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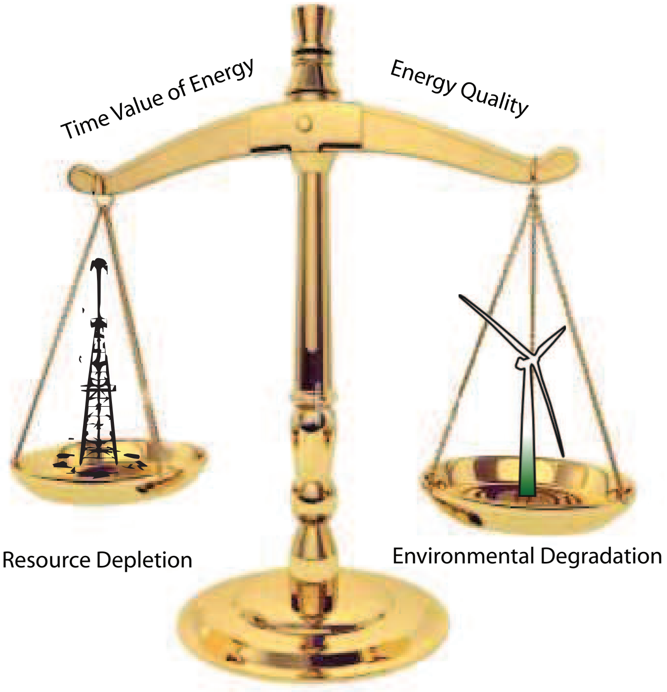

Energymetrics

and the Development of Energy Analysis Tools

Master of Science Thesis
in the Master Degree Program: Sustainable Energy Engineering

GREG W.R. ROCK

Examiner and Supervisor: Tomas Kåberger
Department of: Energy and Environment
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Abstract

The production of useable energy carriers from primary energy sources is a multi-billion dollar industry. Today decision makers within this field predominantly rely on econometric methods, like engineering economics, to evaluate and decide between, and optimize, energy carrier production plants. The life cycle economic value of these energy intensive investments shifts rapidly with changing energy prices meaning that unless we correctly predict future energy prices economic analysis will be incorrect.

Given the volatile, and upward trending, energy prices effect on such an important and expensive industry it is essential that we broaden our analytical techniques beyond econometrics. Energymetrics is the mathematical study of energy using energy units, not the dollar, as the primary numéraire. Energymetrics offers many advantages over Econometrics, and should be used in parallel with econometrics when analyzing any energy intensive investment.

The energymetric system laid out in this thesis is Applied to Argonne National Labs GREET data evaluate some of today's most common energy carrier production plants. To do this quality adjustments factors for the different types of energy carriers produced and consumed today needed to be calculated. These Relative Energy Values are developed based on an energy carrier's ability to achieve a desired energy service, personal transportation, with a given set of technology. Additionally, a method for discounting energy is developed to allow the time and rate that energy carriers are produced to effect an energy carrier production plant's social value.

Keywords: Energy, Analysis, Quality, Time, Value, Relative, Oil, Depletion, Green House Gas, Regulated Emissions, GREET, Transportation

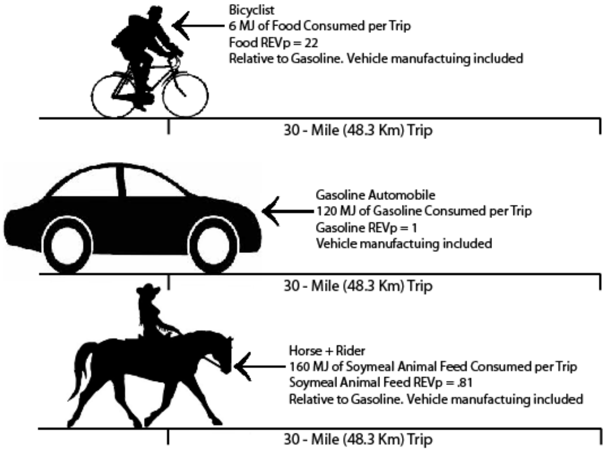
Energymetrics - Executive Summary

Many methods have been proposed to develop an energymetric system where energy units, not currency, are the primary numéraire and for good reason. If energy prices do not match predictions, econometrics can greatly under, or over-value, an energy intensive investment. Upward trending and volatile energy prices are important reasons why we should use energymetrics to assist with evaluating the best energy intensive projects to pursue in the coming decades.

This thesis lays out an energymetric system for evaluating Primary to Carrier technologies (PtCt's); often incorrectly called energy production plants. To accurately compare PtCt's quality adjustments to different energy carriers are required, and the various time factors associated with energy carrier production should be accounted for.

The instrumental value of an energy carrier is relative to the desired energy service and the available technology. Using a defined group of technology, and the energy service goal of moving a person 30 miles in 3 hours I calculate the below Relative Energy Values to personal transportation (REVp). Multiplying a Mega-Joule (MJ) of an energy carrier by its REVp results in a Relative to personal transportation Mega-Joule (RpMJ) which can be used for quality adjusted comparisons.

Relative Energy Value to Personal Transportation Examples



Relative Energy Values to Personal Transportation with Gasoline as Reference Energy Carrier

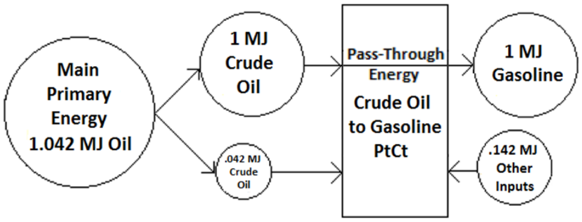
Vehicle - Fuel Chain	Energy Carrier	REVp	Vehicle - Fuel Chain	Energy Carrier	REVp
Bicycle - Metabolic	Food	22.0	Otto Engine - U.S. Mix	Harvested Nat. Gas [3]	0.86
Rickshaw - Metabolic	Labor (1 hour)[1]	4.40	Otto Engine - U.S. Mix	Primary Nat. Gas [4]	0.81
Diesel Engine	Diesel/Kerosene	1.25	Horse - Metabolic	Soy Meal	0.81
Diesel Engine	FTD/Biodiesel	1.25	Otto - H2 - Electrolysis	Electricity	0.81
Diesel Engine	SVO/WVO	1.25	Horse - Metabolic	Palm Kernal Cake	0.67
Diesel Engine	DME/LPG	1.21	Diesel - FTD - FT	Delivered Coal [5]	0.64
Horse - Animal Feed	Metabolisable Energy (ME)[2]	1.19	Horse - Metabolic	DDGS	0.65
Otto Engine	Hydrogen	1.13	Diesel - DME - Gasify	Delivered Biomass [5]	0.62
Diesel - Conventional	Harvested Crude Oil [3]	1.11	Diesel - FTD - FT	Harvested Coal [3]	0.61
Diesel - Conventional	Primary Crude Oil [4]	1.09	Diesel - FTD - FT	Primary Coal [4]	0.61
Otto Engine	Ethanol	1.07	Diesel - DME - Gasify	Uncollected Biomass [6]	0.60
Otto Engine	**Gasoline**	**1.00**	Otto - H2 - Elec - Nuclear	Nuclear (Enthalpic Potential)[7]	0.26
Otto Engine - U.S. Mix	Delivered Nat. Gas [5]	0.92	Otto - H2 - Elec - 13% PV	Incident Solar [8]	0.10

Unless otherwise specified, REVp are quality adjustment factors for converting a "Delivered" Joule of the stated energy carrier's enthalpy into Relative to personal transportation Joule's (RpJ) with gasoline as the reference carrier 1 - REV for converting one hour of work into RpJ. 2 - REV for converting one Joule of Metabolisable Energy into RpJ. 3 - Harvested means produced but not transported. 4 - Primary means stored in its original geographical location and form. 5 - Delivered means final energy carrier is delivered to the fueling pump at atmospheric conditions. 6 - Uncollected Biomass means biomass found in its original geographical location. 7 - Enthalpic potential means the quantity heat, measured in enthalpy, produced by a nuclear fission process. 8 - REV for converting one joule of incident solar energy on a PV panel into a RpJ. All results calculated with data from (GREET1_2011) except for the REVp values for horse and human powered transportation.

An energy carrier available today can be invested in a PtCt with a positive return on energy carrier investment. This means that energy carriers delivered to us today can be more valuable than ones delivered in the future. The Time Value of Energy method discounts future energy carrier flows allowing presently valued energy comparisons. Due to a lack of information time valuation was not applied to the quality adjusted analysis of the PtCt's below.

To aid with the evaluation of PtCt's I define a number of specific energy accounting equations called Energy Analysis Tools (EAT's). The Carrier Return Over Investment (CROI) is the ratio of carrier outputs over inputs; excluding the main primary energy. The Carrier Harvested Over Investment (CHOI) is the ratio carrier outputs over inputs; including the main primary process but not the pass through energy. The Carrier Burned Over Oil Investment (CBOO) is the ratio of carrier output to total oil input.

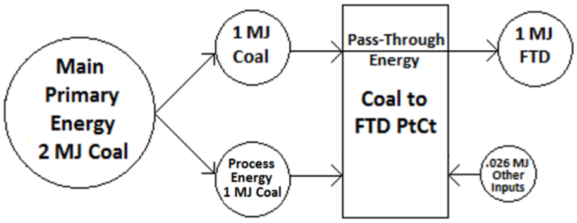
Example: Conversion of Crude Oil into Gasoline



$$\boldsymbol{CROI} = \frac{1MJ}{.142MJ} = 7.0$$
$$\boldsymbol{CHOI} = \frac{1MJ}{.042MJ+.142MJ} = 5.4$$
$$\boldsymbol{CBOF} = \frac{1MJ}{1.042MJ+.134MJ} = .85$$
$$\boldsymbol{CBOO} = \frac{1MJ}{1\mathrm{MJ}+.046MJ} = .96$$
$$\boldsymbol{WtP\eta} = \frac{1MJ}{1.042MJ+.142MJ} = .84$$

$$\boldsymbol{NCP} = (1MJ - .142MJ) = .86MJ$$
$$\boldsymbol{NCH} = (1M - .042\mathrm{MJ} - .142MJ) = .85MJ$$
$$\boldsymbol{NFB} = (1MJ - 1.042MJ - .133MJ) = -.18MJ$$
$$\boldsymbol{NOB} = (1MJ - 1.042MJ - .04MJ) = -.05MJ$$
$$\boldsymbol{NCB} = (1MJ - 1.042MJ - .142MJ) = -.18MJ$$

Example: Conversion of Coal into FTD



$$\boldsymbol{CROI} = \frac{1MJ}{.026MJ} = 41$$
$$\boldsymbol{CHOI} = \frac{1MJ}{1MJ+.026MJ} = .97$$
$$\boldsymbol{CBOF} = \frac{1MJ}{2MJ+.026MJ} = .49$$
$$\boldsymbol{CBOO} = \frac{1MJ}{.018MJ} = 54$$
$$\boldsymbol{WtP\eta} = \frac{1MJ}{2MJ+.026MJ} = .49$$

$$\boldsymbol{NCP} = (1MJ - .026MJ) = .97MJ$$
$$\boldsymbol{NCH} = (1M - 1\mathrm{MJ} - .026MJ) = -.03MJ$$
$$\boldsymbol{NFB} = (1MJ - 2MJ - .025MJ) = -1.03MJ$$
$$\boldsymbol{NOB} = (1MJ - .005MJ) = .995MJ$$
$$\boldsymbol{NCB} = (1MJ - 2MJ - .026MJ) = -1.03MJ$$

The Relative to personal transportation Net Carrier Production (RpNCP) is the difference between the relatively valued carrier outputs and inputs; excluding the main primary inputs. This quantitative value can be used to optimize a PtCt, or be offset against negative aspects like: GHG's, Pollution, Depletion, Economic Cost, etc. A RpNCP/Social Cost EAT allows decision makers to maximize personal transportation valued carrier production while minimizing a social cost.

Summary of Primary to Carrier Technology's EAT's				**(RpJ/Kg CO2e)**	**Units**	**(RpMJ/Year 2000 Euro)**
Feedstock -> Carrier	**RpCROI**	**RpCBOO**	**Feedstock -> Carrier**	**RpNCP/CO2e**	**Feedstock -> Carrier**	**RpNCP/Reg. Emission**
Tree -> Ethanol	**9.6**	12	Biomass -> DME	**-17**	Soybean -> Biodiesel	**1200**
Biomass -> DME	**9.3**	20	Soybean -> Biodiesel	**1100**	Biomass -> DME	**950**
Shale -> Nat.gas	27	100	Rapeseed -> Biodiesel	**670**	Rapeseed -> Biodiesel	**710**
Conv. -> Diesel	11	1.0	Palm Oil -> Biodiesel	**620**	Palm Oil -> Biodiesel	**670**
Conv. -> Nat. Gas	30	210	Jatropha -> Biodiesel	**550**	Jatropha -> Biodiesel	**580**
Biomass -> Electricity	**7.3**	10	Switchgrass -> Ethanol	**130**	Conv. -> Gasoline	**410**
Switchgrass -> Ethanol	**6.2**	18	Biomass -> FTD	**66**	Stover -> Ethanol	**390**
Sugar Cane -> Ethanol	**6.1**	8.6	Biomass -> Electricity	**66**	Tree -> Ethanol	**380**
Conv. -> Gasoline	8.1	1.0	Algae -> Biodiesel	**50**	Conv. -> Diesel	**380**
Palm Oil -> Biodiesel	**5.3**	12	F. Residue -> Ethanol	**34**	Biomass -> FTD	**380**
Soybean -> Biodiesel	**4.9**	12	Sugar Cane -> Ethanol	**27**	Tar Sands -> Diesel	**310**
Algae -> Biodiesel	**4.1**	19	Conv. -> Diesel	**12**	Conv. -> Nat. Gas	**290**
Tar Sands -> Diesel	3.9	1.0	Conv. -> Gasoline	**10**	F. Residue -> Ethanol	**180**
U.S. Corn -> Ethanol	**3.0**	14	Nat. Gas -> Elec.	**9.0**	Biomass -> Electricity	**180**
Tar Sands -> Gasoline	3.0	0.9	Tar Sands -> Diesel	**8.7**	U.S. Corn -> Ethanol	**90**
Coal -> FTD	50	50	Tar Sands -> Gasoline	**6.4**	Coal -> FTD	**40**
Nat. Gas -> Electricity	97	180	Coal -> FTD	**5.5**	Coal -> Electricity	**32**
Coal -> Electricity	40	40	Coal -> Electricity	**5.4**	Sugar Cane -> Ethanol	**20**

All values calculated with (GREET1_2011) data except where specified. 1 - RpCarrier Output divided by RpCarrier Input excluding the main primary energy input. 2 - RpCarrier Output divided by RpCarrier Inputs including the main primary process energy, but excluding pass-through energy. 3 - All Green House Gases compared on Carbon Dioxide equivelant basis. 4 - Costs of regulated emissions based on (IMPACT, 2007) with France as the specified country

Argonne National Laboratory's GREET1_2011 (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model was used within this thesis. No life cycle data is perfect but GREET is broad in scope, detailed, public, and from a credible source. Results presented in this thesis are specific to the exact technologies examined with the given GREET data, and should not be considered generalization of all technologies of a similar nature.

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List of Figures and Tables

Life Cycle Assessment Abbreviations

LCA - Life Cycle Assessment
PtCt - Primary energy To energy Carrier Technology
CtSt - Energy Carrier To energy Service Technology
PtSt - Primary energy To energy Service Technology
WtW - Well to Wheel; LCA accounting including energy inputs for harvesting, converting, distributing, fueling and converting energy carrier into personal transportation.
PtW - Pump to Wheel; LCA accounting including energy inputs for fueling a vehicle, and converting energy carrier into personal transportation.
TtW - Tank to Wheel; LCA accounting including energy inputs for converting energy carrier into personal transportation.
WtP - Well to Pump; LCA accounting including energy inputs for harvesting, refining and distributing energy carrier to an atmospheric fuel pump. Excludes pass through energy as an input.
WtP+ - Well to Pump plus the pass through energy; LCA accounting including energy inputs for harvesting, refining and distributing energy carrier to an atmospheric fuel pump. Includes pass through energy as an input.
Pass through energy - Enthalpic quantity of energy that is contained within a final energy carrier that was originally part of the main primary energy source.
SC - Social Cost

Energy Analysis Tool Abbreviations

EAT - Energy Analysis Tool; Mathematical formula for describing a specific energy accounting method.
CROI - LCA WtP Enthalpic Carrier Return Over carrier Investment; Carrier output divided by inputs but the main primary energy input, and process energy of the same form, are excluded from the energy accounting calculation.
CHOI - LCA WtP Enthalpic Carrier Harvested Over carrier Invested; Carrier output divided by inputs where pass through main primary energy is ignored but excess process energy derived from the main primary energy is included in the energy accounting calculation.
CBOF - LCA WtW Enthalpic Carrier Burned Over Fossil fuel investment; Carrier output divided by fossil fuel inputs.
CBOO - LCA WtW Enthalpic Carrier Burned Over Oil investment; Carrier output divided by only oil inputs.
CBOP - LCA WtW Carrier Burned Over main Primary investment; Carrier output divided by only the main primary energy, and process energy of the same form.
Rpη - RpEfficiency - LCA WtP Relative to Personal transportation efficiency
NCP - LCA WtP Net Carrier Production; Outputs minus inputs excluding the main primary energy and process energy inputs of the same form.
NCH - LCA WtP Net Carrier Harvested; Outputs minus inputs excluding pass through energy
NFB - LCA WtW Net Fossil Fuel Burned; Carrier output minus total fossil fuel inputs
NOB - LCA WtW Net Oil Burned; Carrier output minus total oil inputs
NCB - LCA WtW Net Carriers Burned; Carrier output minus total carrier input
NCP/SC - LCA WtP Net Carrier Production divided by LCA WtW Social Cost

Relative Energy Value Abbreviations

Rp - Relative to Personal Transportation; Can be added to an EAT's, words or abbreviations to denote the value is reported on a Relative, not Enthalpic, basis. Unless otherwise specified gasoline is the reference energy carrier.
RpMJ - Quality adjusted Relative to personal transportation Mega-Joule with gasoline as the reference carrier.
REV - Relative Energy Value - Generic term used to describe quality adjustment factors calculated using the theory of Energy Relativity.
REVp - Relative Energy Value to Personal Transport with gasoline as the reference energy carrier and the bicycle, horse, IC car as available energy service technology.
REVe - Relative Energy Value to Personal Transport with gasoline as the reference energy carrier and the bicycle, horse, IC/Electric Car as available energy service technology.
.g - Gasoline as reference energy carrier - Applied to RpMJ values as Rp.gMJ for specific indication that gasoline is the reference energy carrier. If not noted gasoline is the assumed value.
.d - Diesel as reference energy carrier - Applied to a RpMJ value as Rp.dMJ indicates diesel is the reference energy carrier and assigned REVp.d = 1 from which all other REVp.d were calculated

Time Value of Energy Abbreviations

TVE - Time Value of Energy
CTL - Carrier Time Line - A graphical representation of a PtCt's carrier inputs and outputs, by type, per year
MAER - Minimum Attractive rote of Energy Return (enthalpic)
ICR - Internal Carrier Rate of Return
P_5Rp - Present and Relative to Personal Transport valuation; Can be added to all EAT's, words, or abbreviations to denote the value is on both an Present and Relative basis. The subscript number denotes the MAER used for calculations.
P_5RpMJ - Quality and Time adjusted Present Relative to personal transportation Mega-Joule with gasoline as the reference energy carrier.
MARR - Minimum Attractive Rate of Return (economic)
PC - Present Carrier Value
FC - Future Carrier Value
CP - Carrier Production
CC - Carrier Consumption

Other Abbreviations

J - Enthalpic Joule; **KJ** = 10^3J; **MJ** = 10^6J; **GJ** = 10^9J; **TJ** = 10^12J
mpg.ge - Mile per Gallon of Gasoline Equivalent
L.ge/100km - Liter of Gasoline Equivalent per 100 km
GHG - Green House Gas Emission
GWP - Global Warming Potential
CO2e - Carbon Dioxide Equivalent quantity of Green House Gas Emission
NEV - Net Energy Value - commonly used abbreviation for energy carrier outputs minus inputs
EROI - Enthalpic Energy Return Over Energy Invested - commonly used abbreviation for the ratio of energy carrier outputs divided by inputs.
EROIpou - Enthalpic Energy Return Over Energy Invested - LCA WtP boundary
EV - Electric Vehicle
2P Reserve - Quantity of resource proven recoverable plus probable to be recoverable in the future
ME - Metabolisable Energy
DDGS - Dry Distillers Grain with Solubles
DDG - Dry Distillers Grain without Solubles
FTD - Fischer Tropsch Diesel
WVO - Waste Vegetable Oil
SVO - Straight Vegetable Oil
DME - Dimethyl Ether
LPG - Liquefied Petroleum Gas
BioD - Biodiesel
VOC - Volatile Organic Compounds
NOx - Nitrogen Oxides
PM2.5 - 2.5 micron Particulate Matter
PM10 - 10 micron Particulate Matter
SO_2 - Sulfur Dioxide
CH_4 - Methane
GWP - Global Warming Potential
StW - Sun to Wall; LCA accounting including energy inputs required to produce electricity from solar energy, and deliver it to a wall outlet.
EIA - U.S. Energy information Administration
IEA - International Energy Agency
CHP - Combined Heat and Power

Objective

The goal of this thesis is to develop non-currency based numerical methods for analyzing, valuing, and comparing different types of energy carriers, as well as the technology used to produce them from a primary energy source. A primary energy source is defined as an energy form in its original geographical location and form. An Energy Carrier can refer to any form of energy, however the main focus within this thesis is to evaluate energy carriers that have been harvested, refined, and transported to an atmospheric pumping station.

The primary objective of this thesis is to develop the necessary numerical methods for comparing the social benefits and costs associated with the conversion of different primary energy sources into a variety of energy carriers available at a pump. This conversion process is often incorrectly called Energy Production; which conflicts with the first law of thermodynamics. Within this thesis I will call this type of energy project a Primary energy to energy Carrier technology (PtCt). Using the non-currency numerical methods developed within this thesis for analyzing energy carriers and PtCt's I will call Energymetrics.

Application of Methods

The Energymetric system developed within this thesis can be used to compare different Primary to Carrier technologies (PtCt's) on a Life Cycle Assessment (LCA) basis. LCA data can be fraught with challenges since authors generally make a wide range of assumptions concerning boundary conditions. While correct decisions are desired, I believe for comparison purposes it is more important that consistent boundary assumptions are made.

In this thesis I make no attempt to develop my own LCA data to analyze. However, I do apply my methods to broad and publically available set of data found in Argonne National Laboratory's GREET1_2011 (Green House Gas, Regulated Emissions and Energy Use in Transportation) model. (GREET_2011) examines a large group of PtCt's and vehicle technologies, hopefully, while maintaining somewhat consistent boundary assumptions. Except where specified, GREET's original assumptions were maintained. I make no attempt to qualify GREET data, and the tables of results that I produce are only examples of how my methods apply to this specific set of data.

GREET data comes from a credible source, but like all LCA data has underlying challenges. To its advantage it is an open-source excel database, which although complex allows readers to trace out the different assumptions made by its author Michael Wang. To assist with this effort I have provided a references to the its specific location within the GREET database for data I use within this thesis.

Readers can make their own evaluation of (GREET_2011) data and by association the tables of results presented in this thesis. The Energymetric methods developed within this thesis could, and should, be applied to a different sets of enthalpic LCA data. I briefly compare GREET data to Pimentel biofuel data which showed a significant shift in an individual PtCt's quantitative results, but only a nominal shift in comparison results; the primary objective of this energymetrics thesis.

Energymetrics and a Summary of the Past

Energymetrics, the numerical study of energy using energy units, uses mathematical formulas to adjust different units of energy into more equalized values. Additionally, specific energy accounting formulas called Energy Analysis Tools (EAT's) are used to compare different aspects of a PtCt using these equalized units of energy. Unlike econometrics, defined by (Ragnar, 1926), an energymetric system does not use currency but instead energy units as the primary numéraire.

Energy accounting proposals have existed for over a century but none have gained wide-spread use due to a number of challenges. Perhaps the biggest is the energy quality challenge. A joule of one energy carrier is not always equal to a joule of another carrier. A review of past attempts to over-come this "apples and oranges" energy quality challenge can be read below.

An accurate energymetric system should also take into account the Time Value of Energy. Energy carriers, like money, can be re-invested into a PtCt yielding a positive rate of energy carrier return. This reinvestment potential allows presently available energy carriers to be more valuable than ones available in the future.

Time and quality adjustments help equalize and compare energy carriers on more of an Apples to Apples basis however there are still numerous different ways to compare the equalized inputs and outputs of different PtCt's. The inclusion or exclusion of different types of energy inputs can be valid for many different analytical techniques. To allow for many different methods while not confusing the results I develop a large group of different EAT's each analyzing a specific aspect of a PtCt's.

In this thesis: I develop a group of Relative Energy Values to personal transportation (REVp) to address the quality challenge. Define a number of specific EAT's with which I compare different PtCt's using quality adjusted GREET data. Develop a method for discounting energy but do not recommend a Minimum Attractive rate of Carrier Return (MACR), or apply time valuation to a large group of PtCt's.

Thermodynamic Energy Quality

From a thermodynamic perspective energy can be quantified by Enthalpy, Gibbs free energy and Entropy. Enthalpy is a thermodynamic quantity of total energy often described as an energy carrier's heat content. Enthalpy is the most frequently used value for official statistics with the units Joules, BTU, KWh, etc. Enthalpy is not a good measure an energy carriers social value because not all of it can be converted into a useful energy service like: lighting, transportation, or space heating. Some Enthalpy can be so diffuse that it is essentially worthless. A joule of gasoline is more valuable to you than a joule of heat dissipating from your brakes. **The social value of an energy carrier is created by the utility benefits we receive by converting an energy carrier into a desired energy service.**

Gibbs Free Energy (Gibbs, 1873) and Entropy (Clausius, 1865) have also been considered as numéraire to use within an energymetric system. (Georgescu-Roegen, 1971) described the Entropy Law - "The Entropy of the universe at all times moves toward a maximum". He points out the impossibility of infinite growth on finite, low entropy, sources which would eventually all be converted into, high entropy, diffuse heat. Long-term growth could only be sustained by harnessing solar energy inputs despite its high entropic nature. Gibbs free energy is the measurement of an energy carrier's ability to produce work relative to a reference state.

End-Use Energy Quality

One of the most recognized alternate numéraire is Exergy (Rant, 1956) and the study of Exergy, or available work. As exergy is consumed entropy is produced. The key difference between exergy and Gibbs free energy is that exergy represents the quantity of work an energy carrier can produce in relation to its surroundings, instead of an isobaric process between the energy carrier and a reference state. Exergy is not a good measure of social value as it represents a theoretical maximum for work potential, given a specific environment, not the actual quantity of work that can be delivered using current technology.

OECD Thermal Equivalents create a group of quality adjustment factors based on the quantity of electricity that can be produced from primary energy sources (Patterson, 1993). This is a step forward as it takes into consideration the conversion technology and its effect on utility production. However, Electricity like heat and work are not the sole energy carrier/service desired. Additionally, I argue that none of these create the greatest social value per unit of additional production, which is the result of producing what I call the Marginal Energy Service.

Production Side Energy Quality

Howard Odum created a detailed method for production side energy analysis. He argued that this method could be used to make quality adjustments based on the relative quantity of original primary energy it took to produce different energy carrier. (Odum, 1988) defined the term Emergy as a the total energy of one type it takes to produce another. Since solar energy is the main driving force on our planet it is commonly used as the reference energy with solar emJoules as the units.

The emergy value of a unit of gasoline is: the solar emJoules absorbed by the associated plants that were trapped under ground + the solar equivalent of geological energy that converted the plants into oil + the solar emJoules used to harvest and refine the oil into gasoline. This historical accounting of energy content could take place over 100's of thousands of years. While interesting, this is not a good method for quality adjustments, as is not directly relate to the social value of an energy carrier.

For example, Biodiesel can be produced from a number of different plants and trees. Each with a different efficiency of converting solar energy into agricultural product, and eventual biodiesel. Despite the different Emergy values of the resulting biodiesel produced. Each unit of biodiesel has the same social value if each can propel a car the same distance. The effect on the millions of years of concentrated plant matter, we call fossil fuels, is more significant.

Economic Energy Quality

Economist (Webb M., Pearce D., 1975) believe energymetrics is totally useless. They argue that reducing all the variables that give different energy carriers social value is exactly what the pricing of commodities within a free market does. They argue, largely on a lack of quality and time valuation methods, that you cannot value energy better with energymetrics than with econometrics since the social value of an energy carrier is a function of so many distinct factors like: energy density, resource-availability, store-ability, cleanliness, timing, social preferences, etc.

I disagree that numerous distinct factors cannot be integrated into an energymetric system. Despite the added complexity, I believe there are two important reasons why we should pursue the use of detailed energymetric systems to compliment our econometric system of analysis.

We do not live in a perfect free market. The market price of a commodity only correctly represents its true social value if we have a perfect market with: perfect information, no barriers to entry/exit, equal access to production technology, and no participants with the power to set prices. (Debreu, 1959) While none of these requirements are true for our marketplace in general, they are especially not true within the energy sector.

- Information is far from perfect. Saudi Arabia, with the largest oil production capacity in the world treats its resource data as a national security secret.
- Energy projects are extremely expensive, require access to scarce resources, limited distribution networks all which create significant barriers to entry.
- Equal access to production technology is especially challenging within the alternative energy sector where patents control key developments.
- Subsidies, tax breaks, political embargo's, and speculation are all examples of market participants effecting or setting the price of energy.

