real-world vehicle undergoes a somewhat more probabilistic driving cycle (at least from person to person or city to city) which does not represent any deterministic driving cycle. Consequently, until good transformations between driving cycles are constructed (if possible), this is the best scientific way to validate a vehicle model – by comparing it to a measured deterministic experiment. Consequently, all the models use deterministic driving cycles.

*Example of Analytical versus Non-Analytical Issue:* With researchers extremely reliant on non-analytical and highly numerical models which may or may not be defined well as a mathematical function, it is imperative to compare models in terms of accuracy level. In all four simulation models, the physics equations of motion and state are governed by analytical functions. However, the engineering design is simplified by look-up tables (i.e. engine map) or correlation results.

*Small Investigation Example.* This author with Carla Silva chose ten vehicles which were sold in the United States, Japan, and European Union simultaneously in 2004. Five vehicles had a diesel engine and five had a gasoline engine. Advisor and EcoGest simulation models used 20 publicly available variables to model the fuel economy of these vehicles and compare them to the measured fuel economy. MINPAR simulation model used only 3 of the 20 variables. All of them had similar percent error. Moreover, MINPAR was better modeling diesel engines than Advisor. One expert suggested that this was because Advisor was not designed for modeling diesel engines. This research was done to understand driving cycle transformations from and to the following: Japanese 10-mode, European NEDC, and EPA's city and highway driving cycles. VESIM was not used because it requires many more variables than what is available publicly.

In this MINPAR simulation model, there were two driving cycles used: urban and highway EPA standardized tests. In the following table, the variables are organized based driving cycle or vehicle-based dependence or estimated based on status-quo design characteristics of manufacturing in 2004.

| Four Variable Sets Used in MIN_PAR | Driving Cycle | Vehicle Based Level 1 | Vehicle Based Level 2 | Status-Quo |
|---|---|---|---|---|
| First Set: $t, v, a, x, d, g, \theta$ | X | | | |
| Second Set: $m, V, N/v, mpg$ | | X | | |
| Third Set: $c_d A, N_{idle}$ | | | X | X |
| Fourth Set: $b, k, \eta_{trans}$, $gears, c_r, P_{acc}$ | | | | X |

The first variable set is completely defined by EPA's urban and highway driving cycles. Each velocity versus time driving cycle was used to calculate the acceleration and distance traveled. The acceleration due to gravity, $9.81 m/s^2$, and grade, $0^o$, are known.

The second variable set was based on EPA's measured data which are publicly available in the car list. This data was solely based on the specific vehicle characteristics of mass, engine size, transmission characteristic (engine speed to ground speed ratio in final gear), and fuel economy (mpg). The variability of these data values in 2004 are the following:

| 2004 Vehicles | $m$ $(lbs)$ | $V$ $(cid)$ | $N/v$ $(rpm/mph)$ | $FE_{measured}$ $(mpg)$ |
|---|---|---|---|---|
| Minimum | 2125 | 61 | 19 | 9.8 |
| Maximum | 6500 | 500 | 54 | 84.1 |
| Mean | 4070 | 201 | 36 | 26.5 |
| Standard Deviation | 786 | 71 | 6 | 8.7 |

Considering this variability, the MINPAR model is able to calculate the fuel economy of all 2004 vehicles by either calculating a relationship a parameter based on vehicle characteristics or by assuming all other parameters based on manufacturing status-quo designs.

The parameter calculated based on vehicle characteristics is air-drag coefficient times area of the vehicle. It varies based on the weight of the vehicle. This is dependent on whether the vehicle is a car or a truck and on year.

$$c_{d-car-04}A = 0.61(m/m_{\min})^{2/3}, c_{d-truck=04}A = 0.84(m/m_{\min})^{2/3}, c_{d-car-86}A = 0.72(m/m_{\min})^{2/3},\ c_{d-truck-86}A = 0.92(m/m_{\min})^{2/3}$$

This relationship uses the dimensionality scaling argument that two of the three dimensions of the vehicle's mass are correlated to the area of the vehicle. The next variable in this group is the engine's idle speed and is dependent on year.

$$N_{idle-04} = 900 - V,\ N_{idle-86} = 1100 - V$$

This was investigated by Marc Ross and the linear relationship was strongly correlated to engine size (i.e. the larger the engine, the lower the idle speed).

| Status-Quo Variables | $b(1/\eta_{engine})$ | $\eta_{trans}$ | $c_r$ | $P_{acc}(kW)$ | $k(kJ/rev/L)$ | $gears$ Shift points |
|---|---|---|---|---|---|---|
| Values in 1986 | 2.45 | 0.75, 0.85 | 0.010,0.011 | 0.25 | 0.260 | EPA's regulation guidelines |
| Values in 2004 | 2.45 | 0.80, 0.95 | 0.009,0.098 | 0.75 | 0.205 | |

These status-quo variables change over the years but the argument here is that these variables do not vary greatly in a given year.

