An Integrated Approach To Measuring The Environmental, Economic And Social Impacts Of Investments In Climate Change Mitigation In Ecuador

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Abstract

This paper examines an integrated modeling approach to decision support services for climate change mitigation utilizing Threshold 21 (T21), a Systems Dynamic model developed by the Millennium Institute (Washington, D.C.) and other modeling methodologies. Utilizing a key conclusion of the *Stern Review on the Economics of Climate Change* – that is, an annual investment of 1% of world Gross Domestic Product (GDP) to mitigate the negative economic impacts of climate change – this paper summarizes the application of T21 to a country-wide analysis for the Republic of Ecuador (Ecuador). The analysis of Ecuador assumed an investment of 1% of GDP in energy efficiency and renewable energy technologies to measure the potential to stabilize carbon emissions from fossil fuel electric power generation. Based upon the conclusions of this analysis, the authors argue that while a 1% investment annual in GDP through 2025 would reduce GHG emissions in the electric power sector in the near term, it would not stabilize national emissions. Furthermore, avoided consumer electricity costs contributed significantly to poverty alleviation with projected cumulative avoided costs exceeding USD 4 billion. Jobs were added to the economy, and Ecuador was able to reduce consumption of refined fuels.

Keywords: energy policy, sustainability, integrated dynamic modeling

Introduction

On October 26, 2006 economist Sir Nicholas Stern, Head of the Government Economic Service and Adviser to the Government of the United Kingdom (U.K.), released the *Stern Review on the Economics of Climate Change* (Stern Review) (Stern, 2007) to the Prime Minister and the Chancellor of the Exchequer. The Stern Review offers a comprehensive survey of the evidence on the economic impacts of climate change resulting from the anthropogenic release of greenhouse gases into the Earth's atmosphere.

A key position advocated in the Review is a global investment equivalent to 1% of world GDP per annum to make a transition from carbon-based fossil fuels to a low-carbon economy. The Stern Review argues for the stabilization of emissions at 500 – 550 ppm CO_2 in order to avoid the environmental, economic and social impacts of catastrophic climate change (Stern, 2007; p. 13). The Review further cautions that the failure to invest in greenhouse gas mitigation represents a serious economic risk: "*Analyses that take into account the full ranges of both impacts and possible outcomes - that is, that employ the basic economics of risk - suggest that BAU [Business-as-Usual] climate change will reduce welfare by an amount equivalent to a reduction in consumption per head of between 5 and 20% . . . now and into the future. Taking account of the increasing scientific evidence of greater risks, of aversion to*

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the possibilities of catastrophe, and of a broader approach to the consequences than implied by narrow output measures, the appropriate estimate is likely to be in the upper part of this range" (Stern, 2007; p. 10).

Growing scientific evidence concurrent with and subsequent to the release of the Stern Review details an even greater potential risk of BAU climate change on environment, economy and society. Given that the Review's estimated cost of mitigation is small relative to the projected economic risks of unmitigated climate change, the authors argue that it is incumbent upon all nations to conduct risk assessments and evaluate appropriate mitigation policies consistent with the recommendation of the Stern Review: an annual investment of 1% of world GDP for the development of a low-carbon economy.

This paper provides a general overview of how an integrated approach utilizing Millennium Institute's (MI)[2] Minimum Country Model (MCM) (Pedercini et al., 2008) was applied to a country-wide analysis of the energy sector of the Republic of Ecuador. The intent of the country-wide analysis was to demonstrate the efficacy of utilizing an integrated approach to modeling utilizing MCM could provide useful decision support services for climate change mitigation utilizing "*a broader approach to the consequences than implied by narrow output measures*." (Stern, 2007; p10)
The analysis focused on investments in electricity subsector to project reductions in carbon emissions from fossil fuel power generation. Outcomes across spheres of the model – environment, society and economy – were projected through 2025. Ecuador was selected for analysis due to research conducted by SolarQuest® (Chelsea, VT) in the Province of the Galapagos under agreement with e8 Network for Expertise on the Global Environment (e8), Fideicomiso Mercantil San Cristobal (San Cristobal Wind Project Commercial Trust), and agencies of the United Nations and Ecuador. SolarQuest® researched energy supply and demand models subsequent to planning a proposed Renewable Energy Application Laboratory (REAL) of the Galapagos Archipelago. The proposed REAL will provide technical assistance services in energy efficiency and renewable energy technologies for developing nations. MCM emerged as an integrated modeling software under consideration by SolarQuest® for core laboratory services.