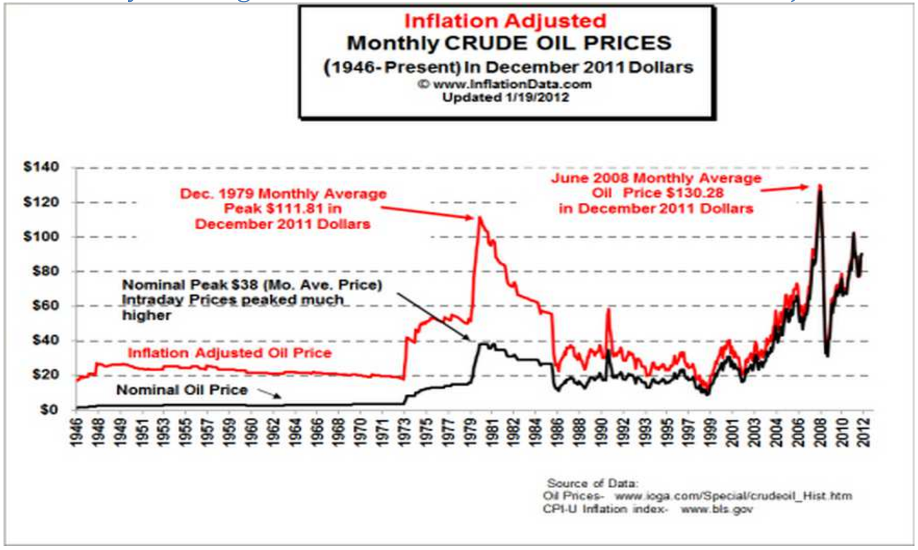
More importantly, using econometrics to evaluate long-term energy intensive investments can create huge miscalculations because energy prices can, and do, change rapidly. Engineering economics is commonly used to optimize or decide between two PtCt's but often leads to improper investment, with lower than expected returns, if energy prices do not match an expected average over the life of the project. This is almost guaranteed since prices change every day and most PtCt's last at least 20 years and some over a hundred. Energymetrics can offer a more static analysis tool since calculated values will stay the same regardless of potentially rapid changes in energy prices.

From an inflation adjusted perspective the change in annual average oil prices from 1950 - 1970 averaged just 2.4% per year staying close to the historical average oil price of $23/barrel.[1] This slow rate of change allowed engineering economics to successfully produce static design and selection results for a wide variety of PtCt's and accurately predicted returns.

From 1970-2010 annual price changes have averaged over 20%; a dramatic increase in price volatility. Both the upward movement in the 70's, and downward movement in the 80's significantly altered an installed PtCt's values from an econometric perspective. This lead to many improper investments in new PtCt's in the 70's, and bankrupted many unprepared PtCt's in the 80's. A crystal ball is needed, and unavailable, to make correct energy intensive investments using econometrics.

The last decade, (2001-2011) was the most volatile on record and we have faced an upward price trend. Unlike the 70's, the tripling of oil prices this decade is not political. Rapid demand growth lead by Asia has run into supply constraints due to the peak in world conventional oil production in 2006 (IEA, 2010). The damage caused by volatile swings can be muted by the law of averages if the company can sustain the swings but is generally detrimental to small players. A continuous upward price trend however can be even more damaging to installed PtCt's than volatility swings. If current trends continue the real average price over the life of today's PtCt could be many multiples over the predicted average used to design and decide between them.

Figure 1 - Monthly Average Historical Nominal and Inflation Adjusted Oil Prices[2]



Source of Data:
Oil Prices- www.ioga.com/Special/crudeoil_Hist.htm
CPI-U Inflation index- www.bls.gov

Econometrics is by nature is dynamic, and that dynamic nature appears to be increasing making it less useful as a static analysis tool. Yet, some hybrids combining the idea that price is the best indication of an energy carriers value within an energymetric system have been created and are worth noting. These methodologies are described, and used as quality adjustment factors for analyzing oil harvesting by (Cleveland, 1992).

The Relative Price Approach calculates quality adjustment factors by dividing the $/MJ of an energy carrier by the $/MJ of a reference carrier. By multiplying different carriers by their quality adjustment factor each is adjusted to the markets estimate of its value, considered equalized and used within an energymetric framework. This approach has been criticized since it assumes that all energy carriers are substitutable which is not the case. (Berndt, 1978) applies the Divisia index (Diewert, 1976) to account for these real world substitution constraints.

The Marginal Product of Energy approach (Adams and Miovic, 1968) compares the total dollars of industrial output of an economy to the total energy carrier's of input. By analyzing many economies he calculates which carrier inputs produce the most industrial output and these carriers are assigned the highest quality adjustment factors. The findings show that consuming electricity produces fourteen times more industrial output than burning coal.

Life Cycle Assessment

Any energymetric analysis done for comparison purposes should be a complete Life Cycle Assessment (LCA). An LCA examines the total inputs required for locating a resource, constructing equipment, operating equipment, transporting carriers, and finally decommissioning facilities. Standardized methodologies for LCA studies are laid out by (ISO, 2006). However, The International Organization for Standardization does not lay out rules for boundary conditions making it difficult, and often misleading, to use different LCA studies for comparison purposes.

LCA data from (GREET, 2011) includes: Construction and operation of the PtCt plus transportation energy but does not include energy for locating or decommissioning. Also excluded from GREET's Well to Pump (WtP) values are the indirect energy investment for constructing: transport trucks, fueling stations, pipelines, roads, etc.

Energy Return Over Investment and Net Energy Value

The Energy Returned Over energy Invested (EROI) termed by (Cleveland and Hall, 1984) is a unit-less ratio between the outputs and inputs of a PtCt. The Net Energy Value (NEV) is the difference between the outputs and inputs of a PtCt. Both are EAT's but some challenges exist with their application.

- Boundary conditions are often not fully disclosed with reported values. An effort to address this challenge is discussed by (Murphy, 2010). The EROIpou (point of use) most closely matches the Well to Pump (WtP) values used throughout this thesis.
- The accounting of inputs can follow many different assumptions which are often not fully defined. Notably, the inclusion or exclusion of process energy that is derived from the main primary energy being harvested.
- EROI has been used to describe the instantaneous production ratio, instantaneous discovery ratio and the LCA ratio of energy outputs and inputs. Only LCA values should be used for PtCt comparison purposes.
- When comparing energy flows that occur over a number of years or decades the Time Value of Energy should be considered.
- Enthalpy is the most common method used to assign value to different energy carriers leading to ratios that do not take into account quality differences between outputs and inputs.

Addressing the Energy Quality Challenge - The Theory of Energy Relativity

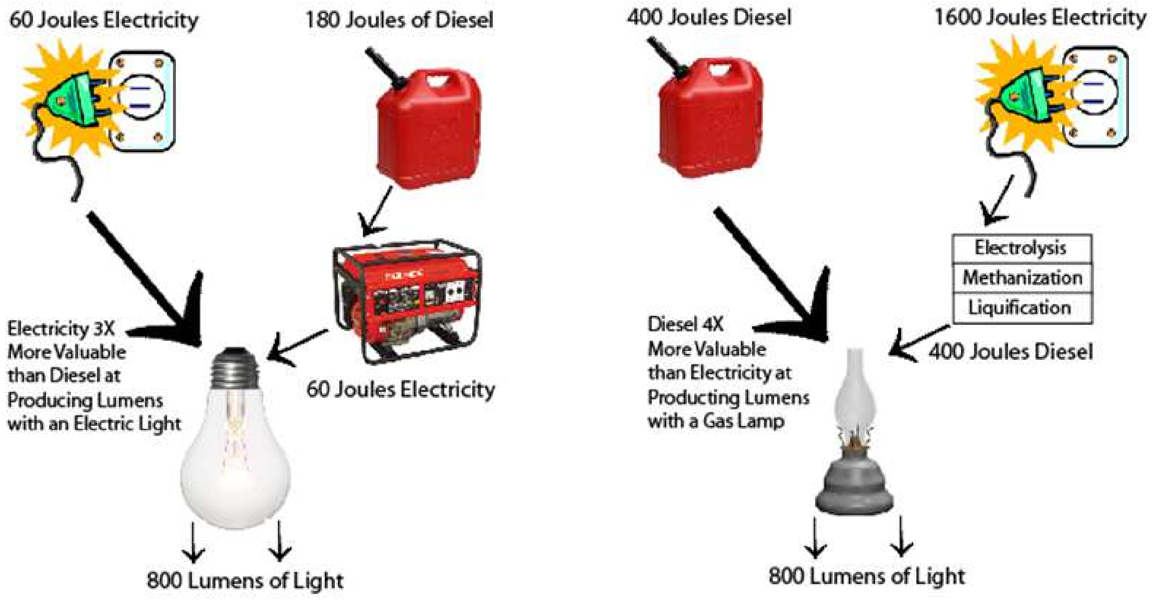
The term "Instrumental Value" defined by (Kåberger, 1991) is the portion of a primary energy that our society can utilize for final energy services. Exergy represent a primary energy's instrumental value if: it could be harvested without inputs, and work could be converted into services without losses. I believe this energy-service end-use method is the most directly related approach to an energy carrier's social value. In practice the instrumental value of a primary energy sources is a function of:

- The energy service that is desired
- The Primary to Carrier Conversion Technology (PtCt)
- Carrier to Service Conversion Technology (CtSt)

I propose that quality adjustment factors which I call Relative Energy Values (REV's) should be developed using this theory of Energy Relativity - **The instrumental value of an energy carrier is relative to the desired energy service and the available technology**.

A specific group of REV's is not universally applicable, but I argue the theory itself is. Application of this theory raises two questions who's answers will change over time with new technology and shifting social desires; but not as rapidly as energy prices. For example, without the electric light-bulb electricity would have a much lower Relative Energy Value compared to diesel for the goal of producing light.

Figure 2 - Energy Relativity Examples for Energy Service Goal of Light



Which Desired Energy Service?

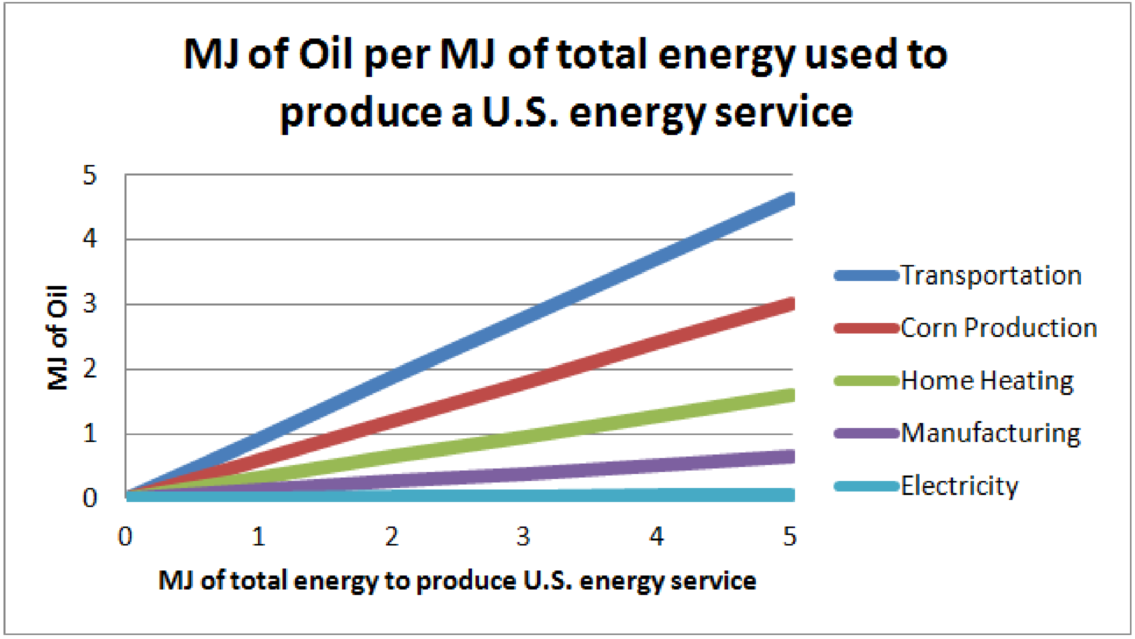
The desired energy service should be the Current Marginal Energy Service; which creates the greatest increase in social benefit per enthalpy offset caused by a free unit of service production. The Current Marginal Energy Service should also contribute to a significant portion of the total social cost.

Marginal analysis is the focus of econometrics and should be the focus of energymetrics. Examining the greatest quantitative, or an average of all desired energy services is not as relevant for developing quality adjustment factors as marginal analysis.

I believe that conventional world oil production peaked in 2006 (IEA, 2010), and as a result oil prices will never return to historic $25/barrel prices. Keeping oil prices from continuing their upward trend while the world economies develop is perhaps our greatest economic challenge. To mitigate this challenge we can attempt to reduce oil demand and stabilize prices. If reducing oil demand is in fact our greatest challenge, be it for economic or environmental reasons, the Current Marginal Energy Service would be within the transportation sector.

The transportation sector today is the most directly connected energy service to our oil demand. Using U.S. data as an example, 93% of our transportation is powered by oil. Compared to only: 1% of energy used for electricity production[3] (EIA, 2011), 13% of energy used for U.S. manufacturing[4], 32% of energy consumed for home heating[5]. I also estimate with (Pimentel, 2005) that 60% of the energy used to produce U.S. corn comes from oil. These oil intensity values set the slopes below.

Figure 3 - Oil intensity of different energy services



If I set the social benefit goal to saving oil, an additional unit of free transportation energy service added to the market would create the greatest increase in social benefit. In addition to the highest oil intensity, the Transportation sector is the largest consumer, 70%, of oil in the U.S. (DOE, 2010).

I believe that transportation is the general Current Marginal Energy Service for numerous different social goals including: maximizing energy price adjusted Gross Domestic Product, stabilizing oil prices, minimizing consumer dollars spent on energy, and minimizing dollars spent on U.S. energy imports.

Personal Transportation

The transportation sector includes moving people and goods via boat, plane, train and automobile. Developing REV's for the entire sector would be very difficult, and it is not clear which segment should be used as a more specific Current Marginal Energy Service.

Cars represent the largest portion (32%) of the transportation sector (DOE, 2010). The predominate use of the car is for local personal transportation, with the average car in the U.S. traveling 32 miles (51.5 km) per day (DOT, 1995). Strong growth in car ownership, especially in China and India, leads me to believe that the personal automobile is also the fastest growing segment within the transportation sector. This does not dictate that local personal transportation should be the specific Marginal Energy Service, but it is certainly near the top as one of the most oil intensive, while also quantitatively significant consumers of oil within the sector.

Personal transportation was additionally chosen as the specific energy service goal because credible automobile data was available within GREET, and it provided an opportunity to establish REV's for a diverse group of energy carriers including food and animal feed. Changing the specific segment analyzed within the transportation sector to Air Travel would alter these results, and is examined in Appendix A.

Personal transportation is defined in this thesis as moving a 160 lb person from one specific point, 30 miles (48.3 km) to another specific point within 3 hours.

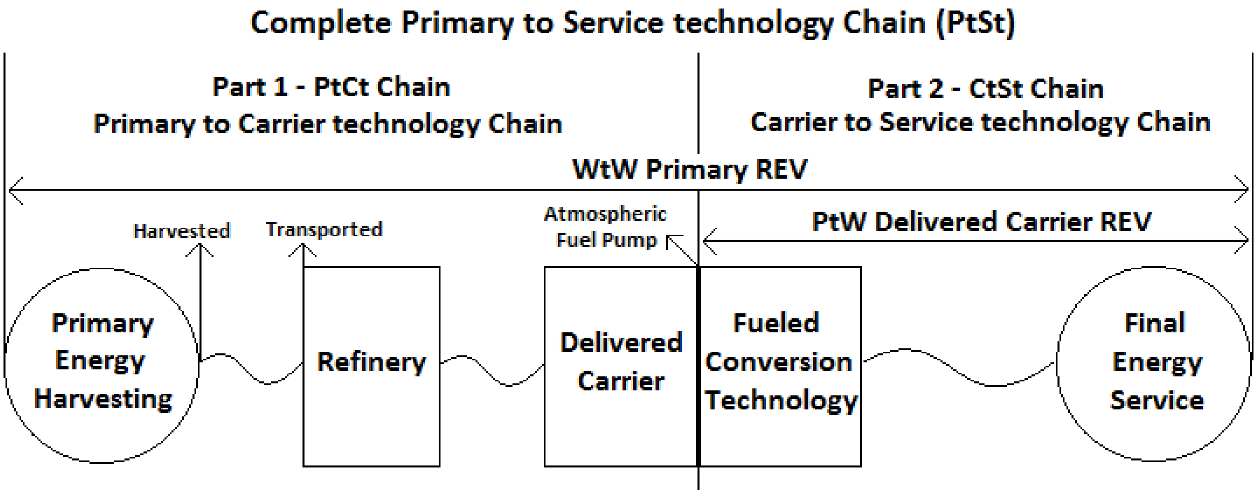
What Available Technology?

Available technologies should be capable of taking a significant market share during the average half-life of the PtCt's being studied without creating significant new capital costs to society.

To simplify and reduce the number of possible and over-lapping technology options I break the entire primary energy to energy service chain (PtSt) into two separate parts:

- Part One: The PtCt chain accounts for the energy to harvest and refine primary energy into a carrier, plus the energy for transporting the carrier to its distribution center. Well to Pump (WtP)
- Part Two: The CtSt chain accounts for the energy to fuel the conversion technology, and convert an energy carrier into an energy service. Pump to Wheel (PtW)

Figure 4 - Complete Primary to Service technology chain



Note: For Gaseous fuels the compression energy for storage is accounted for as part of the CtSt chain

From part two of this chain I calculate the REV's for a number of energy carriers without needing to make any assumptions about different PtCt's. Since energy carriers at the pump, not primary energy, are what society produces and consumes establishing REV's for energy carriers at the pump alone provides tremendous analysis potential even for part one of this chain.

In this thesis REV's for primary energy have also been calculated using GREET's best complete Primary to energy Service technology chains. These Well to Wheel (WtW) values likely have more errors, and are more susceptible to change over time, than Pump to wheel (PtW) values due to the increased number of technologies involved. Technology changes with time and will alter the calculated REV's, but this change generally occurs slower, and is more predictable than changes in energy prices.

Available Technology

Otto (30 mpg; 7.8 L/100km) and Diesel (40.6 mpg ; 6.5 L/100km) engine powered cars exist, and there is unlimited access to both. Cars can be modified in regards to their fuel system, fuel mixture and engine timing. Namely, an Otto engine can be modified to run on Natural Gas, Methane, or Gaseous Hydrogen. A Diesel engine can be modified to run on Biodiesel, Straight/Waste Vegetable Oil (SVO/WVO), Dimethyl Ether (DME), Fischer Tropsch Diesel (FTD), or Liquefied Petroleum Gas (LPG).

Horses exist, and can carry a rider 30 miles (48.3 km) at a trot of 8 mph (12.9 km/hr) for 2.75 hours. Horses can eat Pasture Hay, Soybean Meal, DDGS, etc. They require a feed consumption of 68 MJ/Day of Metabolisable Energy (ME) for sustenance, and an additional 10.5 MJ-ME/hour while trotting.[6]

Bicycles exist, and a human (160 lbs; 73kg) is capable of biking 12 mph (19.3 km/hr) while creating an additional daily food consumption of 2.4 MJ/hour.[7] Bicycle powered rickshaws exist and I assume a cyclist can move a person of equal weight the same distance, at the same speed, while consuming twice the additional daily food consumption of a single bicyclist (4.8 MJ/hour).

Fuel Cracking, Electrolysis, Direct Combustion, Gasification, Pyrolysis, Fischer-Tropsch, Fermentation, Anaerobic Digestion and Transesterification are all commercially available conversion processes as are any other technologies used by GREET to convert primary energy into energy carriers.

Distribution, storage, pumping and compression technologies exist for all energy carriers. Photovoltaic cells exist with a solar to electric efficiency of 13%

An emerging technology that would nearly quadruple the REV of electricity, while increasing the REV of Coal, Natural Gas and Biomass is the electric vehicle (EV). EV's have been excluded from my primary analysis as I do not believe they can take a significant market share over the average half-life of the PtCt's being studied without significant additional capital costs. This is arguable, and an alternate set of REV's assuming the existence of EV's is examined in Appendix A.

Developing Relative Energy Values to Personal Transport - (REVp)

Some Notes on Units and Terminology:

Enthalpy is the original measurement value for the different apples and oranges we call energy carriers. Multiplying a Mega-Joule (MJ) of enthalpy by its associated Relative Energy Value to personal transportation with gasoline as the reference energy carrier (REVp.g) results in a Relative to personal transportation with Gasoline as the reference energy carrier Mega-joule (Rp.gMJ).

A gallon of gasoline equivalent (g.ge), and a Liter of gasoline equivalent (L.ge) are alternative units used for measuring enthalpy. The 50/50 reformulated/conventional gasoline mix in GREET contains 121.2 MJ/g.ge and 32 MJ/Lge. This analysis assumes single occupant vehicles so moving one vehicle is equal to moving one person.

Data sourced from GREET comes from an Excel database and calculations are made using a high number of significant digits. It is unclear what input data and detail GREET used, and as a result what the actual significant digits of my results should be. Data sourced directly from GREET and Pimentel are shown with a large number of significant digits to assist anyone cross-checking these values against the original source. Values calculated using this GREET and Pimentel data are generally presented with two significant digits and bolded. The REVp values calculated are intended to be used as operators within future calculation and as such I present them with more, three, significant digits.

"Delivered Carrier" is an energy carrier delivered to a fueling station with atmospheric conditions.

"Harvested Carrier" is an energy carrier that has been harvested but not transported to the refinery.

"Primary Carrier" is an energy carrier that is in its original geographical location and form.

"Uncollected Carrier" is a non-primary energy carrier that is in its original geographical location.

The Automobile

The REV of an energy carrier, for personal transportation, used to fuel a car is determined by the distance it allows a vehicle to travel. The following Tank to Wheel (TtW) values can be found (GREET,Inputs Page,C809:CC809).

Table 1 - GREET Tank to Wheel Efficiencies with Gasoline Otto Vehicle as Reference

Vehicle - Fuel	Energy Carrier	REVp.g
Diesel-Diesel	Diesel/Kerosene	1.20
Diesel - Biodiesel	Biodiesel	1.20
Diesel - FTD	FTD	1.20
Diesel - SVO/WVO	SVO/WVO	1.20
Otto - Hydrogen	Hydrogen	1.20
Otto - LPG/DME	DME/LPG	1.20
Otto - Ethanol	Ethanol	1.07
Otto- Gasoline	Gasoline	1.00
Otto - Nat. Gas	Natural Gas	0.95

A diesel engine can move a vehicle 1.2 times as far as gasoline engine for the same enthalpic input. GREET considers all diesel engine fuels to have the same enthalpic efficiency. Kerosene, not studied by GREET, is essentially a Diesel fuel and included in this group. Ethanol combustion leads to an increase in enthalpic efficiency while burning Natural Gas results in a decrease. Biodiesel and Ethanol yield lower fuel economy values because there is less enthalpy contained per volume of fuel, not because they produces lower enthalpic efficiency's than their conventional counterparts.

These Tank to Wheel (TtW) values need to be adjusted to Pump to Wheel (PtW) values given the boundary of how I split the two parts of the CtSt chain. This is done by taking into consideration energy for fueling a vehicle. For liquid fuels this energy is ignored as it is insignificant.

Natural Gas has a compression efficiency of 97.3% (GREET,NG,AC:87). The same is assumed for Methane, DME and LPG. With GREET data I estimated transportation efficiencies. For Natural Gas the calculated transportation efficiency from wellhead to pump 93.3%. Natural gas's combined harvesting and processing efficiency equals 93.4% (GREET, NG, B87:C87). As a result, Delivered Natural Gas REVp.g = .92; Harvested Natural Gas REVp.g = .86; (WtW) Primary Natural Gas REVp.g = .81.

Equation 1 - $TtW\ REVp.g * \eta_{compression} = PtW\ Delivered\ REVp.g$

Equation 2 - $PtW\ REVp.g * \eta_{transportation} = Harvested\ REVp.g$

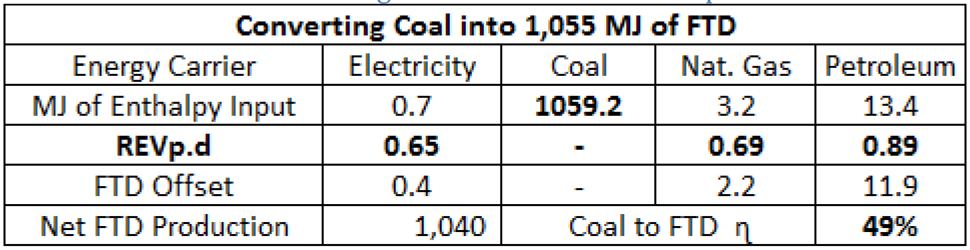
Equation 3 - $Harvested\ REVp.g * \eta_{harvest} = WtW\ Primary\ REVp.g$

Refining diesel from harvested crude oil is 90.6% efficient (GREET, Inputs, E61). The estimated transport efficiency for crude oil is 98%. The harvest efficiency for crude oil is 98% (GREET, Petroleum, B38). Diesel REVp.g = 1.2; Harvested Crude Oil REVp.g = 1.07; WtW Primary Crude Oil REVp.g = 1.04 EV's are not an available technology but Electricity is still a useful transportation fuel. It can be converted into Hydrogen with a 71.5% efficiency, and compressed into a gaseous fuel tank with a 93.9% efficiency (GREET, Hydrogen, BG63:BH63). So, PtW Delivered Electricity REVp.g = .81.

Equation 4 - $TtW\ Hydrogen\ REVp.g * \ \eta_{electrolysis} * \ \eta_{compression} = PtW\ Electricity\ REVp.g$

A bit more complicated, the refinement of 2,114 MJ of harvested coal into 1,055 MJ Fischer-Tropsch Diesel (FTD), presented by GREET, requires the following variety of energy carrier inputs (GREET,NG, BH144:BI160). For offset purposes I multiply each input by their REVp with Diesel as the reference energy carrier (REVp.d). So, Natural Gas's REVp.d, different than its REVp.g, is shown below. The same method was applied to the electricity and petroleum.

Table 2 - Converting Coal into Fischer Tropsch Diesel



Converting Coal into 1,055 MJ of FTD				
Energy Carrier	Electricity	Coal	Nat. Gas	Petroleum
MJ of Enthalpy Input	0.7	**1059.2**	3.2	13.4
REVp.d	**0.65**	**-**	**0.69**	**0.89**
FTD Offset	0.4	-	2.2	11.9
Net FTD Production	1,040	Coal to FTD η		**49%**

Note: GREET presents its inputs with pass-through energy excluded. In this case an additional 1,055 MJ of Coal, the main primary energy source, is not shown but is an input to the process which ends up in the resulting FTD output.

Equation 5 - $\frac{.83\ Primary\ Natural\ Gas\ REVp.g}{1.2\ Delivered\ FTD\ REVp.g} = .69\ Primary\ Natural\ Gas\ REVp.d$

After adjusting all inputs using REVp.d they can be compared to each other and I calculate the quality adjusted efficiency for converting Coal into FTD = 49.2%. This is only slightly lower than the enthalpic efficiency of 49.5%. Multiplying this quality adjusted efficiency by Delivered FTD REVp.g calculates Coal's REVp.g on a PtW basis.

Equation 6 - $.492\ \frac{Coal\_in}{FTD\_out} * 1.2\ Delivered\ FTD\ REVp.g = .59\ Delivered\ Coal\ REVp.g$

Note: This calculation is slightly incorrect as the FTD being offset is refined but not yet delivered.

This is an abstract calculation of Coal's value after the resulting FTD is delivered to the fuel pump. Harvested and primary REV's for coal may be more useful for most studies but this delivered value can be used to approximate the value of coal delivered to a PtCt, with a small error as the last leg would incorrectly include transporting a liquid instead of solid to the point of fueling. The harvest efficiency of coal is 99.3% (GREET,Coal, B18) and I assume a coal transport efficiency of 96%. So, Delivered Coal = .59; Harvested Coal = .57; Primary Coal = .56.

I used the same method to analyze converting biomass into Diesel equivalents. The production of DME via gasification had a greater WtW REVp.g than the Fischer-Tropsch process and is considered the best technology for converting biomass into personal transportation energy. I analyzed Corn-Stover and Forrest Residue with nominal variation and expect similar results for all biomass. I estimate a total transport efficiency of 96%. So, the Delivered Biomass REVp.g = .59; Uncollected Biomass REVp.g = .57.

In order to use Straight and Waste Vegetable Oil (SVO/WVO) a pre-heating fuel tank must be installed on the vehicle. Generally the vehicle starts on diesel or biodiesel and then the waste heat from the engine is used to pre-heat the SVO/WVO tank. Heat inputs to the tank are assumed to come from engine waste heat and thus the Delivered SVO/WVO REVp.g = 1.2; the same as for Diesel.

The Horse

The horse is a historical and functional mode of personal transportation which can carry a person 30 miles (48.3 km) at a trot of 8 mph (12.9 km/hr) for 3.75 hours. 30 miles is the assumed maximum distance a horse can travel in a single day so the entire daily maintenance feeding of 68 MJ/day of Metabolisable Energy (ME) is applied to this trip. An additional 39.4 MJ of ME feed is required to maintain a trot for 3.75 hours. In total a horse consumes 107.4 MJ of ME to transport a person 30 miles (48.3 km). A gas car burns 121.2 MJ of Gasoline to accomplish this same journey. So, Metabolisable Animal Feed's REVp.g = 1.13.

Equation 7 - $$1.13\ Animal\ Feed\ (ME)\ REVp.g = \frac{\frac{121.2\ MJ\ gasoline}{30\ miles}}{\frac{107.4\ MJ\ ME}{30 miles}}$$

This is not on an enthalpic, but instead ME basis which is the quantity of energy that can be digested and is not lost in manure and urea. The REV for ME can be applied more easily to the large number of animal feeds present in today's energy production arena. Soybean Meal has an ME of 12 MJ/kgDM[3] while its enthalpic energy value is 17.6 MJ/kgDM[8]. So, Soy Meal's REVp.g = .77 on an enthalpic basis.