## APPENDIX B. PHYSICS AND BUSINESS OF ENERGY SAMPLE LESSON PLANS

# Physics of Energy: Section 1 – Mechanical to Electrical Energy Conversion

Fort Portal, Uganda, East Africa
Mountains of the Moon University (MOMU) and St. Joseph's Technical Institute
Professors: Abigail Mechtenberg and John Vianna Makaanda

| **Names** | **Expertise** |
|---|---|
| Abigail Mechtenberg | Physics |
| John Vianna Makaanda | Business |

| **Number of Technicians** | **Title** |
|---|---|
| 10 | Auto Mechanic |
| 10 | Auto Electric Mechanic |
| 5 | Electrician |
| 2 | Civil Engineer |
| 2 | Rewinder/Electrician |
| 10 | Solar/Electrician |

Schedule: Two weeks- Monday, Wednesday, Friday
Time: 2:00pm to 5:00pm
Dates: Part A-13, 15, 17 and Part B-20, 21, 22, 23, 24 October 2008
Place: Part A-Mountains of the Moon University, Part B-St. Joseph's Technical Institute

Curriculum

Section 1: Mechanical to Electrical Energy Conversions

Section 2: Thermal to Mechanical to Electrical Energy Conversions

Section 3: Chemical Conversions and Storages

Section 4: Solar Conversions

Goals:

1. To identify various types of energy forms properly and to calculate the magnitude of them
2. To understand how energy can be transformed or converted from one form of energy into another form of energy
3. To design energy converting designs based on equipment and technical experience here in Fort Portal (INNOVATE WITHIN)
4. To create marketing plans for various businesses which suffer when (a) the electric grid is off or (b) in villages where there is not electric grid available

Mechanical Energy: is either the potential energy (PE) or kinetic energy (KE) of a macroscopic[34] object. Every object has many types of energy. The potential energy of an object is its stored energy due to its position. The kinetic energy of an object is it energy due to motion.

Instructor explained with an example of a pencil dropping to the ground. While at a height above the ground, the instructor asked what type of energy does the pen have? The answer was potential energy. This energy was due to the gravitational pull of the Earth on the pencil (gravity). Right before the pen hits the ground, the instructor asked what type of energy does the pen have? The answer was kinetic energy. The energy of the pen transformed from potential energy into kinetic energy. When the pen hit the ground and stopped, the instructor asked what was the final energy? The answer was heat. So all the energy went into heating the pen and the ground.

Review: Mechanical Energy, Potential Energy, Kinetic Energy, Heat Board Problem for calculations

Part One: A 100 kg rock falls from a height of 1 m. What is its potential energy?

m(mass)= 100 kg
h(height)=1 m
g(gravity)=10m/s$^2$
PE(potential energy due to gravity)=mgh=(100 kg)(10 m/s$^2$)(1 m)=1000 J (pronounced Joules)

Part Two: Someone runs a radio for 10 min, how much energy is consumed?

The typical power of a small radio is 10 Watts. This is the power of the radio. Power is the speed at which energy is consumed (or is converted from one form into another form). For the radio it is the rate at which electrical energy is converted into sound energy. So, the amount of energy consumed is the power multiplied by the time the radio is on.

P(power) = 10 W
t(time) = 1 min = 60 s
E(energy)=Pt=(10 W) (60 s) = 600 J

Part Three: If there was a way to convert the potential energy of the rock into electrical energy, would the rock have enough energy to run the radio for one minute:

The potential energy of the rock was 1000 J. The electrical energy needed to run the radio was 600 J. So there was more energy in the rock than needed for the radio. If it could be done it would work!!! How does one do this…. that is the question and we will have an answer, but we must remember efficiencies.

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[34] Macroscopic versus microscopic – microscopic is very small… what one can only see with a microscope whereas macroscopic is what one can see without a microscope – big enough to see with regular eye vision.

Let’s take a look at a couple of potential energy types

(1) Gravitational: This is the energy from the force acting on an object from the Earth’s pull.

    F(force)=m(mass)g(gravity)=mg, PE = m(mass)g(gravity)h(height)=mgh

(2) Spring: This is the energy from the force acting on an object from the push or pull of a spring

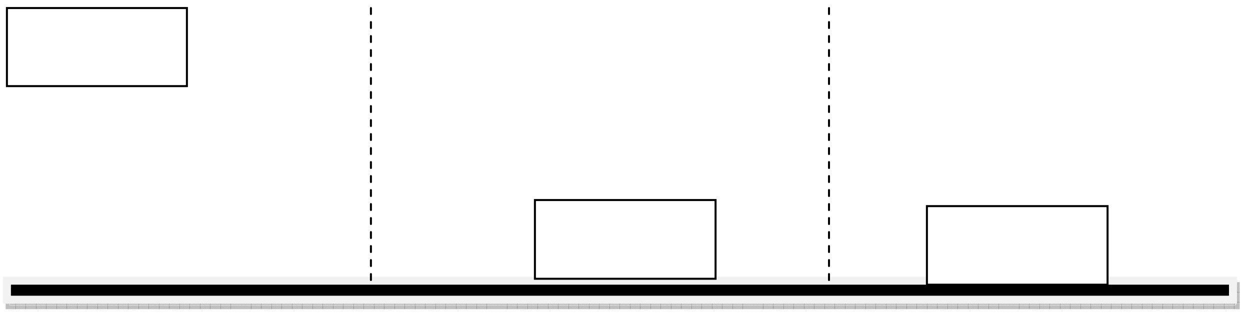
    F(force)=k(spring constant)d(distance)=kx, PE = ½ k(spring constant)d(distance)$^2$= ½ kd$^2$

(3) Human: This is the energy from the force acting on an object from the push or pull of a person.

    Force needs to be measured based on what someone can do. It can be estimated based on how much someone can pick up. For example, if one can pull up a 50 kg rock, then the force would be mass multipled by gravity or F=mg=(100 kg)(10 m/s2)=1000N.