While global climate change models exist which forecast key elements of environmental, economic and/or social impacts, few models apply an integrated systems approach equivalent to the capacity of Millennium Institute's Threshold 21 (T21) (Millennium Institute, 2005) and MCM to examine consequences across a broad spectrum of output measures. Moreover, the methodology utilized for data collection and the assessment of the output measures confirmed by MCM, a simplified version of T21, demonstrated the efficacy to accelerate climate mitigation deploying an education-based human capacity building mechanism, the primary mechanism examined for the proposed REAL.
Based on the preliminary outcomes of this analysis, the MCM model proved useful to understanding the key position advocated in the Stern Review and demonstrated its usefulness as a tool for inclusion in the technical services portfolio for the proposed REAL. The authors further concluded that national energy assessments aggregated into an integrated T21 or

[2] The Millennium Institute (MI) is a not-for-profit development research and service organization headquartered in Arlington, Virginia, USA. Founded in 1983 by Dr. Gerald O. Barney as follow up to the Global 2000 Report to the President, MI is committed to finding practical means to promote sustainable development. MI's mission is (1) to develop and provide advanced analytical tools for national and global development; and (2) to formulate values-related questions and analyses on the consequences of alternative development strategies. www.millennium-institute-org

MCM-based System Dynamics global energy model can provide participants of the United Nations Convention on Climate Change (UNCCC) and the Conference of Parties (COP) critical decision support services – in situ – to assess global climate change mitigation policies as they face the challenge of formulating a legally-binding agreement(s) to limit or reduce greenhouse gas emissions in advance of the expiration of the Kyoto Protocol in 2012.

Simulation Results

Baseline Scenario: Business As Usual

The baseline scenario assumes no changes in any of the current patterns or policies and projects behavior of these variables from 1990 to 2025. Results of the simulations show that greenhouse gas emissions will continue to rise well into the 21st century, driven by growing fossil fuel consumption. This consumption tracks increasing energy demand, which grow both as a result of population trends and continued growth in GDP. Conversely, projections indicate that improvements in technology will lower energy demand by increasing the efficiency of consumer appliances. Average energy efficiency was exogenously set to rise 60% by 2025, reaching the efficiency of today's new appliances.

Assuming the current trends continue in Ecuador, which includes the electricity imports are held steady at the 2007 level (6% of demand), greenhouse gas emissions will have increased to 35.6 million tons/yr by 2025, a 50% growth from 2007 (23.63 million tons/yr) levels (Figure 1).

The immediate cause of this rise is an increase in fossil fuel consumption to 472 trillion Btu from a 2007 value of 309.2 trillion Btu. This fossil fuel consumption occurs partly due to rise of total energy consumption from 424.6 to 676.6 trillion Btu (Figure 2), driven by GDP and population.

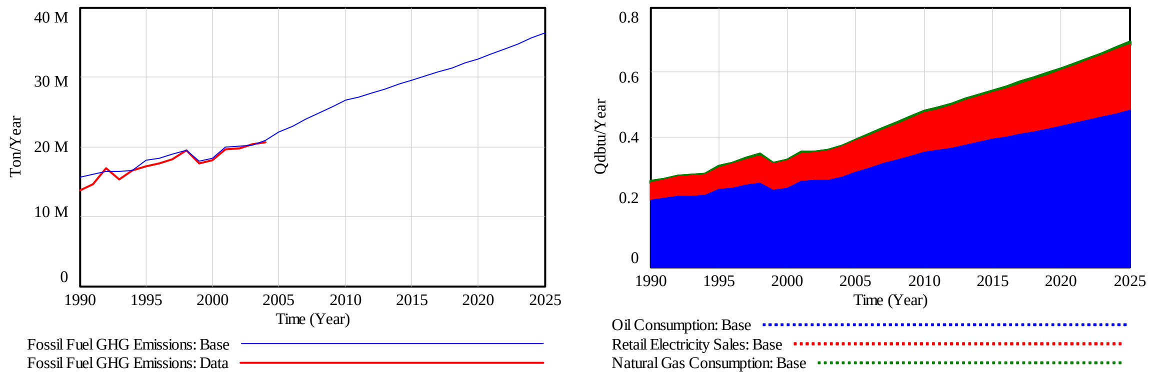


Figure 1 and 2: Baseline Scenario, projection of GHG emissions and energy consumption by source for the period 1990-2025.