Equation 8 - $$.77\ Soy\ Meal\ REVp.g = 1.13\ Animal\ Feed\ ME\ REVp.g * \frac{\frac{12\ MJ\ ME}{kgDM\ Soymeal}}{\frac{17.6\ MJ}{kgDM\ Soymeal}}$$

The Bicycle

A human being can bicycle 30 miles (48.3 km) in 2.5 hours at a speed of 12 mph (19.3 km/hr). This trip requires an additional food consumption of 6 MJ of enthalpy. Humans exist and eat regardless of the desire to transport themselves so I ignore human daily maintenance energy. This is different from a horse which can be raised and feed solely for the purpose of providing transportation. Comparing the 6 MJ of enthalpic food consumption to the 121.2 MJ for a gas car leads to Food's REVp.g = 20.2.

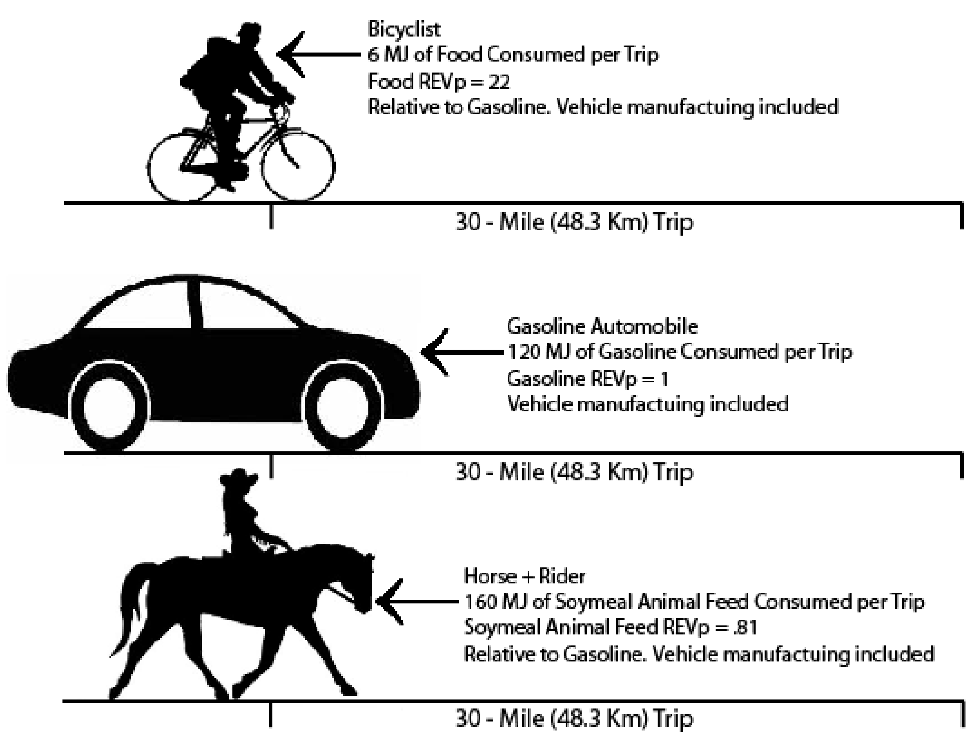
Equation 9 - $$20.2\ Food\ REVp.g = \frac{\frac{121.2\ MJ\ gasoline}{30\ miles}}{\frac{6\ MJ\ Food}{30 miles}}$$

It might be surprising that food is 20 times more valuable than gasoline as a transportation fuel. This higher value is not unjustified when compared to economic valuation methodologies. It would take 70 cans of corn (each 29 fl. oz, 8.6 dl) to accumulate the same quantity of enthalpy found in a gallon (3.79 Liters) of gasoline.[9] At a cost of $1.8 per can of corn[10]and $4/gallon ($1.05/liter) of gasoline, processed corn on an enthalpic basis is 32 times more expensive than gasoline.

A laborer can operate a bicycle powered rickshaw carrying a 160 lb passenger 30 miles (48.3 km) in 2.5 hours. I estimate this requires twice as much extra daily food consumption as riding a bicycle the same distance alone. This leads to 12 MJ of additional food consumption per journey and a REVp.g value of 2.5 hours of Labor equal to 10.1; or 1 hour of Labor's REVp.g = 4.0

Labor can create transportation but I do not believe it should be counted as an energy input to a PtCt. Human beings exist in large numbers on this planet and need employment. Employing humans should be viewed as a social benefit not a negative aspect of a PtCt. Other authors would disagree, with this analysis and believe we should include labor as an energy input to the process. As shown this can still be done while following the theory of Energy Relativity for valuation purposes.

Figure 5 -Relative Energy Values to Personal Transportation (REVp) Examples



Life Cycle Adjustments to REVp

A complete LCA study of these REV's should allocate a portion of the vehicle's construction and maintenance energy to each personal transportation trip. The conventional internal combustion vehicle requires 99,000 MJ worth of fossil fuel energy to construct and maintain (GREET_2.7).

Quality adjusting these inputs results in 84,000 Rp.gMJ to construct and maintain an automobile. Assuming an Otto powered vehicle has a useful life of 200,000 miles (322,000 km) then 12.1 Rp.gMJ should be allocated to every 30 mile (48.3 km) trip accomplished with an Otto engine. This adjustment does not change the REVp.g for vehicles that uses the same Otto engine as the reference Gasoline powered car for propulsion, but does decrease it's equivalent fuel economy which shows the distance that a vehicle can travel per quantity of gasoline equivalent enthalpy input.

(GREET_2.7) does not differentiate between the manufacturing energy for an Otto and Diesel engine. Assuming a Diesel vehicle has a useful life of 350,000 miles (563,000 km) 6.9 Rp.gMJ should be allocated to every 30 mile (48.3 km) trip accomplished with a Diesel engine. This LCA adjustment increases the REVp.g for Diesel fuel from 1.2 to 1.25.

Assuming that a horse's useful life is from the age[11] of 2 until[12] 30 it can carry a passenger 307,000 miles (493,000 km). Raising a horse to the useful age of two requires 50,000 MJ ME, assuming that it eats the same maintenance feed as an idle adult horse. This means that 5.76 Rp.gMJ of energy should be allocated to every 30 mile trip accomplished using a horse.

I was unable to locate manufacturing and maintenance energy values for a bicycle which should be small compared to either a horse or a car. For this thesis, I assumed 1.2 Rp.gMJ should be allocated to every 30 mile (48.3 km) trip accomplished on a bicycle or rickshaw.

With these LCA vehicle manufacturing adjustments included, and after an iterative process, I calculate my final set of Relative Energy Values to personal transportation with Gasoline as the reference energy carrier (REVp.g) below. Included are the equivalent fuel economy values for the associated vehicle and fuel chains. These show the distance that can be traveled per quantity of gasoline equivalent enthalpy burned which may help you relate the values to the reference 30 mpg gasoline car.

From here forth gasoline will always be the reference energy carrier, and the terminology shorted to Relative Energy Value to personal transportation (REVp) and Relative to personal transportation Mega-Joule (RpMJ). In an effort to shorten text I also us Rp as a prefix to words. A RpInput should be read as a Relative to personal transportation Input

Table 3 - Summary of Relative Energy Values to Personal Transportation (REVp)

Relative Energy Values to Personal Transportation				
Vehicle - Fuel Chain	**Energy Carrier**	**REVp**	**mpg.ge**	**L.ge/100Km**
Bicycle - Metabolic	Food	22.0	600	0.4
Rickshaw - Metabolic	Labor (1 hour)[1]	4.40	300	0.8
Diesel Engine	Diesel/Kerosene	1.25	34.1	6.9
Diesel Engine	FTD/Biodiesel	1.25	34.1	6.9
Diesel Engine	SVO/WVO	1.25	34.1	6.9
Diesel Engine	DME/LPG	1.21	33.1	7.1
Horse - Animal Feed	Metabolisable Energy (ME)[2]	1.19	32.3	7.3
Otto Engine	Hydrogen	1.13	30.7	7.7
Diesel - Conventional	Harvested Crude Oil[3]	1.11	30.2	7.8
Diesel - Conventional	Primary Crude Oil[4]	1.09	29.6	7.9
Otto Engine	Ethanol	1.07	29.2	8.1
Otto Engine	**Gasoline**	**1.00**	**27.3**	**8.6**
Otto Engine - U.S. Mix	Delivered Nat. Gas[5]	0.92	25.2	9.3
Otto Engine - U.S. Mix	Harvested Nat. Gas[3]	0.86	23.5	10.0
Otto Engine - U.S. Mix	Primary Nat. Gas[4]	0.81	22.0	10.7
Horse - Metabolic	Soy Meal	0.81	22.1	10.7
Otto - H2 - Electrolysis	Electricity	0.81	22.0	10.7
Diesel - FTD - FT	Delivered Coal[5]	0.64	17.5	13.5
Diesel - DME - Gasify	Delivered Biomass[5]	0.62	16.9	14.0
Diesel - FTD - FT	Harvested Coal[3]	0.61	16.8	14.0
Diesel - FTD - FT	Primary Coal[4]	0.61	16.6	14.1
Diesel - DME - Gasify	Uncollected Biomass[6]	0.60	16.2	14.5

Unless otherwise specified, REVp are quality adjustment factors for converting a "Delivered" Joule of the stated energy carrier's enthalpy into Relative to personal transportation Joule's (RpJ) with gasoline as the reference carrier 1 - REV for converting one hour of work into RpJ. 2 - REV for converting one Joule of Metabolisable Energy into RpJ. 3 - Harvested means produced but not transported. 4 - Primary means stored in its original geographical location and form. 5 - Delivered means final energy carrier is delivered to the fueling pump at atmospheric conditions. 6 - Uncollected Biomass means biomass found in its original geographical location. All results calculated with data from (GREET1_2011) except for the REVp values for horse and human powered transportation.

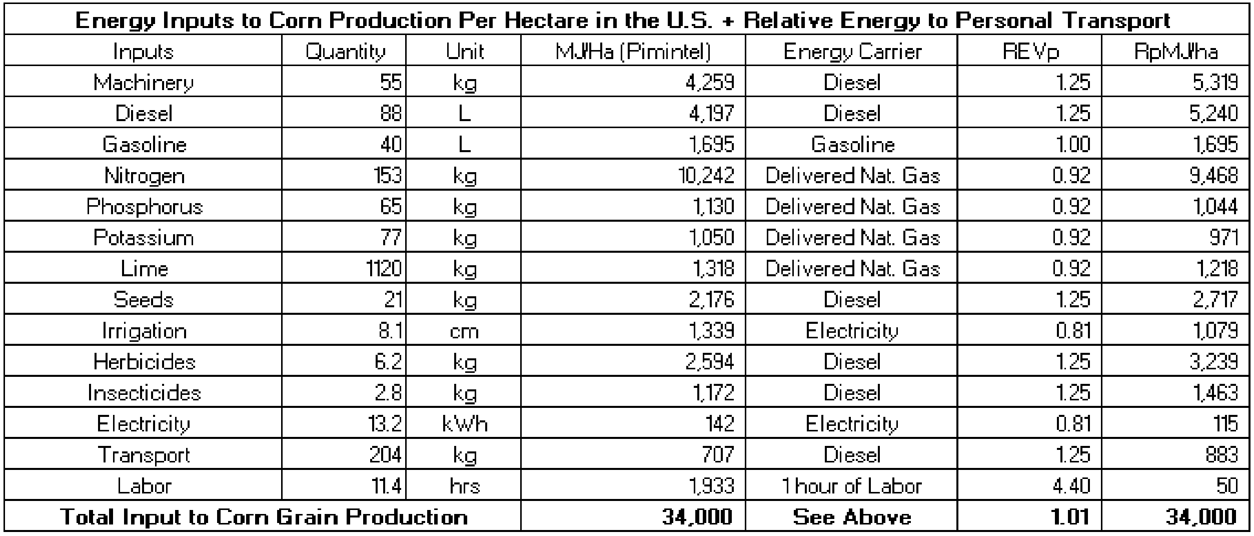
Energymetrics using REVp

Adjusting Pimentel's Biofuel data using REVp

One of the most published and pessimistic authors in the field of Biofuels is David Pimentel. Here I will make quality adjustments to the data presented by (Pimentel, 2005) using REVp. Pimentel's shows an enthalpic Energy Return Over Energy Investment (EROI) less than one for both ethanol from U.S. corn and biodiesel from U.S. Soybeans. He argues that neither should be pursued as they require more energy inputs than we get back from burning the resulting biofuels.

Co-product valuation significant variation between different published biofuel studies today. Using the theory of Energy Relativity I can apply a consistent valuation method to both the primary and co-products. By using the calculated REVp values I can now calculate the Relative to personal transportation Energy Return Over Investment (RpEROI) of a specific PtCt; in this case Pimentel's vision of the prototypical U.S. Sun->Corn to Ethanol facility.

Table 4 - Pimentel inputs for U.S. Corn production per hectare with REVp adjustments



Energy Inputs to Corn Production Per Hectare in the U.S. + Relative Energy to Personal Transport						
Inputs	Quantity	Unit	MJ/Ha (Pimintel)	Energy Carrier	REVp	RpMJ/ha
Machinery	55	kg	4,259	Diesel	1.25	5,319
Diesel	88	L	4,197	Diesel	1.25	5,240
Gasoline	40	L	1,695	Gasoline	1.00	1,695
Nitrogen	153	kg	10,242	Delivered Nat. Gas	0.92	9,468
Phosphorus	65	kg	1,130	Delivered Nat. Gas	0.92	1,044
Potassium	77	kg	1,050	Delivered Nat. Gas	0.92	971
Lime	1120	kg	1,318	Delivered Nat. Gas	0.92	1,218
Seeds	21	kg	2,176	Diesel	1.25	2,717
Irrigation	8.1	cm	1,339	Electricity	0.81	1,079
Herbicides	6.2	kg	2,594	Diesel	1.25	3,239
Insecticides	2.8	kg	1,172	Diesel	1.25	1,463
Electricity	13.2	kWh	142	Electricity	0.81	115
Transport	204	kg	707	Diesel	1.25	883
Labor	11.4	hrs	1,933	1 hour of Labor	4.40	50
Total Input to Corn Grain Production			**34,000**	**See Above**	**1.01**	**34,000**

The total RpInputs for grain production is essentially identical to Pimentel's data. Pimentel calculates "that a person works 2,000 hr per yr and utilizes an average of 8,000 L of oil equivalents per yr". It seems to be an unreasonable claim that all the energy a human consumes per day should be allocated to the product they produce. Pimentel's methods results in labor being 3,750% more valuable than REVp would indicate. This difference is offset by a undervaluation's diesel inputs which are 25% more valuable for personal transportation than their enthalpy would indicate.

Table 5 - Pimentel Inputs per 1000L of Ethanol from U.S. Corn with REVp adjustments

Inputs per 1000 L of 99.5% Ethanol Produce from Corn + Relative Energy for Persontal Transport						
Inputs	Quantity	Units	MJ/1000 L (Pimintel)	Energy Carrier	REVp	RpMJ/1000L
Corn Grain	2,690	kg	10,553	See Above	1.01	10,707
Corn Transport	2,690	kg	1,347	Diesel	1.25	1,682
Water	40,000	L	377	Electricity	0.81	303
Stainless Steel	3	kg	50	Diesel	1.25	63
Steel	4	kg	50	Diesel	1.25	63
Cement	8	kg	33	Diesel	1.25	42
Steam	10.6525	MJ_fuel	10,652	Delivered Coal	0.64	6,819
Electricity	392	kWh	4,230	Electricity	0.81	3,408
Upgrading	9	kcal/L	38	Electricity	0.81	30
Sewage Effluent	20	kg BOD	289	Electricity	0.81	233
Total Input to Ethanol Production			**28,000**	**See Above**	**0.85**	**23,000**

Refining Ethanol from corn grain results in a greater divergence between Pimentel's inputs and the RpInputs. The greatest variation comes from Steam produced from Coal which has a low REVp value. In total the RpInputs for Ethanol production from U.S. corn is a factor of .85 lower than Pimentel's values.

The greatest variation comes from the handling of co-products. It is not surprising to me that published studies from credible sources show such a wide variety of EROI results as (ISO, 2006) does not define a single, or in my opinion an accurate, method for assigning value to co-products.

Table 6 - Comparing Biofuel EROI results from multiple studies and methodologies

Comparing Studies	Corn Ethanol EROI	Soy Biodiesel EROI
Pimentel (Hybrid)	0.8	1.0
GREET (Enthalpic)	2.4	4.0
GREET (Substitution)	1.6	-21
GREET (Market)	1.8	3.4
GREET (Mass)	-	7.5

Note: The GREET substitution value for soy-meal is more than the total inputs leading to a negative EROI. Co-products should be treated as additional outputs not as offsets to inputs to avoid this problem.

The primary co-product associated with dry-mill Ethanol production from Corn Grain is Dry Distillers Grain with Solubles (DDGS). The enthalpic value of the DDGS produced is 8.3 times larger than Pimentel's assigned value. Using (GREET1_2011) data I calculate that DDGS has approximately .8 times the ME as soy-meal resulting in DDGS's REVp = .65 on an enthalpic basis. This means the 10,000 RpMJ I believe should be assigned to the 889kg of DDGS is 5.4 times larger than the value assigned by Pimentel.

Table 7 - Pimentel Ethanol from Corn inputs and outputs with REVp adjustments

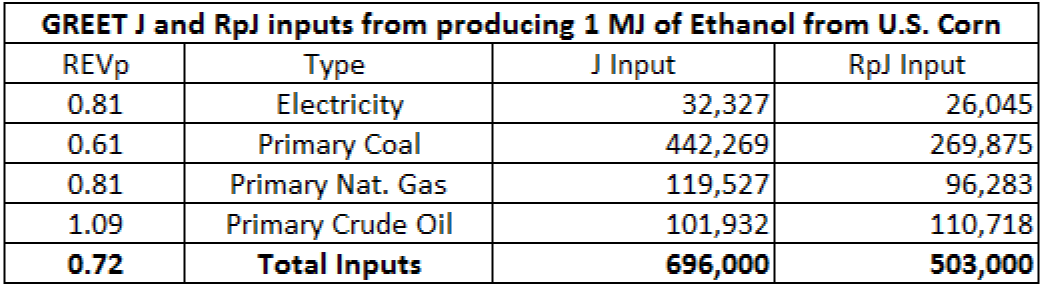
Summary of Ethanol Production Input, Outputs and Relative Energy to Personal Transport						
In/Out	Quantity	Units	MJ/1000 L (Pimintel)	Energy Carrier	RpMJ/1000L	REVtoPim
Ethanol Produced	1000.0	L	21,464	Ethanol	22,966	1.07
DDGS Co-Product	887.7	Kg DDGS	1,862	Metabolisable (ME)	10,079	5.41
Total Product Outputs			23,326	See Above	33,045	1.42
Total Inputs for Production			27,619	See Above	23,349	0.85
Net Production, EROI, RpEROI			**(4,300)**	**0.8**	**9,700**	**1.4**

Comparing RpOutputs to RpInputs I calculate that Ethanol from U.S. Corn has a RpEROI = 1.4. This specific corn to Ethanol PtCt creates 1.4 times more personal transportation valued energy carriers than it requires as inputs. The greatest difference between Pimentel's EROI and my RpEROI come from the assigned value to the DDGS co-products.

Similar results can be seen by adjusting Pimentel's biodiesel from U.S. soy-bean data using REVp. The largest variation comes from the quality adjustment made to the primary co-product Soy-Meal where REVp assigns 7 times more energy than Pimentel and results in a RpEROI = 2.4. (Appendix B)

Adjusting GREET's Biofuel data using REVp

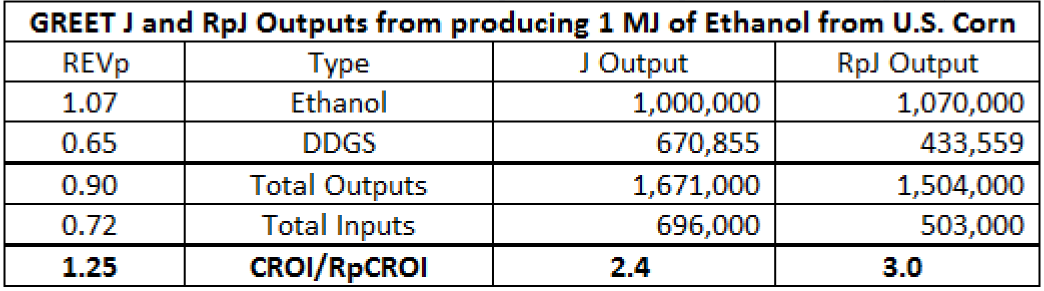
Table 8 - GREET Inputs per 1MJ of Ethanol from U.S. Corn with REVp adjustments



GREET J and RpJ inputs from producing 1 MJ of Ethanol from U.S. Corn

REVp	Type	J Input	RpJ Input
0.81	Electricity	32,327	26,045
0.61	Primary Coal	442,269	269,875
0.81	Primary Nat. Gas	119,527	96,283
1.09	Primary Crude Oil	101,932	110,718
0.72	**Total Inputs**	**696,000**	**503,000**

Table 9 - GREET Ethanol from Corn inputs and outputs with REVp adjustments



GREET J and RpJ Outputs from producing 1 MJ of Ethanol from U.S. Corn

REVp	Type	J Output	RpJ Output
1.07	Ethanol	1,000,000	1,070,000
0.65	DDGS	670,855	433,559
0.90	Total Outputs	1,671,000	1,504,000
0.72	Total Inputs	696,000	503,000
1.25	**CROI/RpCROI**	**2.4**	**3.0**

Michael Wang the author of GREET is considered an optimist when it comes to biofuels so it is interesting to compare the two studies side by side. By applying REVp to GREET's data I calculate that U.S. Corn Ethanol production has a RpEROI = 3.0. For Biodiesel production from U.S. Soybeans the RpEROI = 4.9. (Appendix B)

After using the Theory of Energy Relativity to consistently assign a REVp to inputs and outputs GREET's RpEROI is still twice as large as the value calculated using Pimentel's data. Some of this difference was caused by me guessing which carriers were used to produce Pimentel's different reported inputs. Equalizing this assumption by applying GREET's total inputs REVp to Pimentel's total inputs increased the RpCROI for Ethanol from 1.4 to 1.7 and Biodiesel from 2.5 to 2.6. (Appendix B)

The biggest difference between these two studies comes from the fact that Pimentel's data includes 80% more enthalpic inputs than GREET. A challenge with LCA is knowing where to draw proper boundaries. The standardization of boundary conditions, rather than just requesting transparency, for comparison studies should be created by the International Organization for Standardization (ISO).

Table 10 - Comparing biofuel EROI's from other studies to calculated RpEROI values

Comparing Studies	Corn Ethanol CROI	Soy Biodiesel CROI	% Soy Better
Pimentel (Hybrid)	0.8	1.0	17%
GREET (Enthlapic)	2.4	4.0	68%
GREET (Substitution)	1.6	-20.6	-1366%
GREET (Market)	1.8	3.4	84%
GREET (Mass)	-	7.5	
Rock/Pimentel (RpCROI)	**1.7**	**2.6**	**60%**
Rock/GREET (RpCROI)	**3.0**	**4.6**	**55%**

Note: When comparing these two studies to each other, the GREET glycerin output for Biodiesel has been ignored as it was not counted by Pimentel. For comparing different PtCt's within GREET I assume that Glycerin has the same REVp as Coal.

In this thesis I use primarily (GREET1_2011) data with the hope that consistent boundary assumptions were made within this single study despite the wide range of PtCt's analyzed. For comparison purposes it is more important that consistent assumptions are made than "correct" ones.

Since Michael Wang and David Pimentel are considered biofuel optimists and pessimist respectively the actual RpEROI is likely somewhere between 1.7 - 3.0 for Ethanol from U.S. corn, and 2.6 - 4.9 for Biodiesel from U.S. Soybean.

It is important to recognize that this thesis doesn't seek to calculate the exact EROI of a specific PtCt but to develop a numerical method for comparing different PtCt's to each other. I can more confidently say that producing Biodiesel from U.S. soybean is 55-60% better than producing ethanol from U.S. corn for the goal of producing personal transportation energy. Here there is only a 5% deviation between two studies which have significantly different boundary assumptions, pointing out the strength of this method as a comparison tool.

Specific Energy Analysis Tools

Where you start and stop your energy accounting is a very important and often overlooked assumption for any Energy Analysis Tool (EAT). For the EROI/RpEROI values presented above I assumed that the main primary energy input is ignored. It is the market ready energy carrier inputs required to produce the feedstocks for biofuel production, not the solar energy used to grow the plants that was counted. However, EROI as a concept can, and has, follow many different accounting rules which can easily lead to totally incomparable values. For this reason I create the following abbreviations which I can apply specific definitions too. The most commonly used definition for LCA EROI I will now call CROI.

CROI - LCA WtP Carrier Return Over Investment

CROI values do not count the main primary energy, or any process energy of the same form as inputs. For an oil field Crude and Residual oil are considered to be of the same form and excluded from inputs while Gasoline and Diesel are counted. CROI values rank PtCt's on their ability to produce market ready energy carriers while ignoring depletion of the main primary energy source.

CHOI - LCA WtP Carrier Harvested Over Investment

CHOI values follow the format that the GREET data is presented. Pass-through energy, which ends up in the final energy carrier, is ignored as an input. However, all other main primary energy inputs used for the process are counted. CHOI values offsets the benefit of carrier production against the cost of consuming market ready energy carriers, and the main primary energy process energy.

CBOF - LCA WtP+ Carrier Burned Over Fossil Fuel Investment

CBOF values look at the total quantity of Fossil Fuels consumed to produce and burn a final energy carrier. This means that all main primary energy is counted as an input if it is a fossil fuel. The pass-through energy is consumed when the final energy carrier is burned. CBOF values compare the benefit of energy carrier production against the costs of depleting fossil fuels.

CBOO - LCA WtP+ Carrier Burned Over Oil Investment

CBOO values looks at the total quantity of Oil that is consumed to produce and burn a final energy carrier. If Peak Oil represents the greatest near-term economic challenge for society, an oil focused EAT is a useful mitigation tool. CBOO values show which PtCt's can produce the most carrier production benefit while minimizing oil depletion.

CBOP - LCA WtP+ Carrier Burned Over Main Primary Input

CBOP is the ratio of carrier outputs to the total quantity of the main primary energy inputs including the pass-through energy.

Rpη - LCA WtP+ Relative to personal transportation efficiency

Rpη mirrors a Well to Pump (WtP) thermodynamic efficiency. RpEfficiency is the ratio of the total RpOutputs compared to the total RpInputs; including the main primary and pass-through energy. Unlike a thermodynamic efficiency, a RpEfficiency can be greater than one indicating that the PtCt being study is better than the perceived best technology used to calculate REVp. If said technology has gained a significant market share REVp values should be re-calculated based on this technology shift.

NCP - LCA WtP Net Carrier Production

NCP follows the same accounting rules as the CROI not counting the main primary energy, or any process energy that is of the same form, as inputs. NCP is not a unit-less ratio but instead looks at the difference between outputs and inputs. NCP is quantitative measurement of the net non-main primary energy carrier production benefits which is a good optimization tool for designing a PtCt's.

NCH - LCA WtP Net Carrier Harvested

NCH follows the same accounting rules as CHOI not counting pass-through energy as an input but counting all other main primary energy used for process energy. NCH is a quantitative measurement of net market ready energy carriers harvested from a main primary energy source, and can be a good optimization tool for designing a PtCt's.

NFB - LCA WtP+ Net Fossil Fuel Burned

NFB is the difference between the carrier output of a PtCt and the total fossil fuel inputs including main primary pass-through energy.

NOB - LCA WtP+ Net Oil Burned

NOB is the difference between the carrier output of a PtCt and the total oil inputs including main primary pass-through energy.

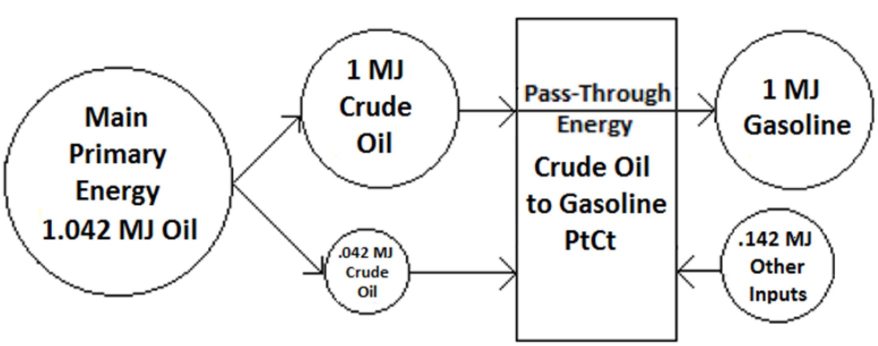
NCB - LCA WtP+ Net Carrier Burned

NCB is the difference between the carrier output of a PtCt and the total carrier inputs including all of the main primary energy. The NCB of a PtCt will always be a negative number due to the second law of thermodynamics.

NCP/SC - LCA WtP+ Net Carrier Production / WtW Social Cost

Dividing the quantitative LCA Net Carrier Production benefit of a PtCt by one of its quantitative LCA Social Costs creates an EAT that can be used to maximize market ready energy carrier production while ignoring depletion but offsetting against a specific social cost. The Social Cost does not need to be in energy units but should be calculated on a complete LCA basis; generally WtW.