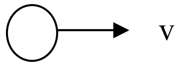
    If the person picks it up to a height of 1 meter, then the potential energy gained by the rock would be PE=mgh=(1000N)(1m)=1000 J.

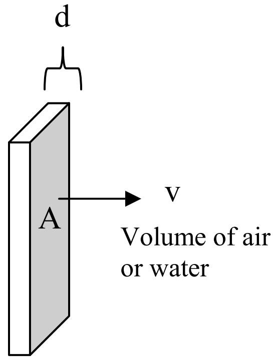
Problem One – Label the energy types of a 100 kg rock falling from a height of 1 m at the following three stages:



Problem Two – A human pushes a 1 kg rock up into the air. The rock goes to a height of 1 m and then falls back down to the ground. Label the energy types at the following stages:

Let's take a look at a couple of kinetic energy types (ignoring where the objects got the speed from)





1. Any object with speed
   KE = $\frac{1}{2}mv^2$
2. Wind[35]: air molecules moving with a speed
   KE = ½ $\rho$(density of air-standard)A(area)$v^2$(speed)d(distance)
   KE = $\frac{1}{2}\rho A v^2 d$
3. Water[36]: water molecules moving with a speed
   KE = ½ $\rho$(density of water-standard)A(area)$v^2$(speed)d(distance)
   KE = $\frac{1}{2}\rho A v^2 d$

Problem One – Label the energy types of air molecules hitting a wind turbine at the following two stages:

Problem Two – Label the energy types of water molecules hitting a hydro-turbine or water wheel at the following two stages:

Simon's answer for wind energy question would look like the following:

Intial Energy = KE of air ($KE_{air}$) with Final Energy = KE of air & wind turbine ($KE_{air} + KE_{turbine}$)

$KE_{air} = KE_{air} + KE_{turbine} \rightarrow \frac{1}{2}\rho A v_{fast}^2 d = \frac{1}{2}\rho A v_{slower}^2 d$ + Energy of Wind Turbine ($\frac{1}{2}I\omega^2$)

---

[35] Note: Air is a compressible gas. So, the pressure and speed changes differently than with a liquid.

[36] Note: Water is a incompressible liquid. So, the pressure and speed changes differently than with a gas.

Conservation of Energy:

This is one of the key ideas of both classical and modern physics. That is, energy is neither created nor destroyed. It is only transformed from one form into another.

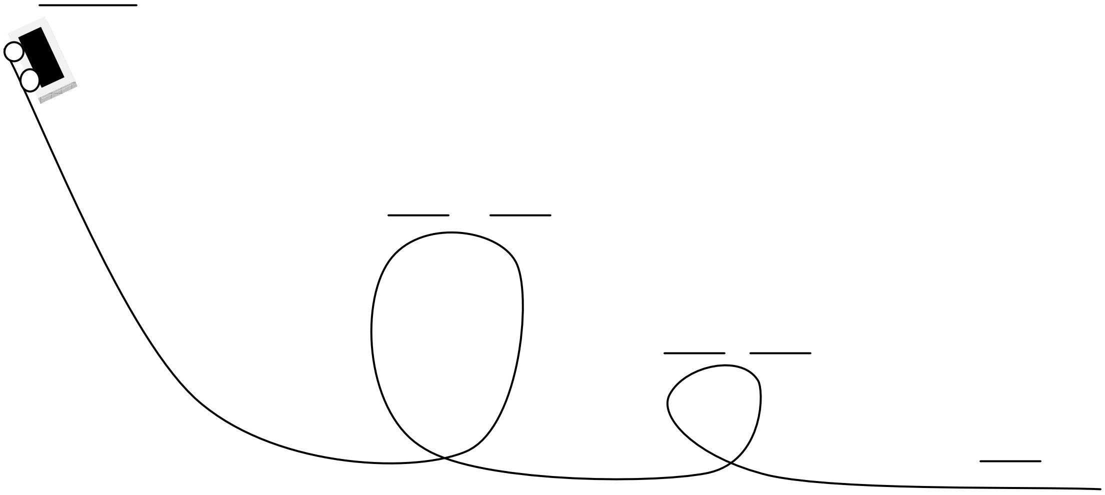
Question 1: Why is there an energy crisis if there is always the same amount of energy?

Answer: It is because as energy transforms from one form into another form, it loses its usefulness. Energy becomes more chaotic and harder to transform into electrical and mechanical energy. For example, when the rock falls it transforms its potential energy into kinetic energy. If it were to be converted into electrical energy, then the energy of the rock could have been used. However, once the rock hits the ground, then the energy is transformed into heat. The heat is impossible in this case to be transformed back into electrical energy.

Another way to look at the conservation of energy is to say that the initial energy is equal to the final energy. Moreover, the energy at any instant in time is equal to the energy at any other instant in time. The total energy is ALWAYS the same. If one object has two types of energy simultaneously, then one adds the energies to calculate the total energy of the object.

Question 2: In the 1970's the United States called an energy crisis when they did not have oil for driving for a short while. There are many images and pictures associated with people waiting in long lines for petrol or diesel. What would your images be of an energy crisis in Uganda that you have experienced and witnessed?