Ecuador's population, projected to grow from 10 million in 1990 to 17 million in 2025, is party responsible for the rise in energy demand. Energy consumption, however, is rising at a much faster rate, driven more by the increase in real GDP. In fact, doubling of GDP, with respect to 1990, occurs near 2015, the same period when energy consumption doubles. Retail sales of electricity in the residential sector begin at 4 million Kwh in 2007 and grow to 7 million Kwh by 2025 (total electricity retail sales are shown in Figure 3). Electricity sales are growing at a faster rate than overall energy demand, reflective of a disproportional increase in the demand for residential electricity as population and income grow. Hydroelectric generation shows minimal potential to increase in Ecuador (CNCE and Cenance Corporation, 2005), meaning that increased demand for electricity must be met by augmenting fossil fuel capacity. As a consequence, in order to meet rising electric power demand, fossil fuel (thermal) installed capacity is projected to increase to 5500 MW. Correspondingly, the fraction of electricity generated by hydro decreases to 27% in 2025 from its 50% share in 2007 (Figure 4).

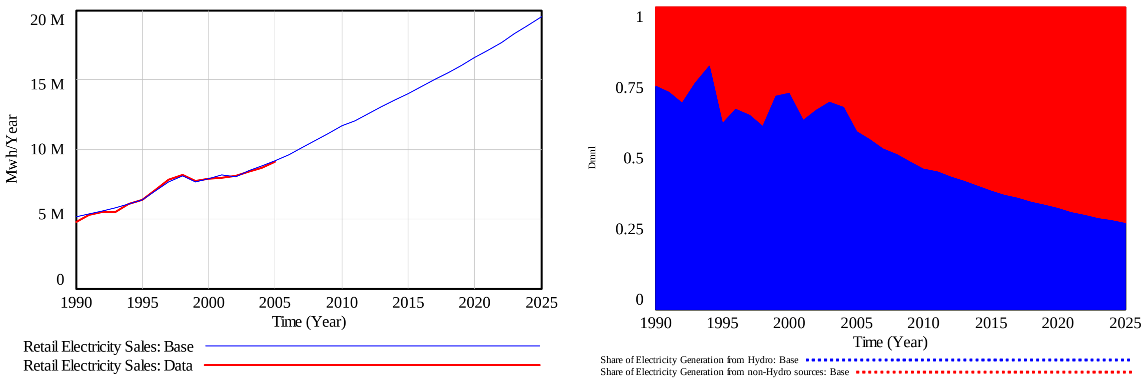


Figure 3 and 4: Baseline Scenario, projection of retail electricity sales and share of electricity generation by source (hydro and non hydro) for the period 1990-2025.

In 2006, total government expenditures (in nominal USD) totaled $8.57 billion, $30.67 million of which are spent in the energy sector. Again assuming no policy changes by 2025, government expenditures on energy will total $66.46 million. Total government investments in 2006 are $1.93 billion, compared with $5 billion of private investments. Per capita real disposable income in Ecuador remained nearly constant from 1990-2007 as the country recovered from the 1999 financial crisis. After 2007 per capita income rises, assuming the Ecuadorian currency remains strong. Ecuador's expenditures in health, education and roads rise with increasing government spending, producing 100% average adult literacy rates by 2021 (95% in 2010). Kilometers of functioning roads also oscillate normally, gradually increasing until 2025. Access to basic health care also reaches 100% by 2010.

Concluding, maintaining business as usual policies in Ecuador will cause gradual improvements in economic conditions met by growth in fossil fuel consumption and carbon emissions. Part of these emissions result from increases in residential electrical demand. The following scenarios analyze the impact of several policy initiatives within this sector and their impacts on greenhouse gas emissions.

Scenario 1: Subsidies for Electricity

Ecuador's newly elected president R. Correa has indicated that when the new Congress convenes in October 2007 he will advocate government subsidies to reduce the price of electricity. Lowering the cost for consumers is a political move designed to increase his draw with voters. This policy, although it is projected to increase the disposable income of the population, may conversely increase electricity demand and worsen greenhouse gas emissions. It may also generate a short-term rise in GDP as consumption increases, but in the long term GDP may decline due to the worsening of government accounts and higher vulnerability to energy markets.

In our model we designated a subsidy of $0.01 per KWh, paid for from government revenues. All other parameters were identical to the baseline scenario. The yearly cost of implementing this model beginning in 2007 would be $101.38 million, approximately 1.5% of total government revenues. A small reduction in expenditures of this magnitude produced no significant effects in government services and expenditures as measured by average literacy rate, access to basic health care or roads. There was also little impact on debt. It did, however, raise the per capita disposable income by 1.5%, a value of $15. Contrary to our expectations, a $0.01 per KWh decrease in prices did not substantively raise electric power demand or increase fossil fuel emissions. This scenario is therefore not depicted in the graphs of model outputs, as projections never substantially differed from the baseline. A $0.04 reduction in the energy price, however, did have a noticeable effect on emissions. This level of subsidy is unlikely based on current prices, which range from $0.08-0.10 (excluding taxes and final mark-ups) per KWh depending on the customer.