Figure 6 - Conversion of Conventional Oil into Gasoline



$$\boldsymbol{CROI} = \frac{1MJ}{.142MJ} = 7.0$$

$$\boldsymbol{CHOI} = \frac{1MJ}{.042MJ+.142MJ} = 5.4$$

$$\boldsymbol{CBOF} = \frac{1MJ}{1.042MJ+.134MJ} = .85$$

$$\boldsymbol{CBOO} = \frac{1MJ}{1\mathrm{MJ}+.046MJ} = .96$$

$$\boldsymbol{WtP\eta} = \frac{1MJ}{1.042MJ+.142MJ} = .84$$

$$\boldsymbol{NCP} = (1MJ - .142MJ) = .86MJ$$

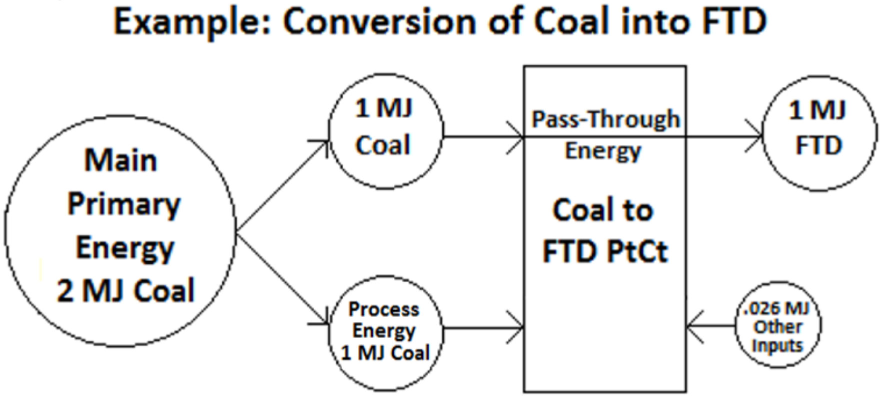
$$\boldsymbol{NCH} = (1M - .042\mathrm{MJ} - .142MJ) = .85MJ$$

$$\boldsymbol{NFB} = (1MJ - 1.042MJ - .133MJ) = -.18MJ$$

$$\boldsymbol{NOB} = (1MJ - 1.042MJ - .04MJ) = -.05MJ$$

$$\boldsymbol{NCB} = (1MJ - 1.042MJ - .142MJ) = -.18MJ$$

Figure 7 - Conversion of Coal into Fischer Tropsch Diesel



$$\boldsymbol{CROI} = \frac{1MJ}{.026MJ} = 41$$

$$\boldsymbol{CHOI} = \frac{1MJ}{1MJ+.026MJ} = .97$$

$$\boldsymbol{CBOF} = \frac{1MJ}{2MJ+.026MJ} = .49$$

$$\boldsymbol{CBOO} = \frac{1MJ}{.018MJ} = 54$$

$$\boldsymbol{WtP\eta} = \frac{1MJ}{2MJ+.026MJ} = .49$$

$$\boldsymbol{NCP} = (1MJ - .026MJ) = .97MJ$$

$$\boldsymbol{NCH} = (1M - 1\mathrm{MJ} - .026MJ) = -.03MJ$$

$$\boldsymbol{NFB} = (1MJ - 2MJ - .025MJ) = -1.03MJ$$

$$\boldsymbol{NOB} = (1MJ - .005MJ) = .995MJ$$

$$\boldsymbol{NCB} = (1MJ - 2MJ - .026MJ) = -1.03MJ$$

All of the enthalpic EAT's above have their associated, and more comparable, Relative to personal transportation values: RpCROI, RpCHOI, RpCBOF, RpCBOO, RpNCP, RpNCH, RpNFB, RpNOB, and RpNCP/SC. The CBOF and CBOO values calculated in this thesis assume that electricity inputs have been produced from 100% renewable sources while hydrogen is grouped with fossil fuels

Table 11 - Summary of Primary to Carrier Technology's EAT results

Summary of Primary to Carrier Technology's EAT's					
Feedstock -> Carrier	**RpCROI**	**RpCHOI**	**RpCBOF**	**RpCBOO**	**Rpη**
Tree -> Ethanol	**9.6**	0.2	9.6	12	0.17
Biomass -> DME	**9.3**	2.0	9.7	20	1.0
Biomass -> FTD	**9.2**	1.7	9.5	20	0.38
Shale -> Nat.gas	27	**8.6**	0.9	100	0.94
Conv. -> Diesel	11	**7.8**	0.9	1.0	0.31
Conv. -> Nat. Gas	30	**7.6**	0.9	210	0.41
Stover -> Ethanol	**7.6**	0.2	7.6	13	1.0
Biomass -> Electricity	**7.3**	0.5	9.6	10	1.0
F. Residue -> Ethanol	**6.2**	0.2	6.3	9.7	0.80
Switchgrass -> Ethanol	**6.2**	0.2	9.6	18	1.0
Sugar Cane -> Ethanol	**6.1**	0.2	6.1	8.6	0.22
Conv. -> Gasoline	8.1	**5.9**	0.9	1.0	0.43
Palm Oil -> Biodiesel	**5.3**	0.3	5.4	12	0.40
Soybean -> Biodiesel	**4.9**	0.4	5.0	12	0.33
Camelina -> Biodiesel	**4.4**	0.3	4.4	11	0.43
Algae -> Biodiesel	**4.1**	0.2	6.1	19	1.0
Jatropha -> Biodiesel	**3.9**	0.4	4.1	8.8	0.39
Rapeseed -> Biodiesel	**3.6**	0.4	3.7	11	0.22
Tar Sands -> Diesel	3.9	**3.3**	0.8	1.0	0.20
U.S. Corn -> Ethanol	**3.0**	0.3	3.2	14	0.21
Tar Sands -> Gasoline	3.0	**2.6**	0.7	0.9	0.85
Coal -> FTD	50	**2.0**	0.7	50	0.68
Nat. Gas -> Electricity	97	**0.7**	0.4	180	0.19
Coal -> Electricity	40	**0.6**	0.4	40	0.32

RpNCP/SC EAT's - Benefit/Cost Analysis

Decision makers should not choose to support the PtCt that offers the greatest carrier production benefit for society but instead the one that has the greatest carrier production benefit to social costs ratio. The Social Costs (SC) associated with carrier production are numerous including: Land-use, Depletion, Water, Air and Noise Pollution.

Costs are generally not reported in energy units and a RpNCP/SC ratio does not need to have consistent units however both the numerator and denominator should be quantitative values calculated on a LCA basis. Unlike the RpNCP which is a WtP LCA value Social Costs should be calculated on a WtW LCA basis which includes the impacts from producing a market ready energy carrier in a PtCt, as well as converting the produced energy carrier into personal transportation.

LCA WtP RpNCP/ WtW CO2e

There are many different types of Green House Gases (GHG's) produced by PtCt's each with a different global warming potential (GWP). GREET's WtW LCA data uses CO_2 emissions as the reference and reports all GHG data on a CO_2 equivalent basis (CO_2e). The RpNCP/CO_2e allows decision makers to determine which PtCt's bring the most transportation valued energy carriers to the market, while minimizing WtW GHG emissions.

Equation 10 - $$\frac{RpNCP}{WtW\ CO2e} = RpNCP/[\sum(GHG * GWP)]$$

LCA WtP RpNCP/ WtW Economic Cost of Regulated Emission

There are many different regulated emissions studied within GREET on a WtW LCA basis including: Volatile Organic Compounds (VOC), Nitrogen Oxides (NOx), 2.5 Micron Particulate Matter (PM2.5), 10 Micron Particulate Matter (PM10), Sulfur Dioxide (SO_2), and Methane (CH_4). To compare these different types of emissions simultaneously quality adjustments are needed.

(IMPACT, 2007) analyzes regulated emissions and assigns an economic cost, (measured in year 2000 Euro's) to each emission based on the country, population density, and environment the emissions are released. IMPACT differentiates between rural and urban emissions for PM2.5 and PM10. GREET's Urban PM emissions are assigned an average of IMPACT's "Metropolitan Urban" and "Urban" costs. GREET Non-Urban PM emissions are assigned IMPACT's "Rural" costs. For this thesis the total cost of the above mentioned regulated emissions was calculated using France as the country of origin.

Equation 11 - $$\frac{RpNCP}{WtW\ Economic\ Cost\ of\ Emission} = RpNCP/[\sum(Emission * Economic\ Cost\ of\ Emission)]$$

Mitigation cost for air pollution will change over time, with accumulation and technology, but generally slower and more predictably than shifts in energy prices making econometrics a more valid quality adjustment method for emissions than energy. The analysis below only accounts for the economic cost of regulated emissions and ignores the economic cost of GHG's.

Table 12 - Summary of Primary to Carrier Technology EAT results part two

Summary of Primary to Carrier Technology's EAT's					(RpJ/Kg CO2e)	Units	(RpMJ/Year 2000 Euro)
Feedstock -> Carrier	**RpCROI**	**RpCHOI**	**RpCBOO**	**Feedstock -> Carrier**	**RpNCP/CO2e**	**Feedstock -> Carrier**	**RpNCP/Reg. Emission**
Tree -> Ethanol	**9.6**	0.2	12	Biomass -> DME	-17	Soybean -> Biodiesel	1200
Biomass -> DME	**9.3**	2.0	20	Soybean -> Biodiesel	1100	Biomass -> DME	950
Biomass -> FTD	**9.2**	1.7	20	Camelina -> Biodiesel	840	Camelina -> Biodiesel	890
Shale -> Nat.gas	27	**8.6**	100	Rapeseed -> Biodiesel	670	Rapeseed -> Biodiesel	710
Conv. -> Diesel	11	**7.8**	1.0	Palm Oil -> Biodiesel	620	Palm Oil -> Biodiesel	670
Conv. -> Nat. Gas	30	**7.6**	210	Jatropha -> Biodiesel	550	Jatropha -> Biodiesel	580
Stover -> Ethanol	**7.6**	0.2	13	Tree -> Ethanol	400	Switchgrass ->Ethanol	460
Biomass -> Electricity	**7.3**	0.5	10	Switchgrass -> Ethanol	130	Conv. -> Gasoline	410
F. Residue -> Ethanol	**6.2**	0.2	9.7	Stover -> Ethanol	120	Algae -> Biodiesel	390
Switchgrass -> Ethanol	**6.2**	0.2	18	Biomass -> FTD	66	Stover -> Ethanol	390
Sugar Cane -> Ethanol	**6.1**	0.2	8.6	Biomass -> Electricity	66	Tree -> Ethanol	380
Conv. -> Gasoline	8.1	**5.9**	1.0	Algae -> Biodiesel	50	Conv. -> Diesel	380
Palm Oil -> Biodiesel	**5.3**	0.3	12	F. Residue -> Ethanol	34	Biomass -> FTD	380
Soybean -> Biodiesel	**4.9**	0.4	12	Sugar Cane -> Ethanol	27	Tar Sands -> Diesel	310
Camelina -> Biodiesel	**4.4**	0.3	11	U.S. Corn -> Ethanol	13	Shale -> Nat.gas	310
Algae -> Biodiesel	**4.1**	0.2	19	Conv. -> Diesel	12	Conv. -> Nat. Gas	290
Jatropha -> Biodiesel	**3.9**	0.4	8.8	Shale -> Nat.gas	11	Nat. Gas -> Elec.	290
Rapeseed -> Biodiesel	**3.6**	0.4	11	Conv. -> Nat. Gas	10	Tar Sands -> Gasoline	240
Tar Sands -> Diesel	3.9	**3.3**	1.0	Conv. -> Gasoline	10	F. Residue -> Ethanol	180
U.S. Corn -> Ethanol	**3.0**	0.3	14	Nat. Gas -> Elec.	9	Biomass -> Electricity	180
Tar Sands -> Gasoline	3.0	**2.6**	0.9	Tar Sands -> Diesel	9	U.S. Corn -> Ethanol	90
Coal -> FTD	50	**2.0**	50	Tar Sands -> Gasoline	6	Coal -> FTD	40
Nat. Gas -> Electricity	97	**0.7**	180	Coal -> FTD	5	Coal -> Electricity	32
Coal -> Electricity	40	**0.6**	40	Coal -> Electricity	5	Sugar Cane -> Ethanol	20

The GREET LCA data used to produce this chart assumes a U.S. average mix for electricity production. Note the conversion of biomass into DME results in a reduction not increase in GHG emissions. This is due to the fact that methane, which has a larger global warming potential than CO2, is captured and not emitted into the atmosphere. A large negative RpNCP/CO2e is the best possible score that could be achieved for a RpNCP/CO2e EAT.

The following RpNCP/SC are not calculated or applied to the group of GREET PtCt's studied above because I did not have easy access to the required data. These EAT's are a small sample of the wide variety of Social Costs that could be examined using the NCP/SC method but represent some of the more important Social Costs that should be considered within a detailed decision making process.

LCA WtP RpNCP/ WtP+ Main Primary Energy Depletion Factor

Depletion of the main primary energy is completely ignored by CROI and NCP values. This is purposefully done as they examine the pure carrier production benefits of a PtCt without considering the depletion of the main primary energy which is best examined separately for each resource due to varying scarcity restraints. When possible using this RpNCP/SC EAT is a better approach than accounting for the depletion of the main primary energy within the energy equation as is done with the other EAT's.

Equation 12 - $$\frac{RpNCP}{Depletion\ Factor} = RpNCP/[\left(\frac{1}{WtP\ RpCBOP}\right) * \left(\frac{World\ Annual\ Consumption}{World\ Remaining\ 2P\ Reserve}\right)]$$

The Depletion Factor is calculated by multiplying the main primary energy's depletion rate by the reciprocal of the RpCBOP to account for the relative rate of main primary energy depletion per market ready energy carrier production. A conventional Diesel PtCt produces a greater quantity of transportation energy than conventional gasoline per main primary Crude Oil input. Production of Gasoline from Tar Sands draws encounters less scarcity constraints than producing it from conventional sources. Both of these aspects of a PtCt's depletion impact are accounted for within the main primary energy Depletion factor.

The main primary energy consumption rate is independent of the studied PtCt and is equal to the world wide total annual consumption divided by the total world remaining 2P (Proven and Probable) reserve size. Remaining 2P reserve size does not include resources which have already been harvested and consumed but does includes strategic reserves.

Since discoveries follow predictable trends, with good data, geologist are able to estimate fairly accurately how much of a primary energy we will likely discover, and what the total size of the resource is. Based on technology and economic trends they can further estimate the probable quantity that will be produced. As described earlier, it is very difficult to obtain good data within the energy sector due to political and technical issues. For this reason other EAT's, which include all or some of the main primary energy inputs within the energy accounting equation, may be useful for analyzing PtCt's when accurate reserve data is unavailable.

The main primary energy could be as broad as oil, but it is better if it is calculated more specifically i.e. for conventional oil, tar sands, shale oil, etc. Each of these different types of oil PtCt's can be examined separately from a RpNCP perspective and the results offset against their specific depletion factors. Tar sands have a smaller RpNCP value than Conventional oil but the depletion factor is a significant advantage over conventional oil.

LCA WtP RpNCP/ Renewable Utilization Rate

Renewable energy isn't depleted but that doesn't mean that it can be harvested and converted into unlimited energy carriers. If we look at a wind PtCt there are a limited number of prime wind corridors on the planet. If we expect to achieve a 30% capacity factor on-shore the quantity of available locations is much smaller than if we are willing to accept a 25% capacity factor and move to off-shore locations.

A specific PtCt's, off-shore wind turbine with 25% capacity factor, carrier production benefits should be compared to the specific utilization rate. The utilization rate for this example is the annual energy in the wind at installed off-shore locations which offer 25% or greater capacity factors divided by the total annual energy in the wind at all un-utilized sights which offer 25% or greater capacity factors.

Equation 13 -

$$\frac{RpNCP}{Renewable\ Utilization\ Rate} = RpNCP/(\frac{Annual\ Renewable\ Energy\ Production}{Annual\ Renewable\ Energy\ Potential - Existing\ Renewable\ Production})$$

This NCP/SC method can also be used to analyze the land use impact of biofuel production. A minimum amount of land is required for human food production, and for simplicity I make the incorrect assumption that food and biofuels cannot be co-produced on the same plot of land. The utilization rate of a soybean biodiesel plant would be the quantity of arable land used for annual biofuel production divided by total arable land less the land required for human food and current biofuel production. The utilization rate for cellulosic Ethanol produced from switch-grass is much smaller since current production is near zero and it can be produced on sub-prime land. When analyzing renewable energy utilization rates regional calculations are generally more valuable than world-wide calculations.

Equation 14 - $$\frac{RpNCP}{Renewable\ Utilization\ Rate} = RpNCP/(\frac{Current\ annual\ Biofuel\ Production}{Arable\ land - Land\ for\ food - Land\ for\ Current\ Biofuels})$$

The calculation of specific depletion and utilization rates can follow a wide range of assumptions which should be well specified by an author who uses this method to compare different PtCt's.

LCA WtP RpNCP/WtP Land Use

While the specific impact of biofuels on arable land is best studied with the RpNCP/Renewable Utilization Rate EAT a simpler EAT can be used to examine the size requirements of a PtCt. Land Use is defined as the geographical area (sq. km, acre, sq. mile, etc) of each different PtCt's.

Equation 15 - $\frac{RpNCP}{WtP\ Land\ Use} = \frac{RpNCP}{Area\ of\ Land\ Used\ by\ PtCt}$

This can be a confusing metric as some PtCt's, like wind farms, occupy a large area but don't eliminate the possibility of other uses on most of that area. The assumptions made here should be well specified by authors. In general the Land Use impact should only include the quantity of land which can no longer be used for other valuable purpose due to the installed PtCt.

LCA WtP RpNCP/ WtP Material Annual Consumption Rate

There are a vast variety of materials each with different value and scarcity within our society. This EAT/SC can most easily be applied to a single resource at a time; like copper. Here material annual consumption rate would be equal to the LCA copper requirements of a PtCt divided by the total world annual copper consumption. Annual material consumption will change over time but the bulk of LCA material consumption occurs during the construction phase of a PtCt so using the value for that point in time is a fairly accurate assumption.

To compare different materials simultaneously quality adjustments would be needed. This cannot be accurately done using economic costs since scarce materials are prone to the same price volatility and unpredictability as energy carriers. Making quality adjustments for different materials is outside the scope of this thesis.

Equation 16 - $\frac{RpNCP}{Material\ Annual\ Consumption\ Rate} = (RpNCP)/(\frac{PtCt\ WtP\ Material\ Consumption}{World\ Material\ Consumption})$

Due to the large difference between a specific PtCt's material consumption and world-wide material consumption this EAT will be more presentable if it is multiplied by an adjustment factor like 10^12.

LCA WtP RpNCP/ WtW Clean Water Annual Consumption Rate

Clean Water Annual Consumption Rate is defined as the volumetric input of clean water to the PtCt less the clean water output divided by total world clean water consumption. If a PtCt uses energy to clean all of its waste water streams and no water is retained within the produced energy carrier it would cause no consumption of clean water. Clearly the definition of "clean" water would need to be clearly specified by an author using this NCP/SC EAT.

Equation 17 -

$$\frac{RpNCP}{WtW\ Clean\ Water\ Annual\ Consumption\ Rate} = RpNCP/(Clean\ Water\ Input - Clean\ Water\ Output)$$

LCA WtP RpNCP/ Remaining Demand %

Not all energy carriers are in infinite demand. It is possible that a PtCt will produce more energy carriers of a specific type than society can put to functional use.

One example is an intermittent provider of electricity such as a wind turbine. Wind turbines only produce electricity when the wind is blowing, which is unpredictable. Our existing grid can handle around 20% of total production coming from intermittent sources but exceeding this quantity can create complications. Since most regional grids today source far less than 20% of their electricity from intermittent sources expanding standard wind PtCt's represents little immediate challenges to our grids, but on a massive scale it would.

If we max out our grid's capacity for intermittent generated electricity we can no longer continue building standard wind PtCt's. Instead we must take on Wind, or other intermittent, PtCt's which include electrical energy storage systems capable of converting intermittent producers into constant, or on-demand, source of electricity. The remaining demand percentage for intermittent electricity production paired with storage is much larger than PtCt's that have no storage. However the Net Carrier Production of a storage inclusive PtCt will generally be lower while the economic costs higher.

Equation 18 -

$$\frac{RpNCP}{Remaining\ Demand\ \%} = RpNCP/(\frac{Annual\ Production\ of\ Specific\ Carrier\ Type}{Max\ Annual\ Carrier\ Demand - Annual\ Production})$$

LCA WtP RpNCP/ WtP Economic Cost

The economic cost of finding, constructing, operating and dismantling a PtCt is certainly a Social Cost that should be considered by Decision makers. Unlike econometrics, energymetrics allows the energy carrier production benefit of a PtCt to be offset against numerous different social costs not just economic ones. Given the nature of our economy this EAT would likely be assigned a heavy weighting factor by most decision makers in a mathematical equation combining many of these different EAT's into one PtCt comparison tool.

Equation 19 -

$$\frac{RpNCP}{WtP\ \$\ Cost} = RpNCP/(\$\ Finding + \$\ Construction + \$\ Operating + \$\ Dismantling)$$

Numerical PtCt Comparison Tool

One important EAT which I did not calculate values for in this thesis is the RpNCP/Main Primary Energy Depletion Factor. I believe it is best to compare a PtCt's NCP, which excludes main primary energy inputs, to different social costs. A detailed analysis would examine each main primary energy's depletion differently based on varying scarcity using the RpNCP/Main Primary Energy EAT while ignoring all aspects of depletion for other EAT's.

However, without the necessary depletion data I instead compare the RpCROI of renewably sourced primary energy to the RpCHOI values of finite sourced primary energy. This comparison accounts for the input of, non-pass through, main primary energy if it comes from a finite energy source but not if it comes from renewable sources.

Additionally I include the WtP+ CBOO which focuses just on oil depletion; the fossil fuel which faces the most immediate scarcity constraints. The combination of these two factors which represent 50% of the potential total point allocation within my example comparison tool equation below are used together to evaluate the carrier production benefits of a PtCt against finite inputs, with a heavier weighting on oil inputs.

In addition to approximating the energy carrier return over investment benefits while considering main primary energy depletion two other RpNCP/SC's were analyzed each accounting for 25% of the potential total point allocation. The WtP NCP/WtW CO2e tells us which PtCt's produce the most energy carrier output per CO2 equivalent production. The WtP NCP/WtW Regulated Emissions Economic Cost tells us which PtCt's produce the most energy carrier output per economic cost caused by regulated emissions.

This equation encompass some of the major social concerns associated with energy carrier production, but the below equation, and results, are only an example of how multiple EAT's can be combined into a single comparison tool. Clearly many other social costs like: economic cost, water consumption, land use, etc should be considered within this type of comparison tool. Additionally, there is likely a much better mathematical formula that could be used to better represent decision makers actual goals and concern

Equation 20 - Example Comparison Tool Equation

Example Comparison Tool Equation = [If(Finite, If(CHOI> 10,10,CHOI), If(CROI > 10,10,CROI)) * 2.5] + [If(CBOO > 50,50,CBOO)/2] + [if({RpNCP/CO2e} < 0, 50 - {RpNCP/CO2e}, If({RpNCP/CO2e} > 500,500,{RpNCP/CO2e}) / 20] + [If({RpNCP/Reg.E} > 500, 500, {RpNCP/Reg.E}) / 20]

Table 13 - Summary of Sample Comparison Equation

Results of Example of Energymetrics Comparison Equation combining multiple EAT's					
Impact on Final Score	25%	25%	25%	25%	100%
Max possible Score	Max 10	Max 50	Max 500 [1]	Max 500	Max 100
Feedstock -> Carrier	**RpCROI/RpCHOI**	**RpCBOO**	**RpNCP/CO2e**	**RpNCP/Reg.E**	**Score**
Biomass -> DME	9.3	17	520	500	**80**
Tree -> Ethanol	9.6	12	400	380	**70**
Palm Oil -> Biodiesel	5.3	12	500	500	**70**
Soybean -> Biodiesel	4.9	12	500	500	**70**
Camelina -> Biodiesel	4.4	11	500	500	**70**
Rapeseed -> Biodiesel	3.6	11	500	500	**60**
Jatropha -> Biodiesel	3.9	8.8	500	500	**60**
Shale -> Nat.gas	8.6	50	11	310	**60**
Conv. -> Nat. Gas	7.6	50	10	290	**60**
Switchgrass -> Ethanol	6.2	18	130	460	**50**
Biomass -> FTD	9.2	17	66	370	**50**
Stover -> Ethanol	7.6	13	120	390	**50**
Algae -> Biodiesel	4.1	19	50	390	**40**
Nat. Gas -> Elec.	0.7	50	9.4	280	**40**
Conv. -> Diesel	7.8	1.0	12	380	**40**
Biomass -> Electricity	7.3	13	66	180	**40**
Conv. -> Gasoline	5.9	1.0	10	410	**40**
Coal -> FTD	2.0	50	5.5	40	**30**
F. Residue -> Ethanol	6.2	9.7	34	180	**30**
Coal -> Electricity	0.6	43	5.5	32	**20**
Tar Sands -> Diesel	3.3	1.0	8.6	310	**20**
Sugar Cane -> Ethanol	6.1	8.6	27	20	**20**
U.S. Corn -> Ethanol	3.0	14	13	91	**20**
Tar Sands -> Gasoline	2.6	0.9	6.3	240	**20**

1 - RpNCp/CO2e score can exceed the 500 maximum if consuming the energy carrier produced by the PtCt reduces total global warming potential; normally through the avoided release of methane into the atmosphere.

Time Value of Energy

By using the theory of energy relativity to make consistent quality adjustment I believe the RpEAT's calculated above are better comparison tools than could be produced on an enthalpic basis. But still two different PtCt's could have the same RpCROI values despite being quite different from each other due to the impact of time on energy. One PtCt may take less time to construct, have a longer life, or produce energy carriers at a faster rate. All these time aspects could increase the overall value of a PtCt to society. To account for these time dependent differences I propose that there is a Time Value of Energy (TVE) just as there is a Time Value of Money.

Consider two hypothetical PtCt's which can be constructed instantaneously and have no construction constrains other than electricity availability.

PtCt A:	PtCt B:
Construction Energy = 1 MJ Electricity	Construction Energy = 1 MJ Electricity
Output Energy = 1 MJ Electricity/Year	Output Energy = 5 MJ Electricity/Year
Useful Life = 10 Years	Useful Life = 2 Years
CROI = 10	CROI = 10
NCP = 9	NCP = 9

Both PtCt's have the same CROI and NCP values but PtCt B brings its 9 MJ of electricity to the market five times faster than project A. If all electricity produced is used to build replications of the original we find PtCt B can produce 10,000 times more replications of itself than PtCt A in 10 years. Without taking the Time Value of Energy into consideration these PtCt's appear to be equivalent; but they are not.

Table 14 - Effect that the rate of energy production has on replicating a PtCt

Number of PtCt's Operational if all Electrcity Produced is Re-Invested in Replicating an New PtCt matching the Original											
Year	0	1	2	3	4	5	6	7	8	9	10
PtCt A	1	2	4	8	16	32	64	128	256	512	1,024
PtCt B	1	6	30	149	739	3,665	18,176	90,141	447,040	2,217,024	10,994,979

Because PtCt's exist with positive CROI values, energy carriers available to us today can be used to produce even more energy tomorrow. It is this positive return on energy carrier investment potential that makes carriers available today more valuable than those delivered in the future. Every year further into the future they are made available the less valuable they become to us today. The Time Value of Energy formula below applies the normal discounting formula for money to energy values.

Equation 21 - Time Value of Energy

$$PC = FC * (1 + i)^\wedge - n$$

Where,

PC = Present Carrier Value
FC = Future Carrier Value
n = Years into the project that the FC is produced or consumed
i = The Minimum Attractive rate of Carrier Return (MACR)

The Internal Carrier Rate of Return (ICR) is the MACR value that makes a PtCt's CROI = 1, and its NCP = 0

The Minimum Attractive rate of Carrier Return, or discount rate, is a key variable which can significantly change the results of applying the Time Value of Energy to a group of PtCt's. The MACR will change with different market conditions and represents the minimum rate of energy carrier return that a company or government is willing to accept from a PtCt. A brief discussion of potential MACR values and the sensitivity of RpCROI values to the MACR can be found in Appendix E.

Carrier Time Line

A Carrier Time Line (CTL) shows the different types of energy carriers produced and consumed each year over the entire life of a PtCt. It is a graphical representation of a project's annual energy flows showing not just the quantity but also the type and timing of energy carrier inputs and outputs.

Once a CTL is created both time valuation or quality adjustments can be made with the order of operations having no effect on the final result. After completing both each carrier's enthalpic value (MJ) can be compared to each other on a Present Relative to personal transportation Mega-Joule basis (P_5RpMJ). In this example the subscript 5 indicates that a 5% discount rate was used for the present energy calculations. All the fore-mentioned EAT's can be calculated on a Present, or Present and Relative basis. For example the P_5CROI or the P_5RpCROI.

Time data is rarely included within LCA studies and proved difficult to find. (GREET_2011) provides no time data so all previous calculations and the tables of results ignore the TVE (MACR = 0%). The resulting quality adjusted EAT's are still good comparison tools but the analysis would be better if time valuation could be applied, with a valid MACR value, to the same broad group of PtCt's in the future.

Below are two examples of how to apply both the TVE and REVp to an LCA study. To do so I had to make many different assumptions. Additionally, the LCA studies sourced likely have different boundary assumptions compared to GREET or each other. This is only an example of how to use the TVE method, and should not be considered an accurate analysis of the stated PtCt's

Vestas Wind Farm

(Vestas, 2006) examines the LCA energy impacts associated with producing, transporting, erecting, operating, dismantling, and removing one hundred V90-3.0 MW turbines and the 140 km of cable to connect them to a nearby grid. The 100 turbine wind farm is assumed to have a 30% capacity factor based on Horns Reef, Denmark. The turbines are assumed to have a 20 year operational life with half the gearboxes needing to be replaced once during this lifespan.