Problem One – Label the energy types of a roller coaster within an amusement park as seen on page 2, second picture in the handouts from Monday. Assume that there is not heat loss, for now. Fill in the energy at the following four stages:



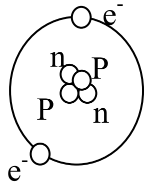
| | First State: | Second Stage: | Third Stage: | Fourth Stage: |
|---|---|---|---|---|
| Energy Type(s) | | | | |
| Total Energy | | | | |

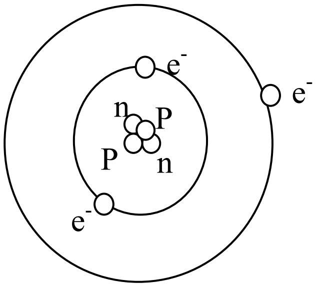
Electrical Energy: is the energy from negative and positive charges. The most common negative charge is called an electron. The most common positive charge is called a proton. All matter is made up of atoms. All atoms have electrons which orbit around the nucleus. The nucleus is made up of protons and neutrons and is tightly bound together.

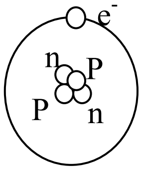
It is only the electrons which are able to move around in some materials and chemicals. As you know and we discussed in class, the current in a copper wire is the flow of electrons. Copper is a material which allows electrons to flow freely (i.e. conductor). Whereas an insulator like wood or plastic does not allow electrons to flow freely.

In a battery, the negative terminal can be thought as either (1) the side with too many electrons or (2) the side where electrons were inserted into the chemical. Whereas, the positive terminal can be thought of as either (1) the side with too few electrons or (2) the side where electrons were taken out of the chemical. Any acidic material or chemical has too few electrons. Consequently, one can make an acidic lemon battery because electrons will flow freely.

Problem One: In the following three diagrams, figure out the charge of the atom.







Charge: ______________ ____________________ ____________

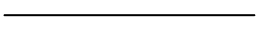
Problem Two: Why is it that you cannot take protons out of the nucleus?

Problem Three: What can take protons out of the nucleus?

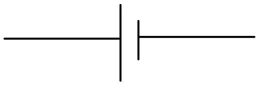
Problem Four: What type of energy deals with protons and neutrons leaving the nucleus?

Electrical Circuit: is a pathway for electrons to flow in a loop. It is the way electrical energy moves. There are two main concepts to understand with electrical energy: voltage (V) and current (amps). Current is again the flow of electrons. Electrons will only flow when there is a pathway to flow and either (1) when they are attracted to a positive terminal from an electric field or (2) when there is a magnetic field (B). This is the beauty of electricity and magnetism, but before we talk about electricity and magnetism, we should understand how to draw a circuit.

A line represents a wire:

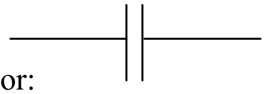


A wire is always used to carry electrons and should be drawn for electricians to understand how to connect a circuit.



A big line and small line with a space in between represents a battery:

A battery is always used to show where electricity can be stored, but is only one way of storing electrical energy.



A big line and another big line with a space in between represents a capacitor:

A capacitor can be used to show where electricity is stored or it can be used as a filter to rectify AC voltage into DC voltage.

A wiggly or seesaw line represents a resistor or load to the circuit:

The load in the circuit is any appliance one wants to use (e.g. a light bulb, tv, computer, etc.).

Example One: A battery's charge can be discharged to charge a capacitor. A capacitor can be discharged to charge a battery. Both charge and discharge electrons, but they behave differently in terms of time and power of discharge.

E(energy)=P(power)t(Time)

E=Pt means that for the same amount of energy, a battery has big time to discharge, but smaller power; whereas a capacitor has big power, but smaller time to discharge.

We will constantly use the following units for electrical circuits: watts, kilowatt*hours, and hours. Power is measured in and uses a unit of watts. Electrical Energy is measured in and uses a unit of kilo-watt*hours. Electrical Circuits Time is measured in and uses a unit of hours.

If you have a 2000 Watt iron and you use it for 0.5 hours, then it consumes 1000 kWh.