Correa's motive in introducing a subsidy is alleviating burdens on the poor, as well as increasing his popularity. Subsidies such as this one, which are tied to KWh consumption, will produce unequal benefits favouring the rich. Customers who consume less will receive substantially less than the projected $15 and the wealthy customers will receive far more.

Scenario 2: Investing 1% of GDP to Improve Consumer's Efficiency

The first policy recommendation simulated takes 1% of Ecuador's GDP and invests it in energy efficiency within only the electric sector. The cost associated for the installation of efficient electricity generation capacity is estimated at $4M per Mw based on SolarQuest's study in the Galapagos. We anticipate this adoption of efficient capital has the potential to reduce electricity demand even as population and affluence increase, as well as produce customer savings through avoided costs. These "avoided costs" are the amount of money saved on a household's electric bill through the reduction of their electric power demand, which are available for reinvestment elsewhere, increased consumption, or savings. Reducing the demand for electricity will correspondingly decrease the need for increasing fossil fuel capacity and consumption, thereby producing a net decrease in emissions.

MCM-Ecuador model calculated an initial (2007) investment level of $203 million, which reaches $450 million by 2025. This 1% investment in efficiency produces a corresponding 38% reduction in overall electricity demand relative to the baseline scenario. Annual avoided costs for the customers will reach a total of $600 million by 2025, around $40 annually per capita. This is three times larger than the personal savings produced by the subsidy in Scenario 1, an increase in per capita disposable income of 2.6% as opposed to 1.5% with subsidies. Annual household savings are near $60, a four times increase with only twice the investment in the first year (2007). Accumulated over the years of the simulation, the total avoided costs will be nearly $5 billion. According to the system of national accounts (SNA) adopted in which households can allocate disposable income into consumption, savings or investment, we assume that 33% of these avoided costs will be reinvested into efficiency technology, which amount to a $1.6 billion cumulative investment in efficiency from 2007-2025. This additional investment is projected to add another 7% to the reduction in electric power demand, yielding an overall 45% decrease in electricity demand in 2025.

Decreasing electric power demand via these investments in efficiency is able to produce a 1500 MW reduction in fossil fuel (thermal) electricity generation capacity compared to the baseline scenario (Figure 5). This indicates that through implementing this policy, Ecuador will greatly decrease the amount of electricity generation capacity they have to build in the upcoming years. Emissions of greenhouse gases, however, are not significantly reduced from 2007 levels. Rather, they increase at a fractionally smaller rate compared to the baseline scenario, reaching 32 million tons/yr, 10% less than in the base case (Figure 6). This is a change of 35% from 2007, a remarkable stabilization considering the projected economic and population growth. Further decreases do not seem to be possible at reasonable cost, because the efficiency investments simulated are targeted only at the fossil fuel contributions of the electrical sector, about 15% of the national fossil fuel consumption in 2007. True reductions in emissions will need to address emissions in the non-electric sector too.

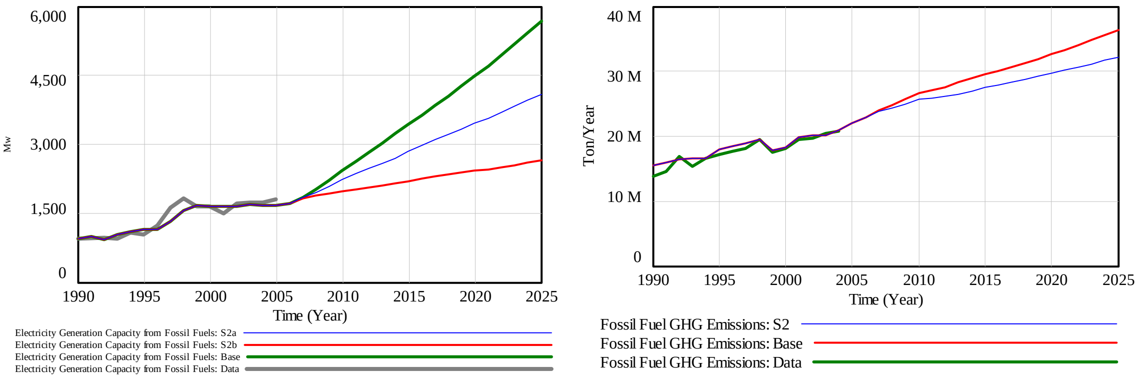


Figure 5 and 6: Scenario two, projection of thermal electricity generation capacity and GHG emissions for the period 1990-2025.