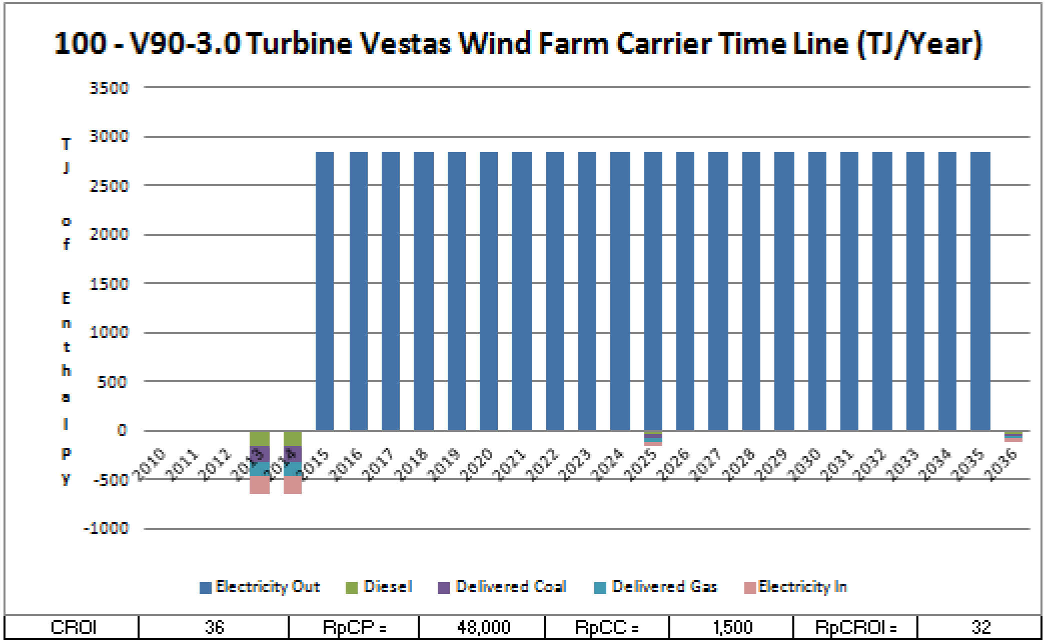
To simplify this analysis I assume: Crude Oil = Renewable Fuel = Diesel, Lignite = Coal, Nuclear power = electricity, Primary Hydro is converted into electricity with a 90% efficiency, Biomass and primary wind is converted into electricity with a 32% efficiency. Based on a different LCA study showing Wind turbine CO2 emissions per phase[13] I assume that 85% of LCA energy inputs are used for producing, transporting and erecting. 3.75% for operating, 3,75% for replacing gearboxes, and 7.5% for decommissioning.

Table 15 - Inputs and Outputs over the life of Vestas wind farm

TJ of Energy Input and Output by Type and Use for 100-Vesta V90-3.0 Turbine Farm					
Energy Carrier	TJ/Plant Life	TJ/Construction	TJ/Operation	TJ/Repair	TJ/Dismantling
Electricity Out	**56,808**	85%	3.75%	3.75%	7.5%
Electricity In	453	385.2	17.0	17.0	34.0
Diesel In	388	330.0	14.6	14.6	29.1
Delivered Coal In	361	306.9	13.5	13.5	27.1
Delivered Gas In	353	300.5	13.3	13.3	26.5
Total Inputs	**1,600**	**1,300**	**58**	**58**	**120**

I assume: one year of operation energy, spread over three years, is used to locate and study the wind site, construction takes 2 years, operation energy is spread equally over the 20 year life, and gearbox repairs occur once in the middle of the PtCt's operational life.

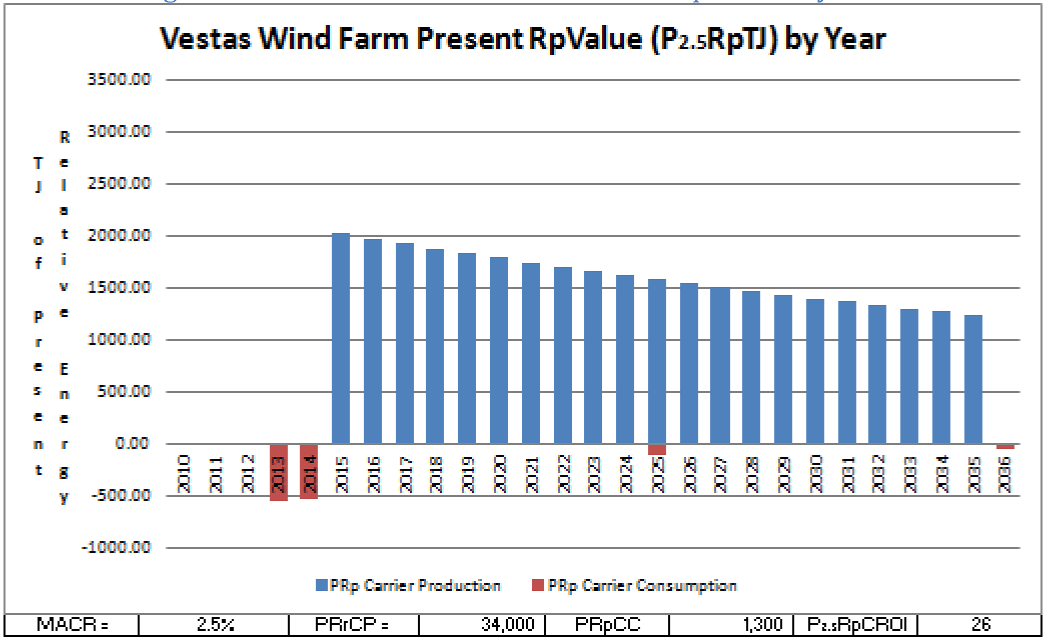
Figure 8 - Vestas Wind Farm Carrier Time Line



CROI	36	RpCP =	48,000	RpCC =	1,500	RpCROI =	32

The chart above shows the enthalpic energy inputs and outputs by carrier type and year that they occur. The chart below shows Present Relative to personal transportation energy that is produced over the life of the project assuming MACR = 2.5%. These values are all adjusted to present 2010 values.

Figure 9 - Vestas Wind Farm Present RpValue by Year



MACR =	2.5%	PRrCP =	34,000	PRpCC	1,300	$P_{2.5}$RpCROI	26

Daqing Oil Field, China

(Hu, 2011) reports that 95% of the enthalpic output at Daqing is Crude Oil while 5% is Natural Gas. Additionally, that the instantaneous production EROI for the Daqing Oil field in China has declined from 10:1 in 2001 to 6.5:1 in 2009. I assume that this decline started when the field peaked in 1995 and that that from 1961-1995 the instantaneous production EROI equaled 12.5. I project that the decline trend continues until 2017 when the instantaneous production EROI = 3:1. From 2017 forward I use a linear decline with the target of 1:1.

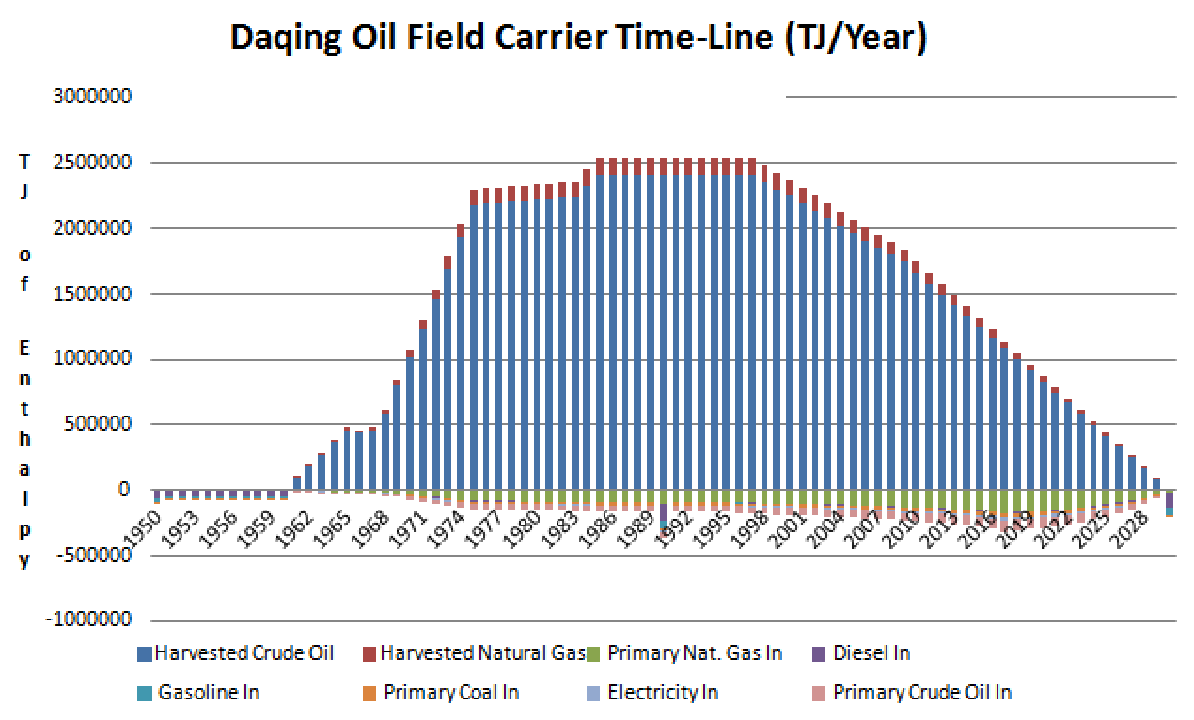
By dividing each annual production value by these calculated instantaneous production EROI values I estimate the total quantity inputs to Daqing oil field for each year. Using the simplified allocation of conventional oil production inputs from GREET (Appendix C) I allocate these total annual inputs to a mix of different energy carriers.

Additionally, I estimated the quantities of inputs that go into the construction of an conventional oil well head using GREET. I assume that 70% of the reported petroleum construction inputs were Diesel and 30% Gasoline. This construction energy was evenly distributed over a construction period of 10 years. (EIA, 2008). At the end of the PtCt's life it is assumed that 1/3 of this construction energy was required for dismantling. I also assumed that 1/3 of the construction energy was invested in maintenance and repairs halfway through the projects life. Construction energy for the refinery was omitted.

The most challenging value to estimate is the quantity of energy that it took to discover the Daqing oil field. I assume that the Daqing field was discovered 15 years prior to 1965 when world-wide oil discoveries peaked. Assuming world instantaneous discovery EROI values follow the same trend as the United States presented by (Guilford, 2011) the instantaneous discovery EROI for the Daqing field would be around 1200:1. This ratio decreases quite rapidly after a peak in discoveries has been reached. By the time U.S. oil production peaked in 1973, 40 years after the region's discovery peak, the instantaneous discovery EROI had declined to 11.6:1 (Guilford, 2011).

Conventional world oil production peaked in 2006 (IEA, 2010) so I assume that if the same quantity of oil field was discovered today it would have an discovery EROI closer to 11.6:1 than 1200:1. Dividing the total energy discovered by 1200 is how I estimated the energy spent discovering this oil field since it was a historical find. However if we are attempting to analyze searching for new oil fields a discovery EROI of 11.6 would be better value to use. The RpCROI values of Daqing would drop from 11.8 to 6 depending on which value was used. This points out that searching for new oil will result in less net carrier production than has been achieved from historical oil PtCt's.

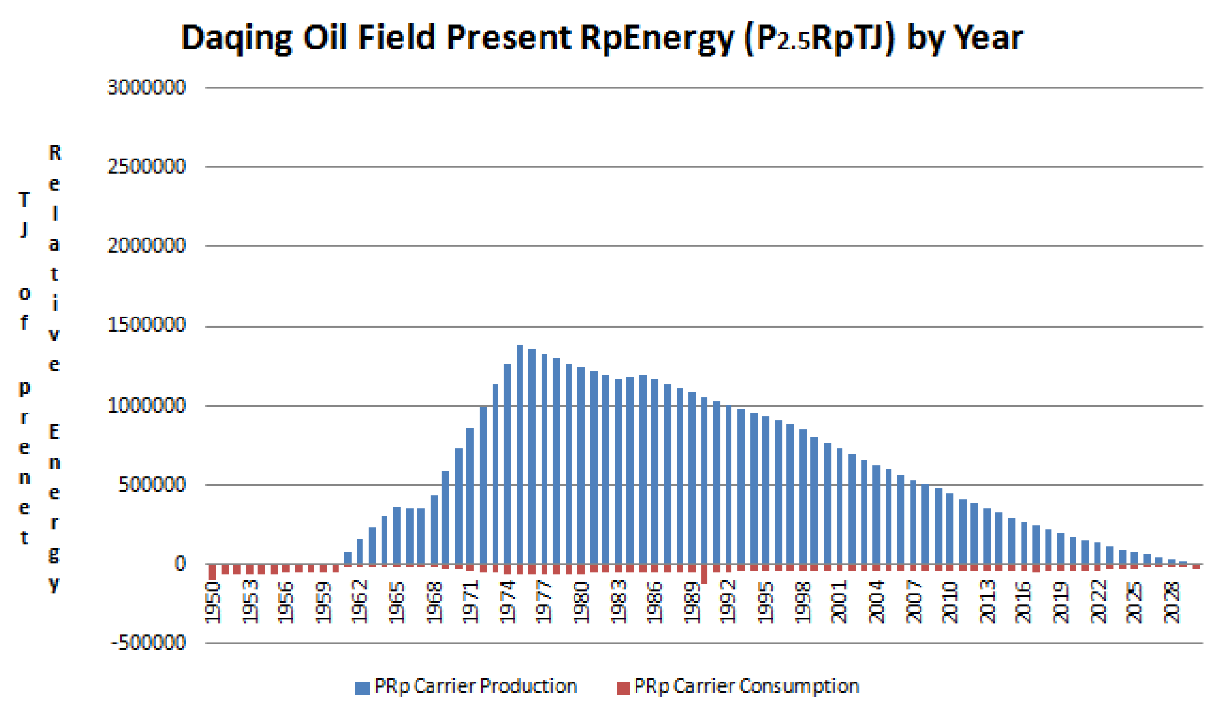
Figure 10 - Daqing Oil Field Carrier Time Line



CROI	9.3	RpCP =	130,000,000	RpCC =	11,000,000	RpCROI =	12

The chart above shows the enthalpic energy inputs and outputs by carrier type and year that they occur. The chart below shows Present Relative to personal transportation energy that is produced over the life of the project assuming MACR = 2.5%. These values are all adjusted to a present 1950 values.

Figure 11 - Daqing Oil Field Present RpEnergy by Year



MACR =	2.5%	PRrCP =	46,000,000	PRpCC	3,700,000	P2.5RpCROI	12

Conclusions

In this thesis I have laid out methodologies for adjusting enthalpic energy values based on both the time/rate that they are produced as well as their quality differences. The Relative Energy Values to Personal Transportation (REVp) is set of quality adjustments factors for different energy carriers based on their ability to provide a useful energy service, local personal transportation, for society.

There are an infinite number of ways to compare PtCt's once you have equalized the energy units and in this thesis I laid out a number of specific energy accounting equations which I call Energy Analysis Tools (EAT's) to assist with this task. If we are willing to introduce an individual's subjective analysis of the different social benefits and costs associated with PtCt's, then numerous EAT's can be combined into a single mathematical scoring system. Such a scoring system could allow decision makers to rank different PtCt's based on the qualities and drawbacks that are most important to them.

While the goal of this thesis was to develop the energymetric methods which could be used to analyze and compare PtCt's I also applied this method to (GREET_2011) data. No LCA data is perfect but Argonne National Labs is a very credible source of data and more importantly since in its freely available to the public the assumptions made within this database can be reviewed by readers. Based on the application of my methods to this specific group of data a few additional conclusions can be made.

Of all the PtCt's studied and analyzed using the four criteria and subjective weighting system included in my comparison tool (RpCROI/RpCHOI, RpCBOO, RpNCP/CO2e, RpNCP/Regulated Emissions) the conversion of Biomass to DME for transportation purposes was the best overall performing PtCt. This technology can produce useable transportation fuel from farmed or waste biomass streams like: forest residues, milling waste, and agricultural waste. According to GREET this can be done with a competitive CROI value while actually creating negative CO2e emissions for every unit of DME produced and burned. This is because methane emissions, which have a larger global warming potential than CO2, are avoided and instead CO2 emissions are created after the combustion of DME. If the co-product Char can offset synthetic fertilizers as most believe it can this PtCt would have an even better energy balance.

Other biofuel PtCt's also performed quite well including many already commercialized biodiesel production processes. Not included in this analysis is the PtCt's impact on clean water consumption. Both represent significant drawbacks of biofuel production however the subjective weighting factor for these values if calculated should change based on the region and the local scarcity issues of land and water.

Often discussed Sugarcane and Corn to ethanol PtCt's scored quite low, with the prior having twice the RpCROI value and better GHG emissions than the later, but producing significantly more regulated emissions. These cost of these regulated emissions is slightly skewed some since the emission are based on Brazilian technology and point of emission while the economic costs from (IMPACT, 2007) used within this study are based on France as the point of emission. The application of my Energymetric methods to GREET data indicate that cellulosic processes appear to be a much better future technology for ethanol production.

Both conventional and shale natural gas score quite well as a source for transportation fuel. They are largely assisted by their high CBOO value since very little crude oil is used during the harvesting and distribution of natural gas. Coal to FTD also has a high CBOO value, but it has a poor RpCHOI value and is very dirty both from a regulated and GHG emission perspective.

The primary objective of this thesis was to develop the methods necessary to compare PtCt's. However, many good energy policies or evaluations of individual technologies could be derived from a careful look at the energy carrier to energy service chains I studied, using GREET data, to create the Relative Energy Values to personal transportation (REVp) values calculated within this thesis.

The Diesel engine appears to be a better all around engine for automobiles compared to a Otto Gasoline engine. The diesel fuel LCA WtW chain is 30% better from a RpCHOI perspective and 25% better from a RpNCP/CO2e perspective. Diesel engines due however cause 7% more LCA WtW economic damage from regulated emissions than their Otto engine counter-parts.

Food production combined with the expanded use of bicycles for transportation represents a significant energy efficiency gain. If it take 7.4 MJ of fossil fuels to grow, harvest, distribute, and prepare one MJ of food (Aleklett, 2012) and I assume 60% comes from Natural Gas and 40% from Diesel. I calculate that it takes 8.2 RpMJ of fossil fuels to produce 1 MJ of food. That 1 MJ of food however is worth 22 RpMJ meaning that growing food to feed bicyclists is a 260% more efficient use of fossil fuel than using gasoline to fuel our cars. Good energy policy should encourage increased bicycle commuting.

Food is a very valuable energy carrier; even as a transportation fuel with a REVp = 22. Creating a biofuel projects which eliminate food production will likely decrease total RpOutput from a specific plot of land. However it is likely that by combining both fuel and food production on the same plot with crop rotations, or by taking advantage of agricultural waste streams, that you could increase the total RpOutput from a single plot of land.

One of the most disruptive technologies to this quality valuation method is the Electric Vehicle. The impacts of wide-scale adoption of the Electric Vehicle is examined in detail in Appendix A. But this single technology would increase the Relative to personal transportation Energy Value of: Electricity 180%, Coal 56%, Natural Gas 47%, and Biomass 43%.

The identification of one technology that would so dramatically increase the social value of such a broad and important group of energy carriers is significant. Policy makers should be careful with subsidies. But in this case, the significant energy carrier utilization efficiency gains which will in turn increase the social value of so many different PtCt technologies leads me to believe that a major subsidy with the aim to accelerate Electric Vehicle adoption is justified.

Table 16 - Summary of Relative Energy Values to Personal Transportation (REVp)

Relative Energy Values to Personal Transportation				
Vehicle - Fuel Chain	**Energy Carrier**	**REVp**	**mpg.ge**	**L.ge/100Km**
Bicycle - Metabolic	Food	22.0	600	0.4
Rickshaw - Metabolic	Labor (1 hour)[1]	4.40	300	0.8
Diesel Engine	Diesel/Kerosene	1.25	34.1	6.9
Diesel Engine	FTD/Biodiesel	1.25	34.1	6.9
Diesel Engine	SVO/WVO	1.25	34.1	6.9
Diesel Engine	DME/LPG	1.21	33.1	7.1
Horse - Animal Feed	Metabolisable Energy (ME)[2]	1.19	32.3	7.3
Otto Engine	Hydrogen	1.13	30.7	7.7
Diesel - Conventional	Harvested Crude Oil[3]	1.11	30.2	7.8
Diesel - Conventional	Primary Crude Oil[4]	1.09	29.6	7.9
Otto Engine	Ethanol	1.07	29.2	8.1
Otto Engine	**Gasoline**	**1.00**	**27.3**	**8.6**
Otto Engine - U.S. Mix	Delivered Nat. Gas[5]	0.92	25.2	9.3
Otto Engine - U.S. Mix	Harvested Nat. Gas[3]	0.86	23.5	10.0
Otto Engine - U.S. Mix	Primary Nat. Gas[4]	0.81	22.0	10.7
Horse - Metabolic	Soy Meal	0.81	22.1	10.7
Otto - H2 - Electrolysis	Electricity	0.81	22.0	10.7
Diesel - FTD - FT	Delivered Coal[5]	0.64	17.5	13.5
Diesel - DME - Gasify	Delivered Biomass[5]	0.62	16.9	14.0
Diesel - FTD - FT	Harvested Coal[3]	0.61	16.8	14.0
Diesel - FTD - FT	Primary Coal[4]	0.61	16.6	14.1
Diesel - DME - Gasify	Uncollected Biomass[6]	0.60	16.2	14.5

Unless otherwise specified, REVp are quality adjustment factors for converting a "Delivered" Joule of the stated energy carrier's enthalpy into Relative to personal transportation Joule's (RpJ) with gasoline as the reference carrier 1 - REV for converting one hour of work into RpJ. 2 - REV for converting one Joule of Metabolisable Energy into RpJ. 3 - Harvested means produced but not transported. 4 - Primary means stored in its original geographical location and form. 5 - Delivered means final energy carrier is delivered to the fueling pump at atmospheric conditions. 6 - Uncollected Biomass means biomass found in its original geographical location. All results calculated with data from (GREET1_2011) except for the REVp values for horse and human powered transportation.

Table 17 - Summary of Primary to Carrier Technology EAT results

Summary of Primary to Carrier Technology's EAT's					**(RpJ/Kg CO2e)**	**Units**	**(RpMJ/Year 2000 Euro)**
Feedstock -> Carrier	**RpCROI**	**RpCHOI**	**RpCBOO**	**Feedstock -> Carrier**	**RpNCP/CO2e**	**Feedstock -> Carrier**	**RpNCP/Reg. Emission**
Tree -> Ethanol	**9.6**	0.2	12	Biomass -> DME	-17	Soybean -> Biodiesel	1200
Biomass -> DME	**9.3**	2.0	20	Soybean -> Biodiesel	1100	Biomass -> DME	950
Biomass -> FTD	**9.2**	1.7	20	Camelina -> Biodiesel	840	Camelina -> Biodiesel	890
Shale -> Nat.gas	27	**8.6**	100	Rapeseed -> Biodiesel	670	Rapeseed -> Biodiesel	710
Conv. -> Diesel	11	**7.8**	1.0	Palm Oil -> Biodiesel	620	Palm Oil -> Biodiesel	670
Conv. -> Nat. Gas	30	**7.6**	210	Jatropha -> Biodiesel	550	Jatropha -> Biodiesel	580
Stover -> Ethanol	**7.6**	0.2	13	Tree -> Ethanol	400	Switchgrass ->Ethanol	460
Biomass -> Electricity	**7.3**	0.5	10	Switchgrass -> Ethanol	130	Conv. -> Gasoline	410
F. Residue -> Ethanol	**6.2**	0.2	9.7	Stover -> Ethanol	120	Algae -> Biodiesel	390
Switchgrass -> Ethanol	**6.2**	0.2	18	Biomass -> FTD	66	Stover -> Ethanol	390
Sugar Cane -> Ethanol	**6.1**	0.2	8.6	Biomass -> Electricity	66	Tree -> Ethanol	380
Conv. -> Gasoline	8.1	**5.9**	1.0	Algae -> Biodiesel	50	Conv. -> Diesel	380
Palm Oil -> Biodiesel	**5.3**	0.3	12	F. Residue -> Ethanol	34	Biomass -> FTD	380
Soybean -> Biodiesel	**4.9**	0.4	12	Sugar Cane -> Ethanol	27	Tar Sands -> Diesel	310
Camelina -> Biodiesel	**4.4**	0.3	11	U.S. Corn -> Ethanol	13	Shale -> Nat.gas	310
Algae -> Biodiesel	**4.1**	0.2	19	Conv. -> Diesel	12	Conv. -> Nat. Gas	290
Jatropha -> Biodiesel	**3.9**	0.4	8.8	Shale -> Nat.gas	11	Nat. Gas -> Elec.	290
Rapeseed -> Biodiesel	**3.6**	0.4	11	Conv. -> Nat. Gas	10	Tar Sands -> Gasoline	240
Tar Sands -> Diesel	3.9	**3.3**	1.0	Conv. -> Gasoline	10	F. Residue -> Ethanol	180
U.S. Corn -> Ethanol	**3.0**	0.3	14	Nat. Gas -> Elec.	9	Biomass -> Electricity	180
Tar Sands -> Gasoline	3.0	**2.6**	0.9	Tar Sands -> Diesel	9	U.S. Corn -> Ethanol	90
Coal -> FTD	50	**2.0**	50	Tar Sands -> Gasoline	6	Coal -> FTD	40
Nat. Gas -> Electricity	97	**0.7**	180	Coal -> FTD	5	Coal -> Electricity	32
Coal -> Electricity	40	**0.6**	40	Coal -> Electricity	5	Sugar Cane -> Ethanol	20

The GREET LCA data used to produce this chart assumes a U.S. average mix for electricity production. Note the conversion of biomass into DME results in a reduction not increase in GHG emissions. This is due to the fact that methane, which has a larger global warming potential than CO2, is captured and not emitted into the atmosphere. A large negative RpNCP/CO2e is the best possible score that could be achieved for a RpNCP/CO2e EAT.

Table 18 - Summary of Sample Comparison Equation

Results of Example of Energymetrics Comparison Equation combining multiple EAT's					
Impact on Final Score	25%	25%	25%	25%	100%
Max possible Score	Max 10	Max 50	Max 500 [1]	Max 500	Max 100
Feedstock -> Carrier	**RpCROI/RpCHOI**	**RpCBOO**	**RpNCP/CO2e**	**RpNCP/Reg.E**	**Score**
Biomass -> DME	9.3	17	520	500	**80**
Tree -> Ethanol	9.6	12	400	380	**70**
Palm Oil -> Biodiesel	5.3	12	500	500	**70**
Soybean -> Biodiesel	4.9	12	500	500	**70**
Camelina -> Biodiesel	4.4	11	500	500	**70**
Rapeseed -> Biodiesel	3.6	11	500	500	**60**
Jatropha -> Biodiesel	3.9	8.8	500	500	**60**
Shale -> Nat.gas	8.6	50	11	310	**60**
Conv. -> Nat. Gas	7.6	50	10	290	**60**
Switchgrass -> Ethanol	6.2	18	130	460	**50**
Biomass -> FTD	9.2	17	66	370	**50**
Stover -> Ethanol	7.6	13	120	390	**50**
Algae -> Biodiesel	4.1	19	50	390	**40**
Nat. Gas -> Elec.	0.7	50	9.4	280	**40**
Conv. -> Diesel	7.8	1.0	12	380	**40**
Biomass -> Electricity	7.3	13	66	180	**40**
Conv. -> Gasoline	5.9	1.0	10	410	**40**
Coal -> FTD	2.0	50	5.5	40	**30**
F. Residue -> Ethanol	6.2	9.7	34	180	**30**
Coal -> Electricity	0.6	43	5.5	32	**20**
Tar Sands -> Diesel	3.3	1.0	8.6	310	**20**
Sugar Cane -> Ethanol	6.1	8.6	27	20	**20**
U.S. Corn -> Ethanol	3.0	14	13	91	**20**
Tar Sands -> Gasoline	2.6	0.9	6.3	240	**20**

Appendix

List of Appendix's Table and Figures

Appendix A - Other Possible Relative Energy Value's to Transportation

The Electricity REVp = .81 is in line with economic quality valuation methodologies if the price of electricity is $.10/kwh and gasoline cost $4/gallon ($1.05/Liter). While these two method's appear to agree there are some strong arguments that can be made that electricity, and other energy carriers, are over or under valued by the specific energy service and available technology I choose to analyze.

REVp might Over-Value Electricity and other Energy Carriers

REVp assumes that hydrogen can be readily burned within otto engines. While this assumption is true, the practicality of converting automobiles to store hydrogen is not as practical as more energy dense natural gas. Additionally the construction of a hydrogen distribution would be a major investment. Due to these challenges it is unlikely that hydrogen will be used as major transportation fuel during the life of most the PtCt's studied.

If hydrogen cannot be used directly it instead must be converted into a synthetic methane to be a substitution transportation fuel. A process called hydrogen to gas is currently being developed by Audi for which combines CO2 with H2 to produce synthetic Methane and H20. (Pengg, 2012) claims they are achieving an 82% methanization efficiency. Combined with GREET's 71.5% electrolysis efficiency (GREET, Hydrogen, BG63:BH63). Electricity could be used to convert water and CO2 into synthetic methane with a 59% efficiency. Not included is the energy cost of creating a pure CO2 stream either by stripping it from atmospheric air, or concentrating fossil fuel flu-gases.

No data was found but for these calculation I assume that CO2 concentration energy input would further reduce the complete electric to methane efficiency to 50%. By multiplying this value by Delivered Natural Gas REVp = .92 I calculate that Electricity REVp = .46. This assumes that hydrogen is not a useful transportation fuel but methane is.

The distance and time associated with the chosen social goal is also very important to consider. If instead of traveling 30 miles in 3 hours we need to go 2500 miles in 8 hours an airplane would be required to produce the desired personal transportation. The same energy carriers that can power a horse and bicycle cannot directly power an airplane. Essentially all non liquid energy carrier would need to be synthesized into liquids.

Once an energy carrier has been converted into methane it can be synthesized into kerosene jet fuel with a 56% efficiency (EPA, 1998). This shift in the desired energy service would further drive down Electricity REVp = .26. Additionally all non liquid fuel carriers REVp would decrease. Biomass gasification and conversion of methane to liquid fuel would result in Delivered Biomass REVp = .34 which would be the value applied to animal feed, food, or any other solid biomass products.