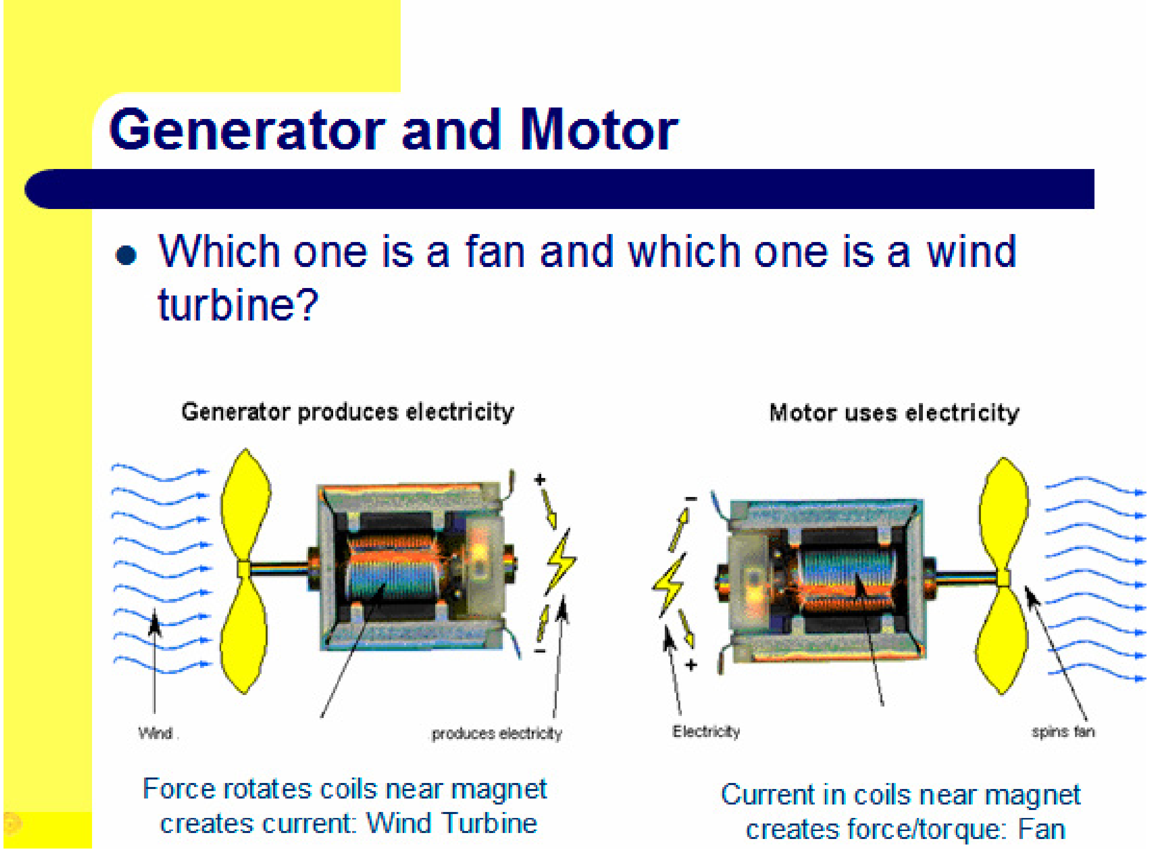
If you have a 2 Watt cell phone and you use it for 500 hours, then it consumes 1000 kWh.

When you increase the electrical power, then you cannot use it for that long or else you consumer more energy.

Problem One:  Choose a set of electrical devices and calculate the wattage of the devices from the voltage (V) and current (I).

Electrical Power is Voltage * Current. P = V*I

Motor and Generators use the same physics we studied in class and can be used in either direction. Consider the following:



## Generator and Motor

- Which one is a fan and which one is a wind turbine?

Generator produces electricity

Motor uses electricity

Force rotates coils near magnet creates current: Wind Turbine

Current in coils near magnet creates force/torque: Fan

If all one needs is a coil of wire and magnet to generate electricity, what is so hard to build it yourself? NOTHING ABOUT IT IS SO HARD!

Let’s do it. There are many ways to execute the design, but I know you are smart enough to design electrical devices by looking at what other people have been doing and considering what is possible and from your own expertise!!!

But first, what are the two ways to get a magnet?

1. Have a permanent magnet (buy it or make it)
2. Create an electromagnet (coil around nail connected to a battery)

## Calculating Power Generated and Consumed

Step One: Electricity Income – this is the amount of electricity which you **earn** based on what someone can generate. For example, biking 10 minutes every day or every other day or 1 hour every day, etc.

Step Two: Electricity Expenses – this is the amount of electricity which you can **spend** based on what someone wants to use. For example, a light bulb or a TV or a laptop, etc.

Step Three: Compare what someone can earn (generate electricity) with what someone will spend (electricity consumed). Are they living in the black (saving money) or red (spending too much money)?

| **Income (in terms of generating electricity)** | | **Matching Energy Generation With Energy Consumption E = P * t** | **Expenses (in terms of consuming electricity)** | |
|---|---|---|---|---|
| Strength of Person (current – A) Calculate Power 12 V * __ A =__W | Biking Hours | | Appliance Calculate Power or Read Power from back of device | Appliance Hours |
| Small Generator<br>12 V * 10A=120W | 10 min/day<br>1 hour | Income: 120 Wh<br>Expense: 70 Wh | Lights (3 - LEDs)<br>5 W | 2 hours/day<br>14 hours |
| Please take notes and show the calculations: | | | | |
| Small Generator<br>12 V * __ A=__ W | | Income:<br>Expense: 154 Wh | Lights ( 1 – CF)<br>11 W | 2 hours/day<br>14 hours |
| Please take notes and show the calculations: | | | | |
| Small Generator<br>12 V * 4 A=48 W | 1 hour/day<br>7 hours | Income: 336 Wh<br>Expense: | TV<br>77 W | __ hours/day<br>__ hours |
| Please take notes and show the calculations: | | | | |
| Solar Panel<br>75 W | 4 hours/day<br>28 hours | Income: 300 Wh<br>Expense: | TV<br>77 W | __ hours/day<br>__ hours |
| Please take notes and show the calculations: By the way, how much does this system cost? | | | | |
| Small Generator<br>12 V * __ A=__ W | | Income:<br>Expense: | | |
| Please take notes and show the calculations: | | | | |

## CREATE YOUR OWN SET OF PROBLEMS FOR TOMORROW’S CLASS

| **Income (in terms of generating electricity)** | | **Matching Energy Generation With Energy Consumption E = P * t** | **Expenses (in terms of consuming electricity)** | |
|---|---|---|---|---|
| Strength of Person (current – A) Calculate Power 12 V * __ A =__W | Biking Hours | | Appliance Calculate Power or Read Power from back of device | Appliance Hours |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
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| | | | | |