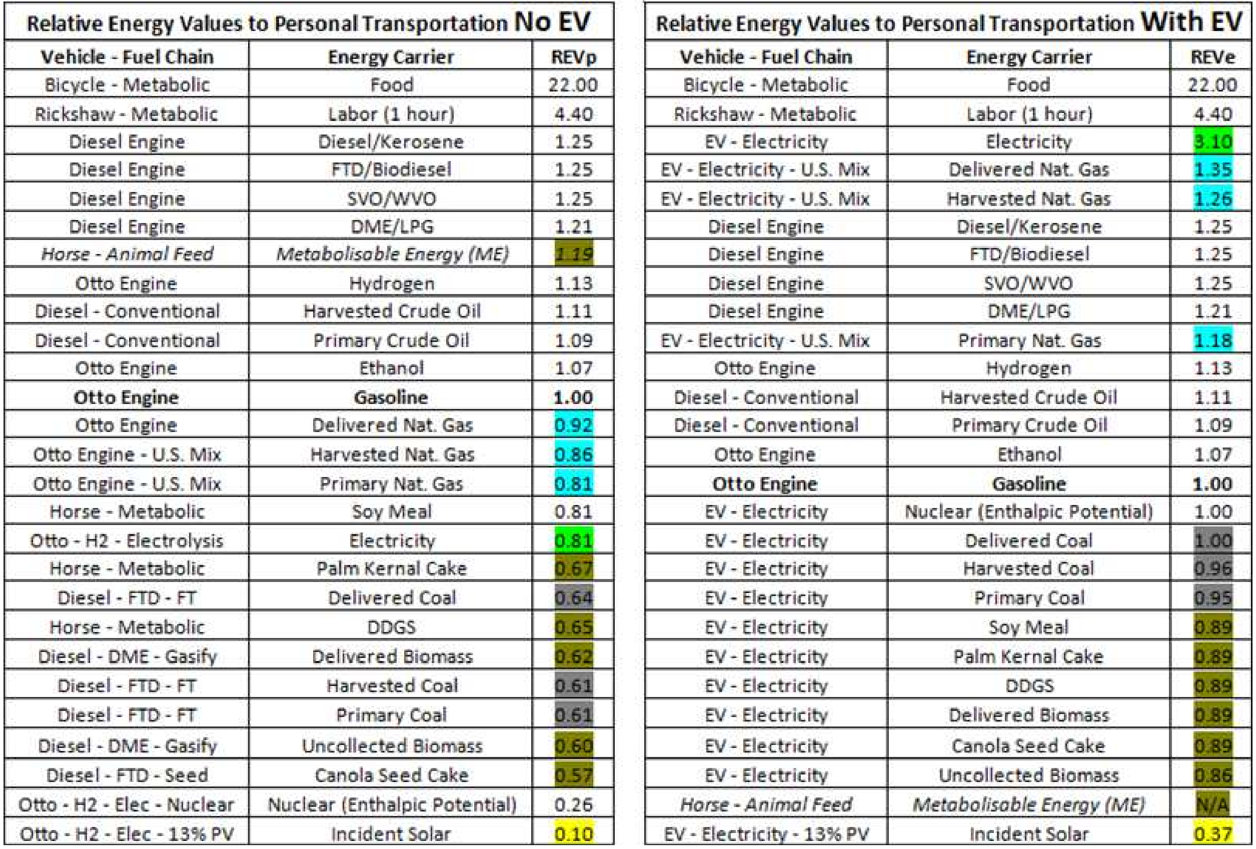
REVp might Under-Value Electricity and other Energy Carriers - REVe

GREET shows the efficiency of an Electric Vehicle is 3.4 times greater than an Otto powered vehicle (GREET,Inputs Page,C809:CC809). I assume that an electric vehicle, excluding batteries, can travel 200,000 miles and requires the same quantity of energy to manufacture and maintain as an Otto powered vehicle. I also assume that a 600 lb battery Li-Ion battery is used with a 100+ mile (160 km) range which has an 8 year useful life. By applying the battery production and recycling impact data from (GREET, 2.7) I calculate an LCA REVe for Electricity equal to 3.1. This is a significantly higher REV than Electricity's REVp value equal to .81.

The existence of EV's does not only increase the REV for electricity but also other energy carriers which can be converted into electricity. Primary Coal's REVp = .61 increases to a REVe = .95. Primary Natural Gas's REVp = .81 increases to REVe = 1.18. Delivered Biomass's REVp = .62 increases to REVe = .89. Converting biomass into electricity to power an EV is a more efficient method of producing personal transportation than using all studied biofuel co-products as animal feed so all biomass, including animal feed, have a REVe = .89.

Gasoline has an equal value if it is burned in a gasoline powered generator and the resulting electricity used to power an EV, or if it is burned directly within an Otto engine. Gasoline, and fuels that have a higher transportation value have the same REVe as REVp. Below find the list of REVe, which has the same social goal and available technology and REVp except that the Electric Vehicle is considered an available technology. REVe has been used to evaluate the same PtCt's as was done with REVp.

Table A1 - Comparing REVp to REVe (with the Electric Vehicle)



Relative Energy Values to Personal Transportation **No EV**		
Vehicle - Fuel Chain	**Energy Carrier**	**REVp**
Bicycle - Metabolic	Food	22.00
Rickshaw - Metabolic	Labor (1 hour)	4.40
Diesel Engine	Diesel/Kerosene	1.25
Diesel Engine	FTD/Biodiesel	1.25
Diesel Engine	SVO/WVO	1.25
Diesel Engine	DME/LPG	1.21
Horse - Animal Feed	*Metabolisable Energy (ME)*	*1.19*
Otto Engine	Hydrogen	1.13
Diesel - Conventional	Harvested Crude Oil	1.11
Diesel - Conventional	Primary Crude Oil	1.09
Otto Engine	Ethanol	1.07
Otto Engine	**Gasoline**	**1.00**
Otto Engine	Delivered Nat. Gas	0.92
Otto Engine - U.S. Mix	Harvested Nat. Gas	0.86
Otto Engine - U.S. Mix	Primary Nat. Gas	0.81
Horse - Metabolic	Soy Meal	0.81
Otto - H2 - Electrolysis	Electricity	0.81
Horse - Metabolic	Palm Kernal Cake	0.67
Diesel - FTD - FT	Delivered Coal	0.64
Horse - Metabolic	DDGS	0.65
Diesel - DME - Gasify	Delivered Biomass	0.62
Diesel - FTD - FT	Harvested Coal	0.61
Diesel - FTD - FT	Primary Coal	0.61
Diesel - DME - Gasify	Uncollected Biomass	0.60
Diesel - FTD - Seed	Canola Seed Cake	0.57
Otto - H2 - Elec - Nuclear	Nuclear (Enthalpic Potential)	0.26
Otto - H2 - Elec - 13% PV	Incident Solar	0.10

Relative Energy Values to Personal Transportation **With EV**		
Vehicle - Fuel Chain	**Energy Carrier**	**REVe**
Bicycle - Metabolic	Food	22.00
Rickshaw - Metabolic	Labor (1 hour)	4.40
EV - Electricity	Electricity	3.10
EV - Electricity - U.S. Mix	Delivered Nat. Gas	1.35
EV - Electricity - U.S. Mix	Harvested Nat. Gas	1.26
Diesel Engine	Diesel/Kerosene	1.25
Diesel Engine	FTD/Biodiesel	1.25
Diesel Engine	SVO/WVO	1.25
Diesel Engine	DME/LPG	1.21
EV - Electricity - U.S. Mix	Primary Nat. Gas	1.18
Otto Engine	Hydrogen	1.13
Diesel - Conventional	Harvested Crude Oil	1.11
Diesel - Conventional	Primary Crude Oil	1.09
Otto Engine	Ethanol	1.07
Otto Engine	**Gasoline**	**1.00**
EV - Electricity	Nuclear (Enthalpic Potential)	1.00
EV - Electricity	Delivered Coal	1.00
EV - Electricity	Harvested Coal	0.96
EV - Electricity	Primary Coal	0.95
EV - Electricity	Soy Meal	0.89
EV - Electricity	Palm Kernal Cake	0.89
EV - Electricity	DDGS	0.89
EV - Electricity	Delivered Biomass	0.89
EV - Electricity	Canola Seed Cake	0.89
EV - Electricity	Uncollected Biomass	0.86
Horse - Animal Feed	*Metabolisable Energy (ME)*	N/A
EV - Electricity - 13% PV	Incident Solar	0.37

Table A2 - Summary of PtCt's EAT's using REVe instead of REVp

Summary of Primary to Carrier Technology's EAT's				(RpJ/Kg CO2e)	Units	(RpMJ/Year 2000 Euro)
Feedstock -> Carrier	**RpCROI**	**RpCHOI**	**Feedstock -> Carrier**	**RpNCP/CO2e**	**Feedstock -> Carrier**	**RpNCP/Reg. Emission**
Tree -> Ethanol	**8.8**	0.1	Biomass -> DME	-20	Nat. Gas -> Elec.	1100
Biomass -> Electricity	**7.3**	1.4	Soybean -> Biodiesel	1020	Soybean -> Biodiesel	1080
Biomass -> DME	**7.2**	1.4	Camelina -> Biodiesel	920	Camelina -> Biodiesel	980
Biomass -> FTD	**7.0**	1.2	Rapeseed -> Biodiesel	660	Biomass -> DME	920
Stover -> Ethanol	**6.5**	0.1	Palm Oil -> Biodiesel	580	Biomass -> Electricity	720
Shale -> Nat.gas	13	**6.4**	Jatropha -> Biodiesel	490	Rapeseed -> Biodiesel	710
Conv. -> Diesel	7.3	**5.8**	Tree -> Ethanol	400	Palm Oil -> Biodiesel	620
Conv. -> Nat. Gas	13	**5.8**	Biomass -> Electricity	270	Jatropha -> Biodiesel	520
F. Residue -> Ethanol	**5.3**	0.1	Switchgrass ->Ethanol	130	Switchgrass ->Ethanol	460
Switchgrass ->Ethanol	**5.3**	0.1	Stover -> Ethanol	120	Shale -> Nat.gas	430
Sugar Cane -> Ethanol	**5.4**	0.1	Biomass -> FTD	60	Conv. -> Nat. Gas	400
Conv. -> Gasoline	5.6	**4.4**	Nat. Gas -> Elec.	40	Conv. -> Gasoline	390
Palm Oil -> Biodiesel	**4.0**	0.1	F. Residue -> Ethanol	30	Tree -> Ethanol	390
Camelina -> Biodiesel	**3.8**	0.1	Algae -> Biodiesel	30	Stover -> Ethanol	380
Soybean -> Biodiesel	**3.6**	0.1	Sugar Cane -> Ethanol	30	Conv. -> Diesel	360
Jatropha -> Biodiesel	**3.0**	0.1	Coal -> Electricity	20	Biomass -> FTD	360
Rapeseed -> Biodiesel	**2.9**	0.1	Shale -> Nat.gas	20	Tar Sands -> Diesel	260
Tar Sands -> Diesel	2.9	**2.6**	Conv. -> Nat. Gas	10	Algae -> Biodiesel	250
U.S. Corn -> Ethanol	**2.2**	0.1	U.S. Corn -> Ethanol	10	Tar Sands -> Gasoline	190
Tar Sands -> Gasoline	2.3	**2.0**	Conv. -> Diesel	10	F. Residue -> Ethanol	170
Algae -> Biodiesel	**1.9**	0.0	Conv. -> Gasoline	10	Coal -> Electricity	120
Nat. Gas -> Electricity	240	**1.6**	Tar Sands -> Diesel	10	U.S. Corn -> Ethanol	80
Coal -> Electricity	100	**1.4**	Coal -> FTD	10	Coal -> FTD	40
Coal -> FTD	36	**1.3**	Tar Sands -> Gasoline	10	Sugar Cane -> Ethanol	20

Electric Vehicles are an emerging, and technically feasible, option for local personal transportation. Despite this fact I do not think it should be considered an available technology. Today close to a billion internal combustion vehicles are on the road. Even if all new cars sold tomorrow were EV's change within our fleet would be slow with only half the IC automobiles being replaced in 10-15 years. (Hirsch, 2005) EV introduction is likely to be much slower than that, and I don't expect EV's to take a significant market share, without significant added costs or active policy, during the average half-life of the PtCt's studied within this thesis.

Appendix B - Indirect and Other REVp's

When completing an LCA of a PtCt there are many other inputs and outputs that exist in addition to the energy carriers studied so far in this thesis. Determining a Relative to personal transportation Energy Value for these can be more complex or impossible to accomplish directly. Still we can establish indirect REVp and RpMJ values associated with a given quantity of materials or potential energy carriers.

Material RpMJ/Unit Analysis with (Pimentel, 2005) Data

Materials have value aside from the energy used to harvest and process them which needs to be studied with the NCP/SC method described earlier. But for energy accounting purposes it may be beneficial to assign RpEnergy value to different quantities of material inputs based on the indirect energy requirements their utilization creates.

Some of these potential indirect energy carriers and their approximate RpEnergy values are shown below. For this rough analysis I assumed that one Energy Carrier was used as the sole input during the production process of each indirect energy carrier examined by (Pimentel, 2005). This is a simplified version of reality and simply an example of how REVp can be applied to indirect energy carriers.

Table B1 - RpEnergy content of various materials

Relative Energy to Personal Transport of Material and other Indirect Energy Carriers based on Pimintel 2005 Data						
Inputs	**Quantity**	**Unit**	**MJ/Unit (Pimintel)**	**Assumed Input**	**REVp**	**RpMJ/Unit**
Herbicides	1	kg	418.4	Diesel	1.25	**520**
Insecticides	1	kg	418.4	Diesel	1.25	**520**
Seeds	1	kg	103.6	Diesel	1.25	**130**
Machinery	1	kg	77.4	Diesel	1.25	**97**
Stainless Steel	1	kg	16.7	Diesel	1.25	**21**
Steel	1	kg	12.6	Diesel	1.25	**16**
Cement	1	kg	4.18	Diesel	1.25	**5**
Liquid Fuel Transport	1	kg-mile	0.004	Diesel	1.25	**0.005**
Corn Transport	1	kg-mile	0.003	Diesel	1.25	**0.004**
Nitrogen	1	kg	66.9	Delivered Nat. Gas	0.92	**62**
Phosphorus	1	kg	17.4	Delivered Nat. Gas	0.92	**16**
Potassium	1	kg	13.6	Delivered Nat. Gas	0.92	**13**
Lime	1	kg	1.2	Delivered Nat. Gas	0.92	**1**
BioRefining Effluent	1	kg-BOD	14.4	Electricity	0.81	**12**
BioRefining Water	1	kg	0.009	Electricity	0.81	**0.008**
Irrigation	1	kg	0.002	Electricity	0.81	**0.001**

Industrial and Waste Heat

Many industrial processes produce waste heat. Hot water or Steam has no real value as a transportation fuel but it does have an indirect value as a transportation fuel. At the most basic level if Steam is produced for an industrial process using a boiler the steam should be ignored and the boundary drawn to include the energy carrier inputs to the boiler to whom a direct REVp value can be applied.

A combined heat and power PtCt produces both heat and electricity. The electricity is put into the grid while the hot water, or steam, is generally distributed within a network of pipes for district heating or used for an industrial process. This combination, which takes advantage of waste heat, can be a very thermodynamically efficient. However, to produce useable mid-grade heat the turbine must be run in a back-pressure mode which reduces the electricity production from the PtCt.

Using data from (Taylor, 2012) who wrote a master's thesis on a backpressure combined heat and power plant - At an outlet pressure of .7 Bar and Steam temperature of 120 C every Ton of Steam output reduces electricity production by 16.7 MJ. Multiplying this value by Electricity REVp = .81 we find that every one ton of 120C Steam requires 13.5 RpMJ of input for production in a Combined Heat and Power plant. If a district hot water distribution network exists this upgraded hot water can be distributed to replace residential hot water offsetting natural gas or electric heating.

Table B2 - Calculating the REVp of 120C (.7 Bar) Steam

Electricity and RpMJ Offset Per Ton of 120C Steam (.7 Bar)			
CHP with DHWS	MJ Electric	REVp	RpMJ
Reduced Electric Out	-17	0.81	-13
Electricity Saved	2250	0.81	1813
Total RpBenifit Electric Heater Offset			**1800**
or	MJ Gas		
Gas Saved	2531	0.92	2340
Total RpBenifit Gas Boiler Offset			**2325**

One Ton of 120C Steam at .7 Bar has an enthalpy of 2700 MJ. This means that the REVp of waste heat which can be upgraded and distributed in a district hot water heating system would be: Waste Heat REVp = .86 if natural gas boilers are offset, and Waste Heat REVp = .67 if electric heaters are offset.

If the electric car existed and REVe was used. Under the scenario where waste heat offset Electric heating it's REVp = 2.6. This means that a Joule of waste heat, via offset electricity, could produce 260% more transportation than a joule of gasoline. Today ~60% of all fossil fuel inputs to electricity producing PtCt's are lost as waste heat. The adoption of electric vehicles and district heating systems would make huge quantities of previously worthless energy 260% more valuable than gasoline.

It is important to recognize that Waste Heat only holds this value in the specific situation where a CHP plant is connected to a district hot water system which would face some regional RpNCP/Remaining Demand % restraints, if the opportunity existed at all.

REVp of Incident Solar Energy

The REVp of incident solar energy was calculated by assuming a photovoltaic cell with a conversion efficiency of 13% is used to convert the solar energy into electricity. GREET's 92% electric transmission efficiency leads to a Sun to Wall efficiency of .12. Multiplying this conversion efficiency by Electricity's REVp = .81 yields a Incident Solar Energy REVp = .1.

If the Electric Vehicle existed Incident Solar Energy REVe = .37. This means that the wide-spread adoption of the Electric Vehicle would make sunlight, the earth's most abundant energy source, 3.7 times more valuable to society from a personal transportation purposes.

Fertilizer, Manure, Solid Waste, Bio-Char, and Municipal Waste

Fertilizer today is primarily produced using Natural Gas. By determining the quantity of RpMJ worth of Natural Gas and other inputs that go into the production of 1 ton of fertilizer we could apply a RpMJ value to one ton of Fertilizers.

Manure can be used in the agricultural process to replace or offset synthetic fertilizers. Manure would have the same RpMJ value as the quantity of fertilizer that it can offset. Since manure also has an enthalpic value a REVp for a J of manure could also be calculated. Alternatively, Manure could be put into a digester and converted into methane to be used for transportation purposes.

Bio-Solids, or human feces, are also very energy rich. While generally unaccepted to be used as fertilizers for food they can be processed into safe food fertilizer substitutes. Like manure bio-solids can also be digested into methane creating a useable transportation fuel.

It would be interesting to run both these calculations and determine whether the indirect offset of fertilizer or the direct production of methane creates the highest value for manure. Whenever possible I would favor towards a direct conversion of an energy carrier into transportation energy over an indirect offset pathway but this is arguable.

Bio-Char is a co-product produced with methane during the gasification of biomass. This co-product was assigned no value earlier in this thesis but it may hold significant value since it is nutrient rich and a fertilizer substitute. Assigning an indirect energy value to char production would likely further increase the top scoring Biomass to DME PtCt which utilizes the gasification process.

Biomass to DME is truly a very exciting PtCt. In combination with conventional food production, agricultural waste can be collected and gasified. This avoids the methane emission into the atmosphere that would have been caused by natural decomposition and instead captures the bio-methane for society's use. The LCA WtW GHG emissions are actually negative for the unit of DME produced and burned due to the higher Global Warming Potential of methane. If the co-product, char, also holds energy value due to the natural nutrients which can offset synthetic fertilizer this PtCt looks like a real winner both from an energy carrier production and environmental perspective.

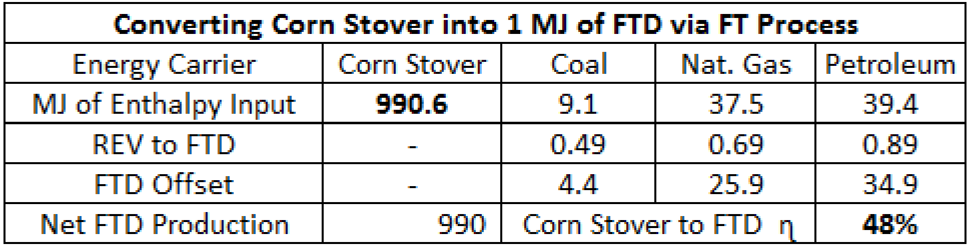
Municipal Waste, or trash, like biomass can be gasified and converted into either methane or DME. While the same energy carrier benefits quoted in my thesis for a biomass to DME PtCt likely apply to Municipal Waste on an enthalpic scale there are likely some differences between technologies when it comes to regulated emissions, and the co-product likely holds less nutritional value, and thus fertilizer offset value than Bio-Char.

Appendix C - Pimentel & GREET Biofuel Calculations

Biomass REVp.g Calculations

I analyzed GREET data, prior to making vehicle LCA adjustments, for converting both Corn Stover and Forrest Residue into FTD via the Fischer Tropsch process and DME via Gasification. Both fuels can be burned within a diesel engine with slightly different enthalpic efficiencies.

Table C1 - Converting Corn Stover into Fischer Tropsch Diesel



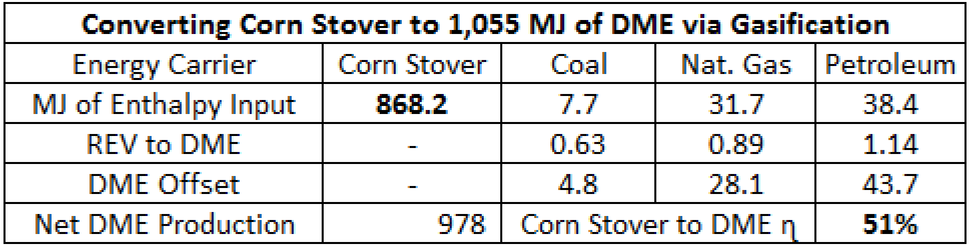
Converting Corn Stover into 1 MJ of FTD via FT Process				
Energy Carrier	Corn Stover	Coal	Nat. Gas	Petroleum
MJ of Enthalpy Input	**990.6**	9.1	37.5	39.4
REV to FTD	-	0.49	0.69	0.89
FTD Offset	-	4.4	25.9	34.9
Net FTD Production	990	Corn Stover to FTD η		**48%**

Example of REVp with FTD as reference calculation

Equation C1 - $\frac{.59\ Coal\ REVp.g}{1.2\ FTD\ REVp.g} = .49\ Coal\ REVp.d$

Equation C2 - $.484\ \frac{Stover\_in}{FTD\_out} * 1.2\ Gasoline\ REVp.g = .58\ Corn\ Stover\ REVp.g$

Table C2 - Converting Corn Stover into DME via Gasification



Converting Corn Stover to 1,055 MJ of DME via Gasification				
Energy Carrier	Corn Stover	Coal	Nat. Gas	Petroleum
MJ of Enthalpy Input	**868.2**	7.7	31.7	38.4
REV to DME	-	0.63	0.89	1.14
DME Offset	-	4.8	28.1	43.7
Net DME Production	978	Corn Stover to DME η		**51%**

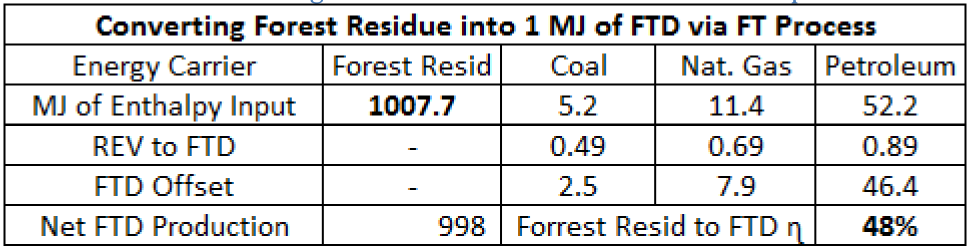
Equation C3 - $.509\frac{Stover\_in}{DME\_out} * 1.17\ DME\ REVp.g = .59\ Corn\ Stover\ REVp.g$

Converting Corn Stover into DME is more efficient than converting it into FTD. The Well to Wheel conversion is also better for the gasification despite DME having a lower REVp.g than FTD. I estimate that the transportation efficiency for the Corn Stover to DME chain is 96%. Uncollected Corn Stover's REVp.g = .57

REVp.g =.59 for Delivered Corn Stover is a bit of an abstract concept as it includes all the conversions, and transportation energy to deliver a unit of FTD to a fuel pump. This value can still be used to estimate the REVp.g of corn Stover that is delivered to a PtCt as process fuel. It incorrectly assesses transporting liquid instead of solid fuel but probably over a shorter distance. If Biomass is used internally within a PtCt like bagasse in a sugar cane to ethanol PtCt a value between delivered and uncollected should likely be calculated. With only a .02 variation between the two values any error should be nominal.

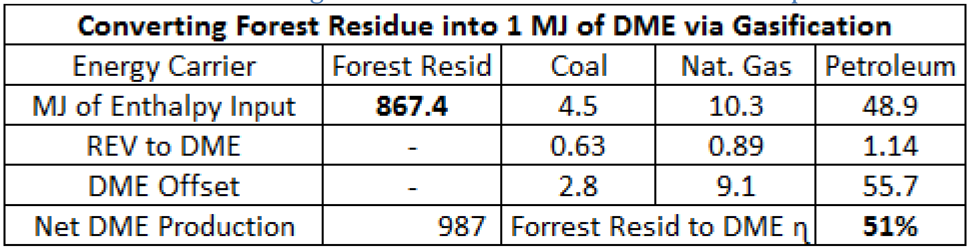
Similarly, gasifying Forest Residues and converting into DME is more efficient than the Fischer-Tropsch at producing transportation energy.

Table C3 - Converting Forest Residue into Fischer Tropsch Diesel



Converting Forest Residue into 1 MJ of FTD via FT Process				
Energy Carrier	Forest Resid	Coal	Nat. Gas	Petroleum
MJ of Enthalpy Input	**1007.7**	5.2	11.4	52.2
REV to FTD	-	0.49	0.69	0.89
FTD Offset	-	2.5	7.9	46.4
Net FTD Production	998	Forrest Resid to FTD η		**48%**

Table C4 - Converting Forest Residue into Fischer Tropsch Diesel



Converting Forest Residue into 1 MJ of DME via Gasification				
Energy Carrier	Forest Resid	Coal	Nat. Gas	Petroleum
MJ of Enthalpy Input	**867.4**	4.5	10.3	48.9
REV to DME	-	0.63	0.89	1.14
DME Offset	-	2.8	9.1	55.7
Net DME Production	987	Forrest Resid to DME η		**51%**

Equation C4 - $.514\frac{Stover\_in}{DME\_out} * 1.17\ DME\ REVp.g = .60\ Corn\ Stover\ REVp.g$

Both of these biomass's can be converted into transportation energy with very little variation between the two. In this thesis I assume that all biomass can be converted into transportation energy via gasification with the same REVp.g as Corn Stover.

Not considered is the fact that gasification produces a potentially valuable co-product in char which can be used as fertilizer. Inclusion of this co-product would increase the REVp of Biomass.

Ethanol Co-Product REVp value

To calculate the DDGS's REVp I reviewed multiple source all which resulted in a higher value for the Corn Ethanol co-product than was assigned by Pimentel. The primary co-product associated with the dry-milling production of Ethanol is Dry Distillers Grain with Solubles (DDGS). Pimentel states that DDG provides .64 the ME as soy-meal. This value disagrees with the following.

Table C5 - Comparing different studies relative DDGS value to Soy-meal

Comparing Studies	(Pimentel, 2005)	(Gibson, 2006)	(Adeola, 2012)	(GREET1_2011)
ME DDG/ME SoyMeal	0.64	-	0.79	-
ME DDGS/ME SoyMeal	-	0.86	1.02	.80

Pimentel analyzed DDG or Dry distiller grains without solubles which has a lower metabolisable energy content than DDGS. This is a strange assumption as dry milling typically leads to the co-production of DDGS not DDG. I assume that the energy content of DDGS should have been used. (Gibson 2006) points out that the ME of a co-product is highly dependent on the input grain, and the refinement method. He indicates that "new technology" produces DDGS with higher than traditional ME. His "new technology" DDGS/SoyMeal ratio = .96 approaching (Adeola, 2012) higher value which was published 6 years later and may be utilizing "new technology". In this thesis I used GREET's value of .80 for the ratio of ME in DDGS compared to Soymeal.

The biggest difference however comes from Pimentel's assignment of energy to the Soy-Meal which he compares the DDGS to. It is unclear how he assigns this value but the result is that the enthalpic value of DDGS is 8.5 times larger than the value that was assigned to it by Pimentel. The value I assign to the co-product using REVp is 5.5 times larger than the value assigned by Pimentel.

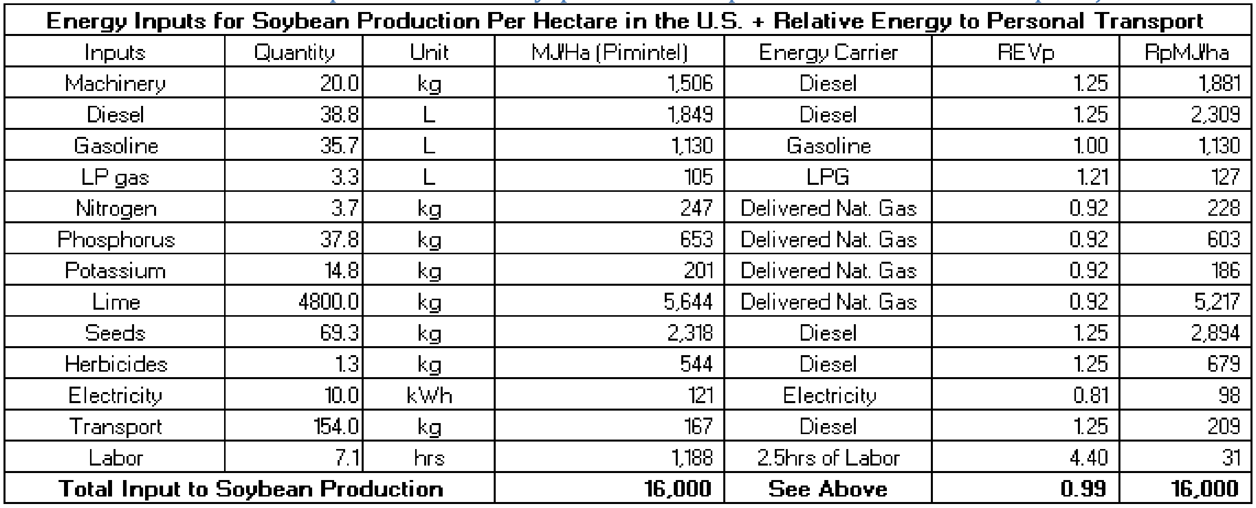
The REVp of four additional co-products were also calculated on an enthalpic basis using the following sources. Of these co-products only Palm Kernal as an animal feed had a higher REVp =.67 than gasified biomass. The higher Biomass REVp = .62 was used in this thesis for the other co-products.

Table C6 - Calculated REVp of different biofuel co-products with source

Vehicle - Fuel	Energy Carrier	REVp	Source
Horse - Animal Feed	Palm Kernal Cake	0.67	Ezieshi (2007)
Horse - Animal Feed	Corn Stover (enthalpic)	0.46/.62	Loy (2008)
Horse - Animal Feed	Canola Seed Cake	0.43/.62	Sell (1966)
Horse - Animal Feed	Camelina Seed Cake	0.43/.62	Assumed Same

Application of REVp to (Pimentel, 2005) Biodiesel data

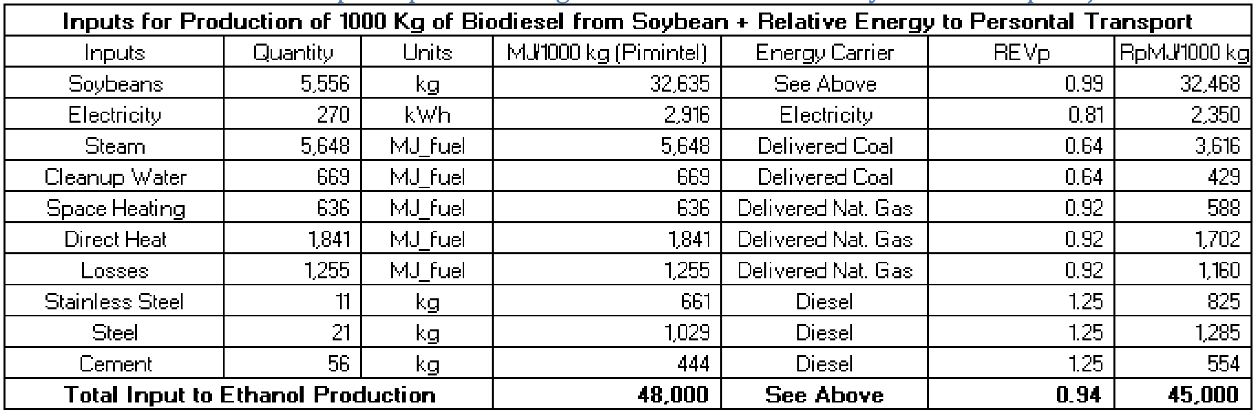
Table C7 - Pimentel inputs to U.S. Soy production per hectare with REVp adjustments



Energy Inputs for Soybean Production Per Hectare in the U.S. + Relative Energy to Personal Transport						
Inputs	Quantity	Unit	MJ/Ha (Pimintel)	Energy Carrier	REVp	RpMJ/ha
Machinery	20.0	kg	1,506	Diesel	1.25	1,881
Diesel	38.8	L	1,849	Diesel	1.25	2,309
Gasoline	35.7	L	1,130	Gasoline	1.00	1,130
LP gas	3.3	L	105	LPG	1.21	127
Nitrogen	3.7	kg	247	Delivered Nat. Gas	0.92	228
Phosphorus	37.8	kg	653	Delivered Nat. Gas	0.92	603
Potassium	14.8	kg	201	Delivered Nat. Gas	0.92	186
Lime	4800.0	kg	5,644	Delivered Nat. Gas	0.92	5,217
Seeds	69.3	kg	2,318	Diesel	1.25	2,894
Herbicides	1.3	kg	544	Diesel	1.25	679
Electricity	10.0	kWh	121	Electricity	0.81	98
Transport	154.0	kg	167	Diesel	1.25	209
Labor	7.1	hrs	1,188	2.5hrs of Labor	4.40	31
Total Input to Soybean Production			**16,000**	**See Above**	**0.99**	**16,000**

Like Ethanol Total RpInputs for soybean production are close to identical to Pimentel's results with offsetting variations seen in labor and diesel carrier inputs.

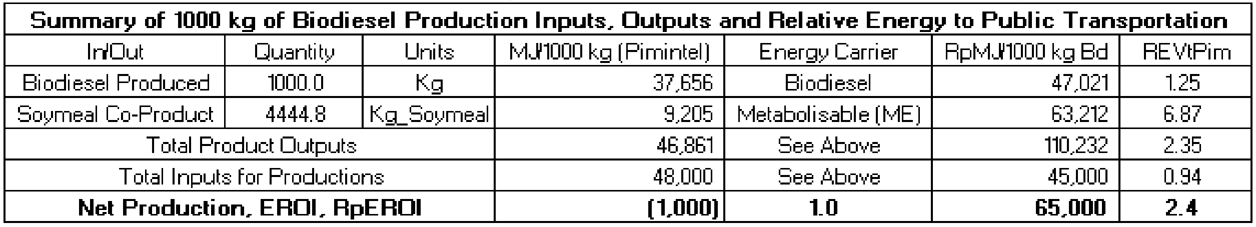
Table C8 - Pimentel inputs per 1000kg of BioD from U.S. Soy with REVp adjustments



Inputs for Production of 1000 Kg of Biodiesel from Soybean + Relative Energy to Personal Transport						
Inputs	Quantity	Units	MJ/1000 kg (Pimintel)	Energy Carrier	REVp	RpMJ/1000 kg
Soybeans	5,556	kg	32,635	See Above	0.99	32,468
Electricity	270	kWh	2,916	Electricity	0.81	2,350
Steam	5,648	MJ_fuel	5,648	Delivered Coal	0.64	3,616
Cleanup Water	669	MJ_fuel	669	Delivered Coal	0.64	429
Space Heating	636	MJ_fuel	636	Delivered Nat. Gas	0.92	588
Direct Heat	1,841	MJ_fuel	1,841	Delivered Nat. Gas	0.92	1,702
Losses	1,255	MJ_fuel	1,255	Delivered Nat. Gas	0.92	1,160
Stainless Steel	11	kg	661	Diesel	1.25	825
Steel	21	kg	1,029	Diesel	1.25	1,285
Cement	56	kg	444	Diesel	1.25	554
Total Input to Ethanol Production			**48,000**	**See Above**	**0.94**	**45,000**

During the refining stage the greatest variation is found in the Steam input.

Table C9 - Pimentel BioD from Soybean inputs and outputs with REVp adjustments



Summary of 1000 kg of Biodiesel Production Inputs, Outputs and Relative Energy to Public Transportation						
In/Out	Quantity	Units	MJ/1000 kg (Pimintel)	Energy Carrier	RpMJ/1000 kg Bd	REVtPim
Biodiesel Produced	1000.0	Kg	37,656	Biodiesel	47,021	1.25
Soymeal Co-Product	4444.8	Kg_Soymeal	9,205	Metabolisable (ME)	63,212	6.87
Total Product Outputs			46,861	See Above	110,232	2.35
Total Inputs for Productions			48,000	See Above	45,000	0.94
Net Production, EROI, RpEROI			**(1,000)**	**1.0**	**65,000**	**2.4**

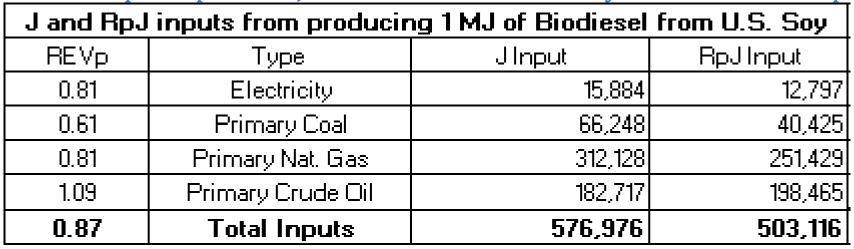
The primary co-product from Biodiesel Production is soy-meal which has a REVp = .81. Assuming that 80% of the soybean weight ends up as soy-meal[14] 1,000 kg of Biodiesel production results in 4,445 kg (63,212 RpMJ) of soy-meal. This is 6.9 times more value than was assigned to the soy-meal co-product by Pimentel.

I calculate that Biodiesel from U.S. soybean has a RpEROI = 2.5. Glycerin, Soap, and Alcohol are additional co-product from biodiesel production who's inclusion would further increase this RpEROI. Corn-Stover is an additional co-product from the U.S. corn to Ethanol process that would increase its

RpEROI vaule. These additional co-products have been ignored by both Pimentel and myself for comparability purposes.

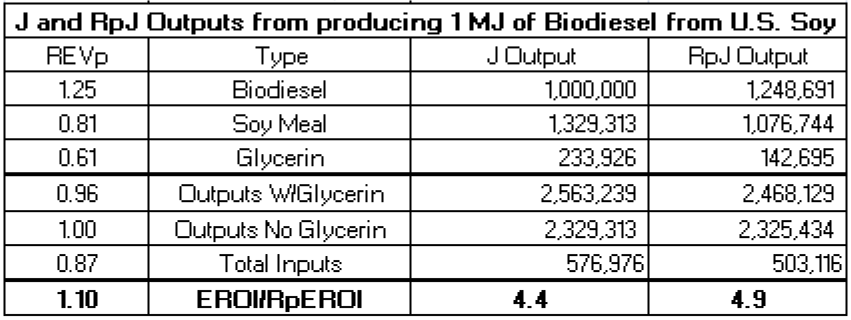
Application of REVp to (GREET1_2011) biofuel data

Table C10 - GREET Inputs per 1MJ of BioD from U.S. Soybean with REVp adjustments



J and RpJ inputs from producing 1 MJ of Biodiesel from U.S. Soy			
REVp	Type	J Input	RpJ Input
0.81	Electricity	15,884	12,797
0.61	Primary Coal	66,248	40,425
0.81	Primary Nat. Gas	312,128	251,429
1.09	Primary Crude Oil	182,717	198,465
0.87	**Total Inputs**	**576,976**	**503,116**

Table C11 - GREET BioD from U.S. Soybean inputs and outputs with REVp adjustments



J and RpJ Outputs from producing 1 MJ of Biodiesel from U.S. Soy			
REVp	Type	J Output	RpJ Output
1.25	Biodiesel	1,000,000	1,248,691
0.81	Soy Meal	1,329,313	1,076,744
0.61	Glycerin	233,926	142,695
0.96	Outputs W/Glycerin	2,563,239	2,468,129
1.00	Outputs No Glycerin	2,329,313	2,325,434
0.87	Total Inputs	576,976	503,116
1.10	**EROI/RpEROI**	**4.4**	**4.9**

GREET RpEROI values are roughly twice as large as the values calculated using Pimentel's data for both Ethanol from U.S. Corn and Biodiesel from U.S. Soybean.

The RpCHOI values for a biofuel PtCt take into consideration the solar energy that drives the agricultural process, except for the pass-through energy. Typically there is around 40-70 MJ of solar input per Mega-Joule of fuel produced making the Rpη almost identical to the RpCHOI values.

To calculate the RpCHOI values below I use the Incident Solar Energy REVp =.1. Appendix F To estimate the Incident Solar Energy input to a biofuel PtCt's I assumed a photosynthesis rate of 4%. I multiplied this value by the enthalpic quantity of biomass inputs calculated using GREET to estimate the total enthalpic solar inputs to the process.

Table C12 - Summary of EAT's for different GREET Ethanol feedstocks

Ethanol Feedstock	**Corn**	**Sugarcane**	**Switchgrass**	**Corn Stover**	**Farmed Tree**	**Forrest Resid.**
RpCROI	3.0	6.1	6.2	7.6	10	6.2
RpCHOI	0.3	0.2	0.2	0.2	0.2	0.2
RpCBOF	3.2	6.1	10	7.6	10	6.3
RpCBOO	14	8.6	18	13	12	10

Ethanol production from Brazilian sugarcane has twice the RpCROI as Ethanol from U.S. Corn. The Sugarcane PtCt has no animal feed output, but co-produces electricity while burning sugar-cane bagasse for process heat. RpCROI values are even higher for cellulosic ethanol PtCt's where less non-solar inputs are required for the agricultural process. Some of these PtCt's are more biomass intensive than others resulting in higher solar inputs and lower RpCHOI values.

Table C13 - Summary of EAT's for different GREET Biodiesel feedstocks

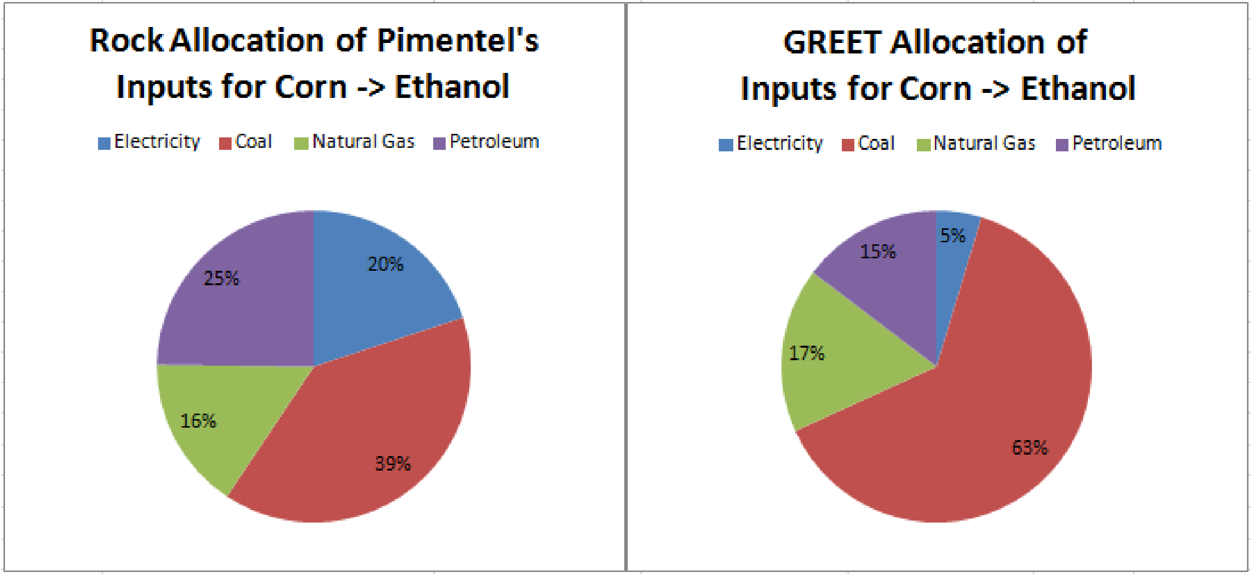
Biodiesel Feedstock	Soybean	Palm	Rapeseed	Jatropha	Camelina	Algae
RpCROI	4.9	5.3	3.6	3.9	4.4	4.1
RpCHOI	0.4	0.3	0.4	0.4	0.3	0.2
RpCBOF	5.0	5.4	3.7	4.1	4.4	6.1
RpCBOO	12	12	11	8.8	11	19

Despite palm tree's lower quality Palm Kernal co-product biodiesel produced from palm requires less carrier inputs and has a higher RpCROI than biodiesel produced from U.S soybean. Algae does not appear to represent a major step forward in regard to its RpCROI. Algae is however believed to produce significantly higher oil output per unit of land. Land and water utilization are two social costs that should be considered when analyzing a PtCt; especially within the biofuel sector.

Using GREET data to correct assumptions made about Pimentel Inputs

GREET's U.S. Corn Total Inputs REVp = .72 compared to my assumption based assessment of Pimentel's data leading to a Total Inputs REVp = .85. GREET's Total Inputs REVp can be used to adjust enthalpic Pimentel's Total Inputs into RpTotal simultaneously. This is believed to be more accurate than my original guesses as to which single energy carrier was used to produce each input.

Figure C1 - Comparing allocation of Ethanol carrier inputs: my assumptions vs. GREET



My estimate of Pimentel's fossil fuel inputs resulted in more transportation valuable petroleum and less lower value coal inputs which shifted both the REVp of the total inputs, and the RpEROI calculations downward. But adjusting Pimentel's Total Input REVp to match GREET Total Input REVp increases Pimentel's RpEROI from 1.4 to 1.7.

The same method was applied to Biodiesel Calculations where GREET's Total Input REVp = .87 was used to replace my estimate of Pimentel's Total Input REVp = .94. This correction increased Pimentel's RpEROI from 2.5 to 2.6.

Appendix D - GREET Fossil Fuel calculations

GREET Calculation Method

GREET1_2011 is a large excel database with a number of user inputs and other variables that can be altered in order to change the calculation results. In this thesis original assumptions except to adjust the model to examine different types of PtCt's and main primary energy sources.

(GREET_Results_A4:AR4) WtP data is reported on a primary energy basis and shows the primary fossil fuel inputs. For this thesis I assume primary petroleum has the same value as primary crude oil. Electricity and biomass values however were not directly reported and I calculated them using the GREET model.

Electricity inputs were calculated by switching between Coal and renewable derived electricity and multiplying the change in coal inputs by GREET's 31.4% conversion plus transmission efficiency for a coal to electric PtCt. Fossil fuel data was recorded with GREET set up with 100% renewable electricity production so electric inputs were not double counted. By zeroing different biomass values within GREET and calculating the change in total WtP energy I was also able to estimate the quantity of biomass inputs to different processes.

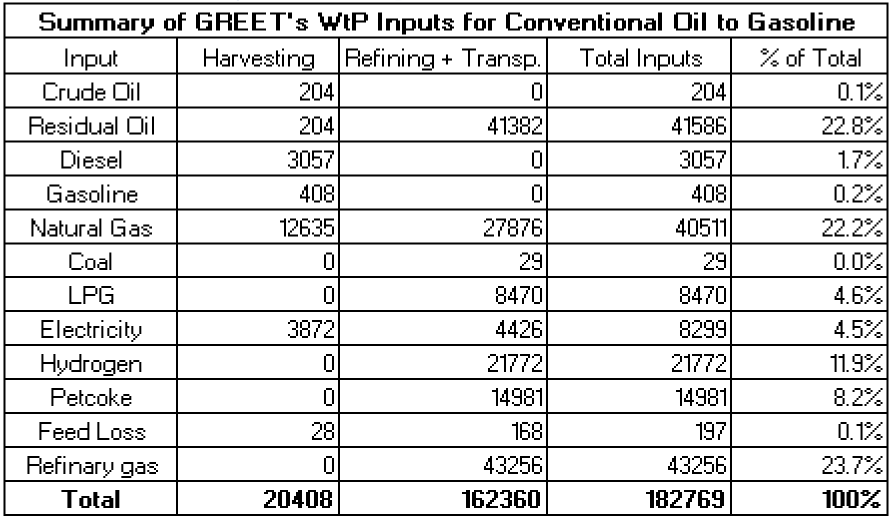
I was unable to locate transportation energy within the GREET database but it clearly seems to be accounted for with most fuel data. To estimate this value I used Excel's goal seek function setting the Rpɳ = 1 for the best perceived technology that was used to establish the REVp values by adjusting a transportation efficiency value. This indirect calculation should be accurate and yields results that were in line with my expectations.

GREET Coal data either already includes transportation energy within the refinery calculations ,or excludes the transportation energy of coal. I assume that the transportation energy was excluded due to an error but it is difficult to determine what is occurring. I used the same goal seek function to calculate an adjusted Primary Coal REVp = .61, slightly larger than previous calculated value of Primary Coal = .59. I believe this is the most accurate method for deriving a Primary Coal REVp but this value may be incorrect by up to 3%. The variation is minor but the largest unknown I am aware of from interpreting GREET data. I applied a transportation efficiency of 96%, same as biomass, to calculate Delivered Coal REVp = .64.

GREET Fossil Fuel Data

(GREET, Petroleum, B42:AW67) shows the allocation of carrier inputs to the petroleum production process. GREET Petroleum data is more detailed than for other PtCt's. To simplify it I assume: Residual Oil is the same as Crude Oil, Petcoke the same as Coal, Feed Losses the same as diesel, and Refinery gases the same as Natural Gas. I multiplied the simplified allocation below by the total WtP energy values (GREET_Results_A4:AR4) to produce the petroleum and tar sand charts in this thesis.

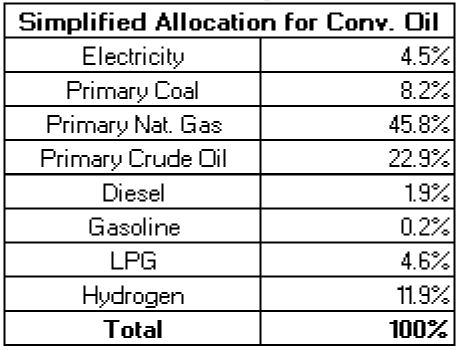
Table D1 - Summary of WtP inputs for Conventional Oil to Gasoline



Summary of GREET's WtP Inputs for Conventional Oil to Gasoline

Input	Harvesting	Refining + Transp.	Total Inputs	% of Total
Crude Oil	204	0	204	0.1%
Residual Oil	204	41382	41586	22.8%
Diesel	3057	0	3057	1.7%
Gasoline	408	0	408	0.2%
Natural Gas	12635	27876	40511	22.2%
Coal	0	29	29	0.0%
LPG	0	8470	8470	4.6%
Electricity	3872	4426	8299	4.5%
Hydrogen	0	21772	21772	11.9%
Petcoke	0	14981	14981	8.2%
Feed Loss	28	168	197	0.1%
Refinary gas	0	43256	43256	23.7%
Total	**20408**	**162360**	**182769**	**100%**

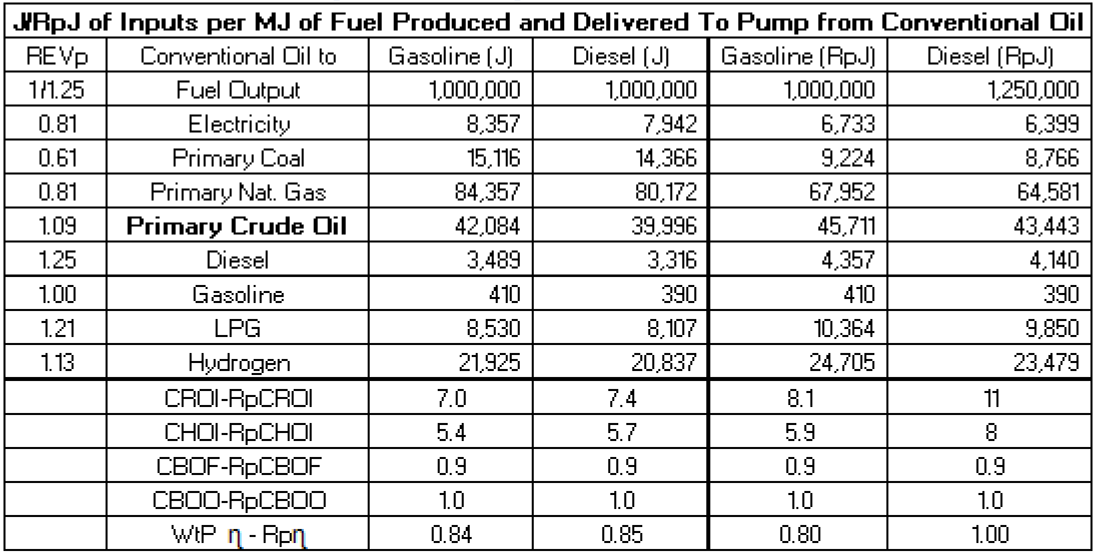
Table D2 - Simplified allocation of inputs for Conventional Oil PtCt's



Simplified Allocation for Conv. Oil	
Electricity	4.5%
Primary Coal	8.2%
Primary Nat. Gas	45.8%
Primary Crude Oil	22.9%
Diesel	1.9%
Gasoline	0.2%
LPG	4.6%
Hydrogen	11.9%
Total	**100%**

The added detail for petroleum was helpful since Diesel and Gasoline inputs would have otherwise been lumped in with petroleum, the main primary energy, and excluded from CROI and NCP calculations. This would have created a 2.1% error for conventional oil production and is likely much smaller for PtCt's which don't have Crude oil as the main primary energy source.

Table D3 - Inputs and outputs for Conventional Oil PtCt



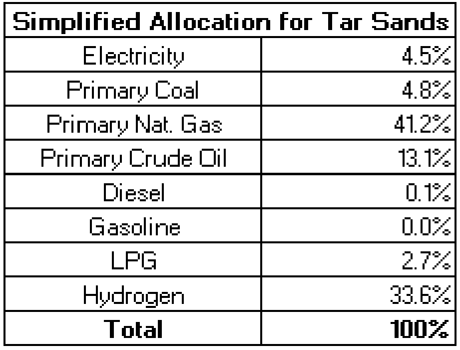
J/RpJ of Inputs per MJ of Fuel Produced and Delivered To Pump from Conventional Oil

REVp	Conventional Oil to	Gasoline (J)	Diesel (J)	Gasoline (RpJ)	Diesel (RpJ)
1/1.25	Fuel Output	1,000,000	1,000,000	1,000,000	1,250,000
0.81	Electricity	8,357	7,942	6,733	6,399
0.61	Primary Coal	15,116	14,366	9,224	8,766
0.81	Primary Nat. Gas	84,357	80,172	67,952	64,581
1.09	**Primary Crude Oil**	42,084	39,996	45,711	43,443
1.25	Diesel	3,489	3,316	4,357	4,140
1.00	Gasoline	410	390	410	390
1.21	LPG	8,530	8,107	10,364	9,850
1.13	Hydrogen	21,925	20,837	24,705	23,479
	CROI-RpCROI	7.0	7.4	8.1	11
	CHOI-RpCHOI	5.4	5.7	5.9	8
	CBOF-RpCBOF	0.9	0.9	0.9	0.9
	CBOO-RpCBOO	1.0	1.0	1.0	1.0
	WtP η - Rpη	0.84	0.85	0.80	1.00

Note: The main primary energy has been bolded in these charts for identification purposes.

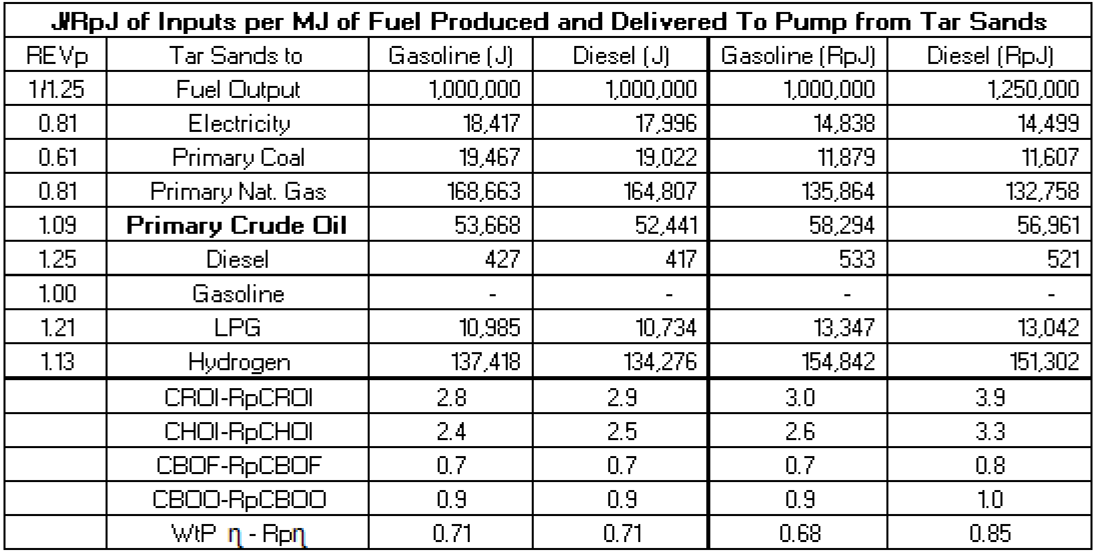
Diesel production performs better than energy than gasoline according to all the listed EAT's. CBOF values will always be less than one for a PtCt that uses a fossil fuel as the main primary energy source. For this analysis hydrogen has been grouped with the fossil fuels. It could be produced from a greater enthalpic quantity of natural. gas, or electricity which could come from non fossil fuel sources.