## Designing a Bicycle Generator for Villagers

| | |
|---|---|
| **Parts for Both** | **Cost (Ush)** |
| 1 – Pulley | |
| 1 – Dynometer or DC motor (rpm & Watts) | |
| 1 – Battery (Ah) | 4 Ah = ________<br>20 Ah = ________ |
| 1 - Belt | |
| 1 – Bicycle (unless they already own a bicycle) | |
| **Parts Specific for Bicycle** | **Cost (Ush)** |
| Welded Stand | |
| **Labor – What do you think?** | **Cost (Ush)** |
| Number of Hours for Bicycle Generator:_________<br>Level of hard work: ___________ (watts)<br>Amount of mechanical energy generated:_____ (kWh) | |
| Hours Biking to Charge Cell Phone: ______ (hours)<br>Energy Needed to Charge Cell Phone: _______ (kWh)<br>Which is more efficient, charging cell phone biking to another village/town or charging cell phone with bicycle generator? | |

## Designing a Merry-Go-Round for Schools

Locally built by St. Joseph's Technical Institute – Uganda and Imported from Brigham Young University - Ghana

| **Parts for Both** | **Cost (Ush)** | | |
|---|---|---|---|
| 1 - Old Differential | | | |
| 2 – Pulley | | | |
| 1 – Dynometer or DC motor<br>(rpm & Watts) | *100-500 W* | *1,000-2,000 W* | *5,000 W* |
| | | | |
| 1 – Battery (Ah) | *4 Ah* | *70 Ah* | *200 Ah* |
| | | | |
| **Parts Specific for Merry-Go-Round** | **Cost (Ush)** | | |
| Box - Bolts | | | |
| Box – Welding Rods | | | |
| Some – Electrical Wires | | | |
| 1 - Belt | | | |
| Flat Wood | | | |
| Cutting Blade | | | |
| 2 - Angle Line (2 inch x 2 inch) | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| | | | |
| **Labor – What do you think?** | **Cost (Ush)** | | |
| Power Generation Curve for child's play: | | | |
| Power Load Curve for night lighting: | | | |

## Designing a Hybrid Wind Turbine where it is Windy

<table>
<tr><th><b>Parts</b></th><th colspan="3"><b>Cost (Ush)</b></th></tr>
<tr><td>1 – Pulley</td><td colspan="3"></td></tr>
<tr><td rowspan="2">1 – Dynometer or DC motor<br>(rpm & Watts)</td><td><i>100-500 W</i></td><td><i>1,000-2,000 W</i></td><td><i>5,000 W</i></td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td rowspan="2">1 – Battery (Ah)</td><td><i>4 Ah</i></td><td><i>70 Ah</i></td><td><i>200 Ah</i></td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>Steel frame</td><td colspan="3"></td></tr>
<tr><td>Steel blades</td><td colspan="3"></td></tr>
<tr><td>Belt/Ropes</td><td colspan="3"></td></tr>
<tr><td>Generator matched to it</td><td colspan="3"></td></tr>
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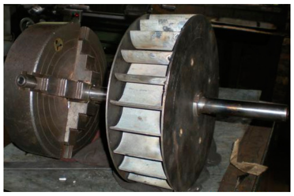
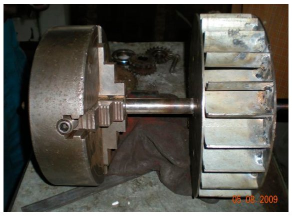
<tr><td></td><td colspan="3"></td></tr>
<tr><td></td><td colspan="3"></td></tr>
<tr><td><b>Labor – What do you think?</b></td><td colspan="3"><b>Cost (Ush)</b></td></tr>
<tr><td></td><td colspan="3"></td></tr>
</table>

## Designing a Water Wheel when Living near Streams/Rivers





| **Parts** | **Cost (Ush)** | | |
|---|---|---|---|
| 2 – Pulley | | | |
| 1 – Dynometer or DC motor (rpm & Watts) | *100-500 W* | *1,000-2,000 W* | *5,000 W* |
| | | | |
| 1 – Battery (Ah) | *4 Ah* | *70 Ah* | *200 Ah* |
| | | | |
| 1 – Storage Tank | *Small L* | *Medium L* | *Large L* |
| | | | |
| | | | |
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| **Labor – What do you think?** | **Cost (Ush)** | | |
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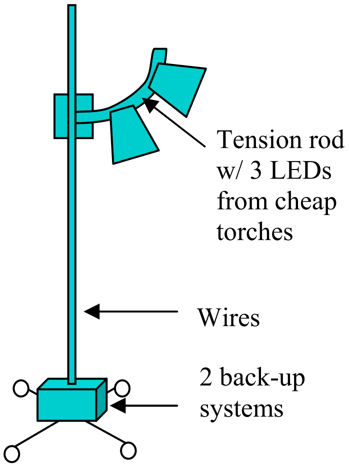
## Designing a Surgical Lighting Device for Hospitals/Health Clinics



| **Parts** | **Cost (Ush)** | | |
|---|---|---|---|
| 2 – Pulley | | | |
| 1 – Dynometer or DC motor (rpm & Watts) | *100-500 W* | *1,000-2,000 W* | *5,000 W* |
| | | | |
| 1 – Battery (Ah) | *4 Ah* | *70 Ah* | *200 Ah* |
| | | | |
| 2 – Bicycle Wheels | | | |
| 3 – Torches | | | |
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| **Labor – What do you think?** | **Cost (Ush)** | | |
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## APPENDIX C. LITERATURE REVIEW OF CYLINDER DEACTIVATION FE IMPROVEMENTS

Cylinder deactivation fuel economy benefit (percentage change in MPG) as a function of regulatory cycle for different engine configurations and vehicle weights.

| Displacement (L) | Vehicle Weight (kg) | Engine Configuration | Transmission | EPA City | EPA Hwy | EPA M/H | NEDC | Japan 10-15 |
|---|---|---|---|---|---|---|---|---|
| 5.8 [27] | 1800 | V8 | | 22.1 | 13.7 | | | |
| 1.4 [34] | | I4 | 4x2-spd man | 11 | | | | 20[37] |
| 1.6 [36] | | I4 | | | | | | 16 |
| 5.0 [33] | 1891[38] | V8 | 5-spd auto[38] | | | 10.3 | 6.5 | |
| 1.6 [41] | 1361 | I4 | | | | | 16[39] | |
| 5.4 [39] | 2722 | V8 | 5-spd auto | 8.8 | 5.2 | 7.5 | 7.6 | 8.9 |
| 6.8 [39] | 2722 | V10 | 5-spd auto | 11.7 | 9.9 | 11.0 | 10.2 | 11.4 |
| 4.6 [39] | 1928 | V8 | 4-spd auto | 9.9 | 7.8 | 9.1 | 9.5 | 7.3 |
| 5.4 [39] | 1928 | V8 | 4-spd auto | 11.6 | 10.7 | 11.3 | 10.6 | 9.1 |
| 5.4 [39] | 2381 | V8 | 4-spd auto | 8.0 | 2.9 | 5.9 | 7.0 | 7.1 |
| 6.8 [39] | 2381 | V10 | 4-spd auto | 11.5 | 7.8 | 10.0 | 9.8 | 10.1 |
| [38] | | V8 | 5-spd auto | | | | ~7 | |
| 1.6 [31][40] | 1405 | I4 | 5-spd auto | | | | 10.2 | |

## UNITS FOR POTENTIAL POWER GRAPHS

$$\frac{1\,Watt}{1\,kg} = \frac{m^2}{s^3}$$

$$\frac{\left(10^3\right)W}{kg} = \frac{m^2}{s^3} * \left(\frac{mi}{1609\,m}\right)^2 \left(\frac{3600\,s}{hr}\right)^2$$

$$C\frac{kW}{kg} = mph * mph/s$$

$C$: conversion factor

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[37] Percent change is calculated in paper from reported km/L data.

[38] Comparable 2006 Model

[39] Percent change is in L/100 km and includes other effects of electromechanical (variable) valve train such as early intake and late intake closing of valves.

[40] Simulation efforts which included Controlled Auto Ignition (CAI) along with cylinder deactivation

# APPENDIX D. ICE ANALYTICAL MODEL REWRITTEN FOR EFFICIENCY

## ICE MODEL FOR OPTIMIZATION

Nomenclature:

| | |
|---|---|
| $\phi$ | Equivalence ratio |
| $\gamma$ | Ratio of specific heats ($c_p/c_v$) |
| $\rho$ | Density of air (kg/m$^3$) |
| $\eta_f$ | Fuel conversion efficiency |
| $\eta_{f,Pmax}$ | Fuel conversion efficiency at maximum power |
| $\eta_m$ | Mechanical efficiency |
| $\eta_{n,Pmax}$ | Volumetric efficiency at maximum power |
| $\eta_v$ | Volumetric efficiency |
| $a$ | Acceleration of vehicle (m/s$^2$) |
| A | Frontal area of vehicle (m$^2$) |
| A/F | Air-to-fuel ratio |
| $b$ | Bore (mm) |
| $bsfc_2$ | Brake specific fuel consumption of alternative fuel ICE (g/kWh) |
| $bsfc_3$ | Brake specific fuel consumption of gasoline ICE (g/kWh) |
| $C_d$ | Coefficient air drag |
| $\text{choice}_1$ | Motors/Generators power management (0/1/2) |
| $\text{choice}_2$ | ICE power management (0/1/2) |
| $\text{choice}_3$ | Battery power management (0/1/2) |
| $C_r$ | Coefficient of rolling resistance |
| $C_r$ | Compression ratio |
| $d_e$ | Exhaust valve diameter (mm) |
| $d_i$ | Intake valve diameter (mm) |
| $eff_1$ | Efficiency of motor |
| $eff_2$ | Efficiency of alternative fuel ICE |
| $eff_3$ | Efficiency of gasoline ICE |
| fmep | Friction mean effective pressure (psi) |
| $G$ | Number of intake valves per cylinder |
| $g$ | Acceleration due to gravity (m/s) |
| $imep$ | Indicated mean effective pressure (psi) |
| $imep_c$ | Corrected imep (psi) |
| $k$ | Bearings friction coefficient |
| M | Vehicle mass (kg) |
| $N_1$ | Motors/generators speed (rpm) |
| $N_2$ | Engine speed of alternative fuel ICE (rpm) |
| $N_3$ | Engine speed of gasoline ICE (rpm) |
| $n_c$ | Number of cylinders |

| | |
|---|---|
| $P_1$ | Power from motors/generators (kW) |
| $P_2$ | Power from alternative fuel ICE (kW) |
| $P_3$ | Power from gasoline ICE (kW) |
| $P_4$ | Power charging battery (kW) |
| $p_a$ | Atmospheric pressure (psi) |
| $P_{acc}$ | Power required for accessories (kW) |
| $p_e$ | Exhaust manifold pressure (psi) |
| $p_i$ | Inlet valve pressure (psi) |
| pmep | Pumping mean effective pressure (psi) |
| $P_{total}$ | Total power required from driving cycle (kW) |
| $Q_{LHV,2}$ | Lower Heating Value of gasoline |
| $Q_{LHV,3}$ | Lower Heating Value of alternative fuel |
| $R_n$ | Number of rings per cylinder |
| s | Stroke (mm) |
| SOC | State of charge of battery (C) |
| $S_p$ | Mean piston speed (m/s) |
| $S_v$ | Surface to volume ratio (1/m) |
| $t$ | Time unit (s) |
| *tmep* | Mechanical mean effective pressure (psi) |
| $v$ | Velocity of vehicle (m/s) |
| $V_d$ | Displacement volume (L) |
| $Z_n$ | Mach index |