Table D4 - Simplified allocation of inputs for Tar Sand PtCt's



Simplified Allocation for Tar Sands	
Electricity	4.5%
Primary Coal	4.8%
Primary Nat. Gas	41.2%
Primary Crude Oil	13.1%
Diesel	0.1%
Gasoline	0.0%
LPG	2.7%
Hydrogen	33.6%
Total	**100%**

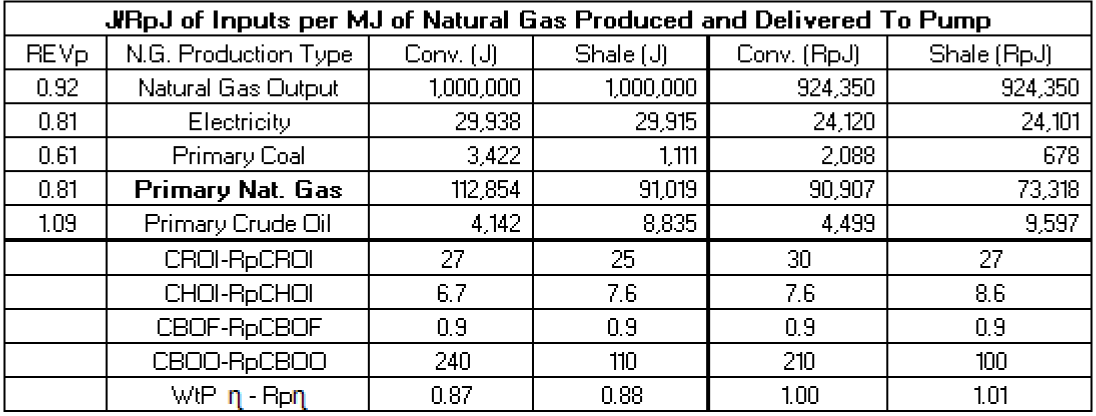
Table D5 - Inputs and outputs for Tar Sand PtCt



J/RpJ of Inputs per MJ of Fuel Produced and Delivered To Pump from Tar Sands					
REVp	Tar Sands to	Gasoline (J)	Diesel (J)	Gasoline (RpJ)	Diesel (RpJ)
1/1.25	Fuel Output	1,000,000	1,000,000	1,000,000	1,250,000
0.81	Electricity	18,417	17,996	14,838	14,499
0.61	Primary Coal	19,467	19,022	11,879	11,607
0.81	Primary Nat. Gas	168,663	164,807	135,864	132,758
1.09	**Primary Crude Oil**	53,668	52,441	58,294	56,961
1.25	Diesel	427	417	533	521
1.00	Gasoline	-	-	-	-
1.21	LPG	10,985	10,734	13,347	13,042
1.13	Hydrogen	137,418	134,276	154,842	151,302
	CROI-RpCROI	2.8	2.9	3.0	3.9
	CHOI-RpCHOI	2.4	2.5	2.6	3.3
	CBOF-RpCBOF	0.7	0.7	0.7	0.8
	CBOO-RpCBOO	0.9	0.9	0.9	1.0
	WtP η - Rpη	0.71	0.71	0.68	0.85

Tar sands uses more natural gas and hydrogen for production leading to lower scores than conventional production for all the listed EAT's Diesel produced from Converting Tar sands into Diesel has a lower RpCROI than Biodiesel produced from U.S. soybeans who's RpCROI = 4.9.

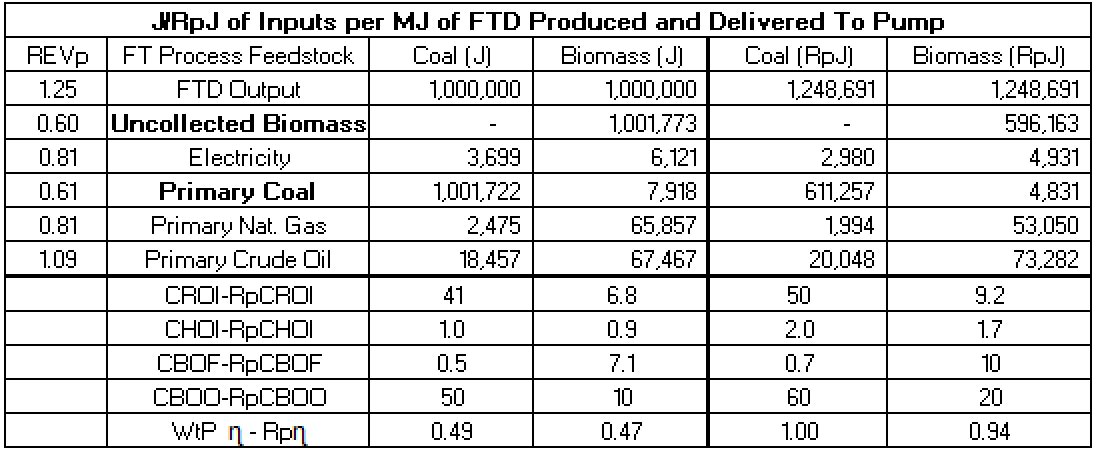
Table D6 - Inputs and outputs for Natural Gas PtCt



J/RpJ of Inputs per MJ of Natural Gas Produced and Delivered To Pump					
REVp	N.G. Production Type	Conv. (J)	Shale (J)	Conv. (RpJ)	Shale (RpJ)
0.92	Natural Gas Output	1,000,000	1,000,000	924,350	924,350
0.81	Electricity	29,938	29,915	24,120	24,101
0.61	Primary Coal	3,422	1,111	2,088	678
0.81	**Primary Nat. Gas**	112,854	91,019	90,907	73,318
1.09	Primary Crude Oil	4,142	8,835	4,499	9,597
	CROI-RpCROI	27	25	30	27
	CHOI-RpCHOI	6.7	7.6	7.6	8.6
	CBOF-RpCBOF	0.9	0.9	0.9	0.9
	CBOO-RpCBOO	240	110	210	100
	WtP η - Rpη	0.87	0.88	1.00	1.01

Unconventional shale Natural Gas production requires less Natural Gas and total Fossil Fuel inputs compared to conventional Natural Gas production and has higher RpCHOI and RpCBOF values. Conventional gas uses less non-Natural Gas inputs and has higher RpCROI and RpCBOO values.

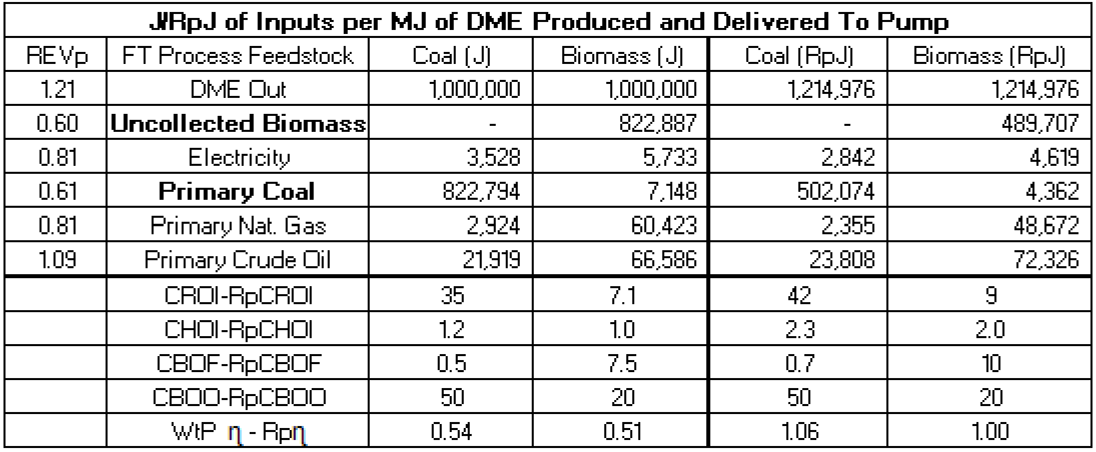
Table D7 - Inputs and outputs for Coal/Biomass to Fischer Tropsch Diesel PtCt's



J/RpJ of Inputs per MJ of FTD Produced and Delivered To Pump					
REVp	FT Process Feedstock	Coal (J)	Biomass (J)	Coal (RpJ)	Biomass (RpJ)
1.25	FTD Output	1,000,000	1,000,000	1,248,691	1,248,691
0.60	**Uncollected Biomass**	-	1,001,773	-	596,163
0.81	Electricity	3,699	6,121	2,980	4,931
0.61	**Primary Coal**	1,001,722	7,918	611,257	4,831
0.81	Primary Nat. Gas	2,475	65,857	1,994	53,050
1.09	Primary Crude Oil	18,457	67,467	20,048	73,282
	CROI-RpCROI	41	6.8	50	9.2
	CHOI-RpCHOI	1.0	0.9	2.0	1.7
	CBOF-RpCBOF	0.5	7.1	0.7	10
	CBOO-RpCBOO	50	10	60	20
	WtP η - Rpη	0.49	0.47	1.00	0.94

The Conversion of Coal or Biomass into FTD are very energy intensive processes and have CHOI values less than one. Due to the upgrading nature of converting low quality inputs into diesel the RpCHOI values are still greater than one. Both have high RpCROI values because most the process energy comes from the main primary energy source.

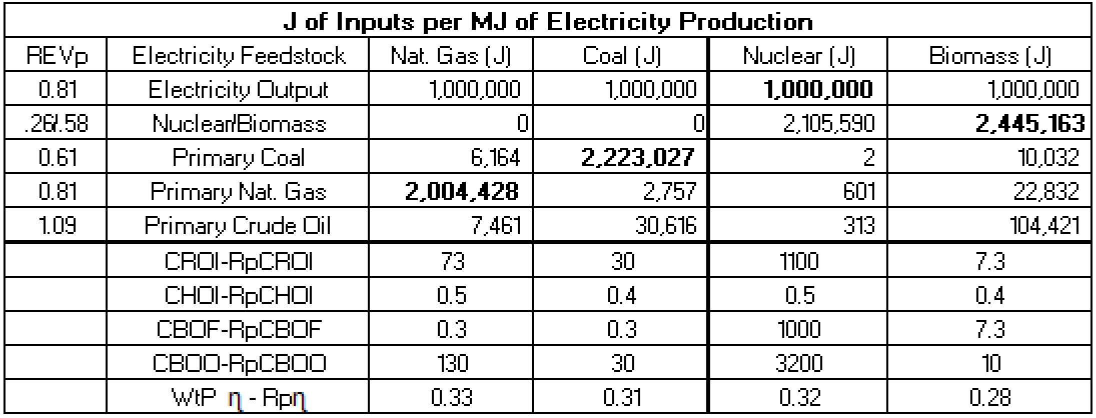
Table D8 - Inputs and outputs for Coal/Biomass to Dimethyl Ether PtCt's



J/RpJ of Inputs per MJ of DME Produced and Delivered To Pump					
REVp	FT Process Feedstock	Coal (J)	Biomass (J)	Coal (RpJ)	Biomass (RpJ)
1.21	DME Out	1,000,000	1,000,000	1,214,976	1,214,976
0.60	**Uncollected Biomass**	-	822,887	-	489,707
0.81	Electricity	3,528	5,733	2,842	4,619
0.61	**Primary Coal**	822,794	7,148	502,074	4,362
0.81	Primary Nat. Gas	2,924	60,423	2,355	48,672
1.09	Primary Crude Oil	21,919	66,586	23,808	72,326
	CROI-RpCROI	35	7.1	42	9
	CHOI-RpCHOI	1.2	1.0	2.3	2.0
	CBOF-RpCBOF	0.5	7.5	0.7	10
	CBOO-RpCBOO	50	20	50	20
	WtP η - Rpη	0.54	0.51	1.06	1.00

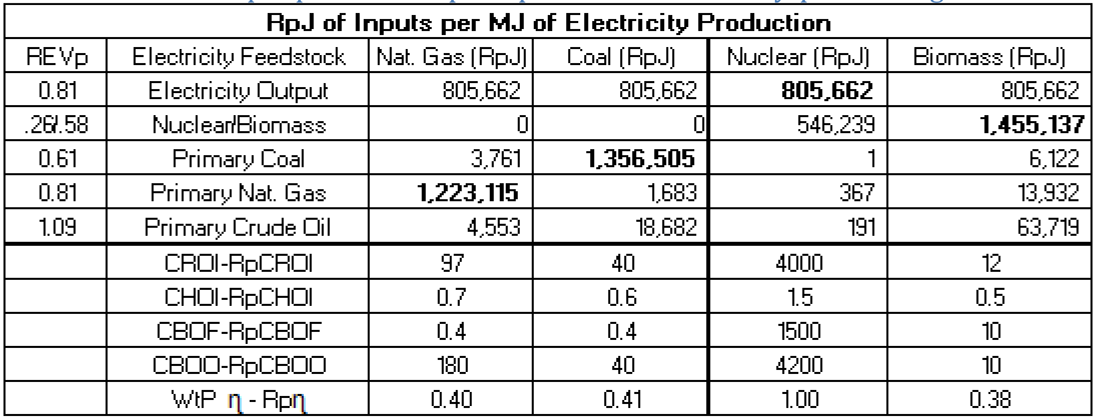
The production of DME via the gasification was the best available WtW technology studied for converting biomass into transportation energy. GREET also has data for converting coal into DME but these values were declared by the author as mainly space holders and not fully verified. If accurate and coal to DME technology is considered commercial technology we should revalue the Primary Coal REVp from .61 to .65. This need for revaluation can be identified by the Rpη which is greater than one.

Table D9 - Inputs and outputs for Electricity producing PtCt's



J of Inputs per MJ of Electricity Production					
REVp	Electricity Feedstock	Nat. Gas (J)	Coal (J)	Nuclear (J)	Biomass (J)
0.81	Electricity Output	1,000,000	1,000,000	**1,000,000**	1,000,000
.26/.58	Nuclear/Biomass	0	0	2,105,590	**2,445,163**
0.61	Primary Coal	6,164	**2,223,027**	2	10,032
0.81	Primary Nat. Gas	**2,004,428**	2,757	601	22,832
1.09	Primary Crude Oil	7,461	30,616	313	104,421
	CROI-RpCROI	73	30	1100	7.3
	CHOI-RpCHOI	0.5	0.4	0.5	0.4
	CBOF-RpCBOF	0.3	0.3	1000	7.3
	CBOO-RpCBOO	130	30	3200	10
	WtP η - Rpη	0.33	0.31	0.32	0.28

Table D10 - RpInputs and RpOutputs for Electricity producing PtCt's



RpJ of Inputs per MJ of Electricity Production					
REVp	Electricity Feedstock	Nat. Gas (RpJ)	Coal (RpJ)	Nuclear (RpJ)	Biomass (RpJ)
0.81	Electricity Output	805,662	805,662	**805,662**	805,662
.26/.58	Nuclear/Biomass	0	0	546,239	**1,455,137**
0.61	Primary Coal	3,761	**1,356,505**	1	6,122
0.81	Primary Nat. Gas	**1,223,115**	1,683	367	13,932
1.09	Primary Crude Oil	4,553	18,682	191	63,719
	CROI-RpCROI	97	40	4000	12
	CHOI-RpCHOI	0.7	0.6	1.5	0.5
	CBOF-RpCBOF	0.4	0.4	1500	10
	CBOO-RpCBOO	180	40	4200	10
	WtP η - Rpη	0.40	0.41	1.00	0.38

All types of electricity production have high RpCROI values since the main primary energy provides most of the process energy. However by reviewing the Rpη values which are smaller than one, except for nuclear, we know that the primary resource could have been converted into a greater quantity of personal transportation energy by pursuing a different PtCt. CHOI values less than indicate that more process energy is consumed than output is created from the pass-through energy.

Nuclear is a different type of energy and difficult to directly compare to the group of PtCt's examined within this thesis. It is examined here based on the quantity of enthalpy a nuclear reactor core can produce. According to GREET 3.105 MJ of Enthalpy produced in Nuclear reactor core is required to produce and deliver 1 MJ of electricity. By multiplying the 1 MJ of electric output by electricity's REVp = .81 and then dividing by the enthalpic input to the process I calculate that Nuclear Enthalpic Potential has a REVp = .26.

Table D11 - Comparing conventional to combined cycle Natural Gas turbine

J/RpJ of Inputs per MJ of Electricity Produced and Delivered To Wall by Technology					
REVp	Type of PtCt	Turbine (J)	CC Turbine (J)	Turbine (RpJ)	CC Turbine (RpJ)
0.81	Electricity Output	1,000,000	1,000,000	805,662	805,662
0.61	Primary Coal	8,128	3,918	4,960	2,391
0.81	**Primary Nat. Gas**	2,642,967	1,274,043	2,128,998	1,026,284
1.09	Primary Crude Oil	9,838	4,742	10,686	5,151
	CROI-RpCROI	60	120	50	110
	CHOI-RpCHOI	0.4	0.8	0.4	0.8
	CBOF-RpCBOF	0.3	0.4	0.3	0.4
	CBOO-RpCBOO	100	210	80	160
	WtP η - Rpη	0.27	0.44	0.27	0.44

The Combined-Cycle Gas Turbine is a better PtCt for utilizing primary Natural Gas than a Simple Gas Turbine scoring higher in every EAT category. It is important to recognize that EAT values in this thesis are specific to the exact PtCt defined by GREET and not applicable to all PtCt's of a similar nature. Natural gas values used within this thesis use GREET's pre-set technology mix of: 44% Combined Cycle, 36% Standard Gas Turbine, and 20% Boiler powered. They also assume a U.S. Natural Gas supply with 22.6% of production coming from shale sources.

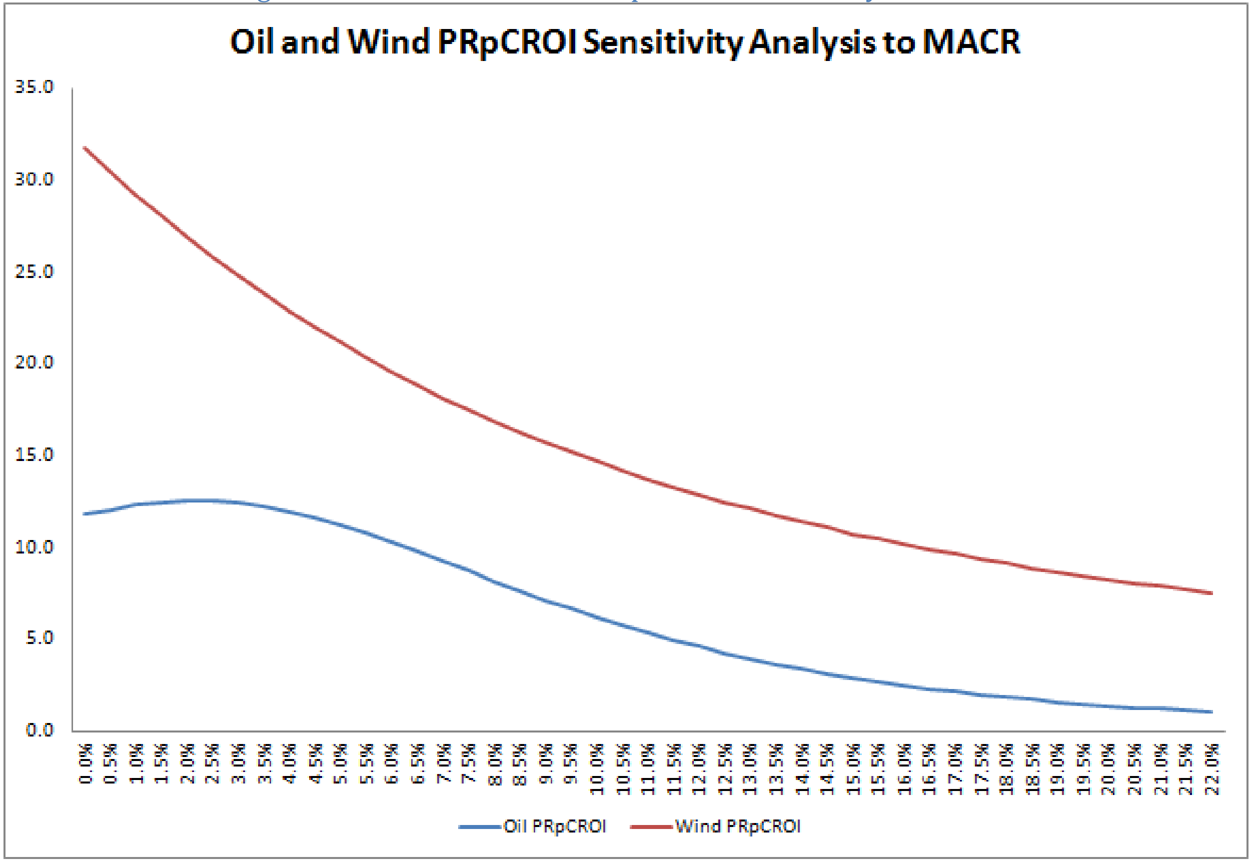
Appendix E- Potential MACR Values

When making Time Value of Energy calculations, the variable that adjusts the effect time has on an energy carriers value is the Minimum Attractive rate of Carrier Return (MACR). With econometrics the Minimum Attractive Rate of Return (MARR) is set by companies, and represents the minimum percentage rate of return a company expects from their investments. Over time the MARR for a company will go up or down normally following government established prime interest rates. When borrowing money is very expensive companies raise their MARR meaning that a project must have a very attractive rate of return to be executed. When interest rates are lower, and money is cheap, companies will accept projects with lower rates of return.

When applied to energy the MACR performs essentially the same function. This value represents the minimum percentage rate of energy carrier return on carrier investments that decision makers expect from a PtCt. When energy is cheap and plentiful a low MACR is justified allowing investments in slow but long lasting energy systems. When energy becomes expensive and we are experiencing shortages a high MACR focuses development on projects that deliver the most energy in the shortest amount of time. This variable should change over time with changing market conditions but it is important to recognize that doing so will alter the results of an energymetric study. When comparing PtCt's it is essential that all calculations were done using the same MACR.

A detailed study of many different PtCt's with accurate time data as well as an analysis of current market conditions would be needed to determine what the current MACR should be set to when using energymetrics to compare PtCt investments today. Below is a sensitivity analysis of the two PtCt's I estimated time data for which provides some insight into the impact of changing the MACR.

Figure E1 - Oil and Wind PRpCROI Sensitivity to MACR



The PRpCROI of the Daqing oil field first increases and then decreases with an increasing MACR due to the offsetting effects of long construction period, and lower instantaneous production EROI during the later part of the PtCt's life. Oil has the largest PRpCROI value when the MACR equals 2.5%. The PRpCROI for oil equals one, the PRpNCP equals zero, when the MACR is set to 22%. The RpICR for the studied oil PtCt is 22%.

At a 5% MACR the percentage difference between the two PtCt's PRpCROI values reaches a minimum with Wind's PRpCROI being 90% larger than Oil. At an 8% MACR the quantitative difference between the two PtCt's PRpCROI values stabilizes; decreasing less than .01 for every .5% increase in MACR. Between 10% and 11% MACR there is no change in the quantitative different between these two PtCt's PRpCROI values.

The RpICR for the studied 100 turbine Vestas wind farm is 118%. If we assume that electricity is over-valued by REVp =.81 and instead it should be half as large indicating that hydrogen produced from electricity could be synthesized into a liquid fuel with a 50% conversion efficiency The Vestas wind farm still always has a larger PRpCROI value than Daqing Oil field. With MACR = 0; Oil PRpCROI = 11.8 and Wind PRpCROI = 18.3. At MACR = 5%; Oil PRpCROI = 11.2 and Wind PRpCROI = 12.1 which is the minimum difference between the two values.

Appendix F - Other Tables

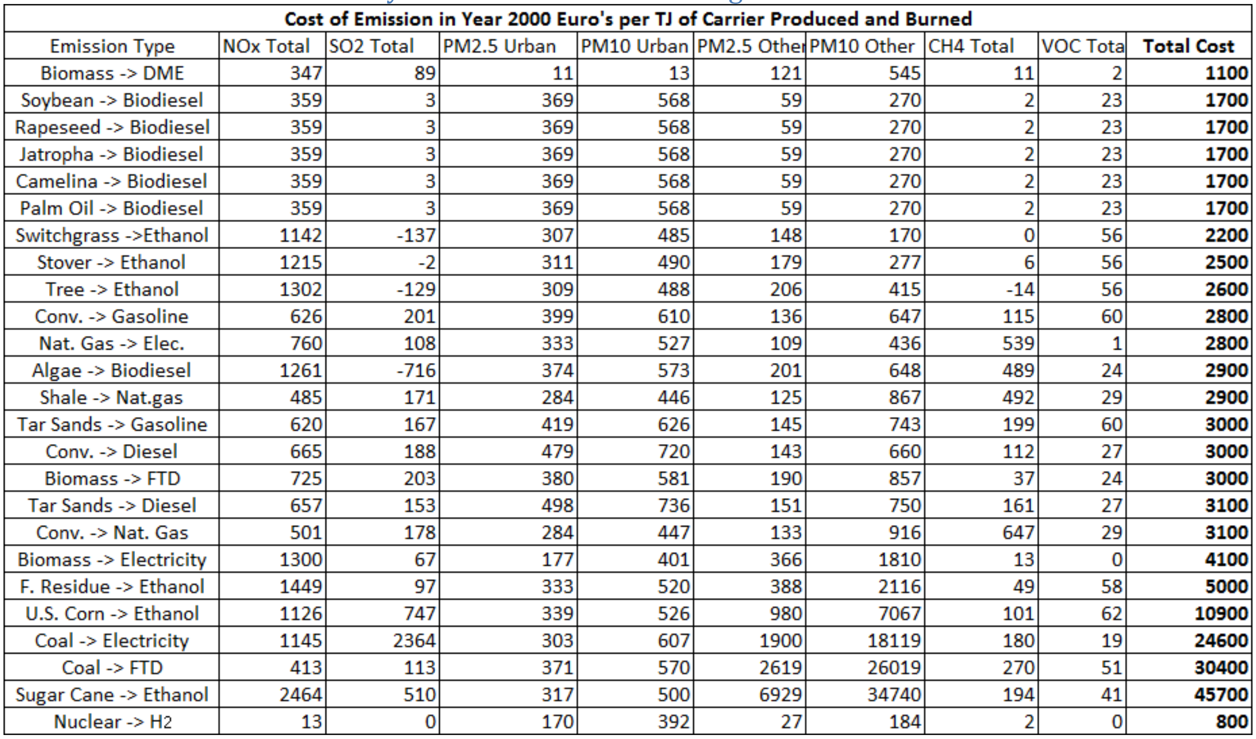
A summary of the REV's calculated without the LCA vehicle manufacturing energy adjustment is shown below. Included are the equivalent fuel economy values for the associated vehicle and fuel chains. These show the distance that can be traveled per quantity of gasoline equivalent enthalpy burned.

Table F1 - REVp prior to vehicle manufacturing LCA adjustment and iteration

Relative Energy Values to Personal Transportation without LCA adjustment				
Vehicle - Fuel Chain	**Energy Carrier**	**REVp.g**	**mpg.ge**	**L.ge/100Km**
Bicycle - Metabolic	Food	20.2	605.9	0.4
Rickshaw - Metabolic	Labor (1 hour)	4.04	302.9	0.8
Diesel Engine	Diesel/Kerosene	1.20	36.0	6.5
Diesel Engine	FTD/Biodiesel	1.20	36.0	6.5
Diesel Engine	SVO/WVO	1.20	36.0	6.5
Diesel Engine	DME/LPG	1.17	35.0	6.7
Horse - Metabolic	Metabolisable Energy (ME)	1.13	33.9	6.9
Otto Engine	Hydrogen	1.13	33.8	7.0
Otto Engine	Ethanol	1.07	32.1	7.3
Diesel - Conventional	Harvested Crude Oil	1.07	32.0	7.4
Diesel - Conventional	Primary Crude Oil	1.04	31.3	7.5
Otto Engine	**Gasoline**	**1.00**	**30.0**	**7.8**
Otto Engine - U.S. Mix	Delivered Nat. Gas	0.92	27.7	8.5
Otto Engine - U.S. Mix	Harvested Nat. Gas	0.86	25.9	9.1
Otto Engine - U.S. Mix	Primary Natural Gas	0.81	24.2	9.7
Otto - H2 - Electrolysis	Electricity	0.81	24.2	9.7
Horse - Metabolic	Soy Meal	0.77	23.1	10.2
Diesel - DME - Gasify	Transported Biomass	0.59	17.8	13.2
Diesel - FTD - FT	Delivered Coal	0.59	17.7	13.3
Diesel - DME - Gasify	Uncollected Biomass	0.57	17.1	13.7
Diesel - FTD - FT	Harvested Coal	0.55	16.5	14.3
Diesel - FTD - FT	Primary Coal	0.55	16.4	14.4

Below is a summary of the Total Costs in year 2000 Euro's created by each studied PtCt calculated by applying (IMPACT, 2007) costs for France to the (GREET1_2011) regulated emissions data.

Table F2 - Summary of economic cost of regulated emissions for PtCt's



Cost of Emission in Year 2000 Euro's per TJ of Carrier Produced and Burned									
Emission Type	NOx Total	SO2 Total	PM2.5 Urban	PM10 Urban	PM2.5 Other	PM10 Other	CH4 Total	VOC Tota	**Total Cost**
Biomass -> DME	347	89	11	13	121	545	11	2	**1100**
Soybean -> Biodiesel	359	3	369	568	59	270	2	23	**1700**
Rapeseed -> Biodiesel	359	3	369	568	59	270	2	23	**1700**
Jatropha -> Biodiesel	359	3	369	568	59	270	2	23	**1700**
Camelina -> Biodiesel	359	3	369	568	59	270	2	23	**1700**
Palm Oil -> Biodiesel	359	3	369	568	59	270	2	23	**1700**
Switchgrass ->Ethanol	1142	-137	307	485	148	170	0	56	**2200**
Stover -> Ethanol	1215	-2	311	490	179	277	6	56	**2500**
Tree -> Ethanol	1302	-129	309	488	206	415	-14	56	**2600**
Conv. -> Gasoline	626	201	399	610	136	647	115	60	**2800**
Nat. Gas -> Elec.	760	108	333	527	109	436	539	1	**2800**
Algae -> Biodiesel	1261	-716	374	573	201	648	489	24	**2900**
Shale -> Nat.gas	485	171	284	446	125	867	492	29	**2900**
Tar Sands -> Gasoline	620	167	419	626	145	743	199	60	**3000**
Conv. -> Diesel	665	188	479	720	143	660	112	27	**3000**
Biomass -> FTD	725	203	380	581	190	857	37	24	**3000**
Tar Sands -> Diesel	657	153	498	736	151	750	161	27	**3100**
Conv. -> Nat. Gas	501	178	284	447	133	916	647	29	**3100**
Biomass -> Electricity	1300	67	177	401	366	1810	13	0	**4100**
F. Residue -> Ethanol	1449	97	333	520	388	2116	49	58	**5000**
U.S. Corn -> Ethanol	1126	747	339	526	980	7067	101	62	**10900**
Coal -> Electricity	1145	2364	303	607	1900	18119	180	19	**24600**
Coal -> FTD	413	113	371	570	2619	26019	270	51	**30400**
Sugar Cane -> Ethanol	2464	510	317	500	6929	34740	194	41	**45700**
Nuclear -> H2	13	0	170	392	27	184	2	0	**800**

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