Optimization:

All optimization iterations for the IC engines were calculated from the brake specific fuel consumption equation.

$$bsfc_{ICE} = \frac{3600}{n_{fuel} Q_{LHV} n_{mech}} \rightarrow eff_{ICE} = \frac{3600}{bsfc_{ICE} Q_{LHV}}$$

This equation can be rewritten for specific equality equations for fuel conversion efficiency and mechanical efficiency of these engines where $\eta_{fuel}$ is the fuel conversion efficiency and $\eta_{mech}$ is the mechanical efficiency the engine. The following set of equations assume the engine will be operating at WOT with smallest values for fmep. Consequently, these equations will only depend on the engine speed N because all other parameters have been calculated in the sub-system optimization algorithms.

$$\eta_{fuel} = 0.90\left[1 - C_r^{(1-\gamma)}\right](1.18 - 0.225\phi) - S_v\left(\frac{1500}{N}\right)^{0.5} \Leftrightarrow \phi \le 0$$

$$\eta_{fuel} = 0.90\left[1 - C_r^{(1-\gamma)}\right](1.68 - 0.7\phi) - S_v\left(\frac{1500}{N}\right)^{0.5} \Leftrightarrow \phi > 0$$

In this study, $\phi$ will be taken as one and the piston top will be assumed to be flat and therefore take the usual

Surface to Volume ratio equation as follows:

$$S_v = \frac{0.8312s + (C_r - 1)(6b + 4s)}{bs(3 + C_r - 1)}$$

Mechanical efficiency can be calculated from the imep, tmep, fmep, volumetric efficiency, Mach Index, pmep, inlet port pressure, and mean piston speed:

$$\eta_{mech} = 1 - \frac{fmep}{imep}$$

$$imep = \frac{\eta_f \eta_v \rho Q_{LHV} 10^3}{(A/F)}$$

$$\eta_v = \frac{\eta_{vb}\left[1 + 7.72\left(10^{-5}N\right)^2\right]}{\left(1 + Z_n{}^2\right)}$$

$$Z_n = \frac{\left[9.428\left(10^{-8}\right)Ns\left(\frac{b}{d_i}\right)^2\right]}{C_s}$$

$$S_p = 2Ns10^{-3}$$

$$\eta_{vb} = 1.067 - 0.038e^{\left[N\left(10^{-3}\right)-5.25\right]} \text{ for N} \geq 5250$$

$$\eta_{vb} = \left\{\begin{array}{l} 0.637 + 0.13N10^{-3} \\ -0.014\left[N\left(10^{-3}\right)\right]^2 \\ +0.00066\left[N\left(10^{-3}\right)\right]^3 \end{array}\right\} \text{ for N} < 5250$$

$$imep_c = 12.8\left(p_a - p_1 - 1.47\right)$$

$$p_1 = p_a - p_i$$

$$p_i = p_a\left[1 - 1.12\left(10^{-8}\right)\left(S_p / 0.3048\right)^2\right]$$

$$tmep = \left\{ \begin{array}{l} \dfrac{53.594\left(sR_n\right)}{b^2} + \dfrac{P_e}{2.75} + P_1 + \dfrac{bNk}{1000s} \\ + \dfrac{p_a - p_1}{14.2}\dfrac{59.69s}{b^2}\left(0.088C_r + 0.182C_r^{\,1.33-0.0238S_p}\right) \\ + \sqrt{\dfrac{p_a - p_1}{14.2}}\left[1.72C_r^{-0.4} - \left(0.49 + 0.15C_r\right)\left(\dfrac{N}{1000}\right)^{1.185}\right] \\ +0.39\left(\dfrac{N}{1000}\right)^{1.5} + \left(30 - \dfrac{4N}{1000}\right)\left[\dfrac{G\left(\frac{d_i}{25.4}\right)^{1.75} 25.4^3}{sb^2}\right] \end{array} \right\} 6.895$$

$$pmep = \left\{ \sqrt{\dfrac{imep_c}{163}}\; 1.3\left(\dfrac{N}{1000}\right)^{1.7}\left[0.05953\dfrac{\left(\frac{b}{25.4}\right)^2\left(\frac{s}{25.4}\right)}{G\left(\frac{d_i}{25.4}\right)^2}\right]^{1.28} \right\} 6.895$$

$$fmep = tmep + pmep$$

Given these calculations, one can calculate the efficiencies for each of the IC engines and run both the sub-system and system optimizations. The only difference between the two are the designed variables (sub-system: bore, stroke, compression ratio, inlet and exhaust valve diameter, and engine speed versus the system: ICE 1 and ICE 2) and the constraints.

$$eff_{ICE} = \frac{3600}{bsfc_{ICE} Q_{LHV}}$$

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