Scenario 3: Increasing Electricity Generated Using Renewable Energy Technology

The second policy scenario simulated adds a layer to the preceding policy analyzed. Keeping the 1% investments and 33% avoided cost investments as detailed above, this simulation adds the contribution of renewable energy at 2007 levels or 50%. Therefore, in order to meet increasing power demand, while the contribution of renewables declined over time in all other scenarios, renewable energy installed capacity will have to increase alongside fossil fuel capacity. This measure has little direct impact on population or energy demand; it is designed only to further reduce the fossil fuel consumption of the power sector and emissions.

Results of the simulation show that by 2025, 10 million Mwh of consumption will have to be met by renewable energy. Assuming that the amount provided by hydroelectricity cannot increase much from 7 million Mwh, an additional 3 million Mwh of equivalent (thermal) capacity will need to be installed, representing a 45% increase from the current levels. Projections indicate that these measures stabilize thermal electricity generation at 2007 levels. Furthermore, fossil fuel consumption in the power sector is projected to represent 20% of total fossil fuel consumption in 2025 (Figure 7), stabilizing emissions from the electrical sector. The continued increase in non-electric petroleum demand, however, causes carbon emissions to maintain their steady, incremental rise reaching 30.26 tons/yr. This is 27% higher than 2007 levels, although 17% less than projected in the base scenario. Even though reduced from both the baseline and the former scenario, emissions have still not reached a point of decline.

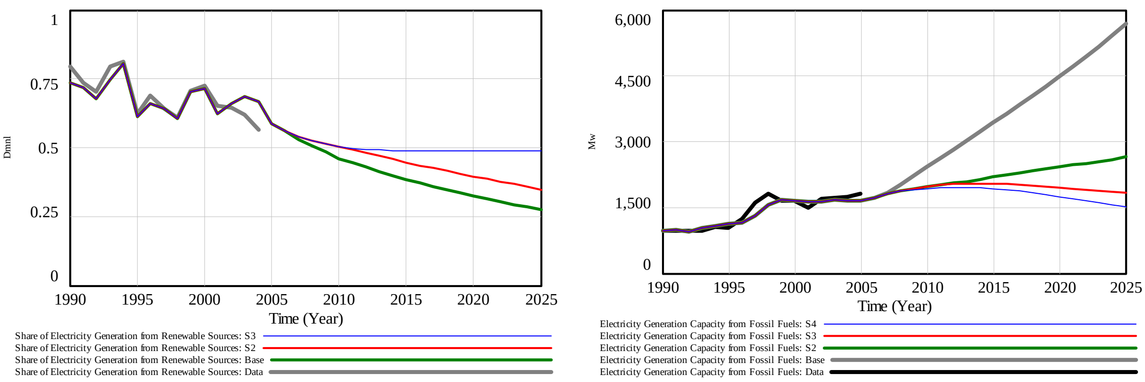
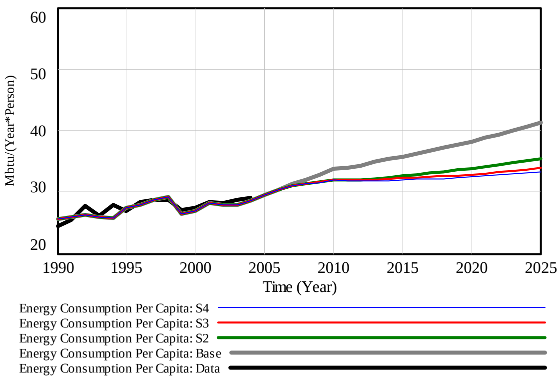


Figure 7 and 8: Scenario three, projection of the share of electricity generated from renewable sources and thermal electricity production capacity for the period 1990-2025.

Scenario 4: Increasing Electricity Imports

In a climate of rising oil prices, Ecuador's government generates a considerable portion of its revenues by exporting petroleum rather than using it to generate domestic energy (exploration of and recovery activities for oil accounts for more that 20% of total national revenues in the last 10 years according to the Central Bank of Ecuador - BCE) (BCE, 2007). The balance of their energy demand is then met by imports from Colombia and Peru. Assuming that oil prices remain high, Ecuador is likely to continue its policy of importing electricity and may even expand into the future. In such a way, the government would record higher revenues, obtained through increasing oil export, and could afford to import expensive electricity. This will reduce fossil fuel consumption and emissions in Ecuador, although it may not address the problem at a global scale.

In 2006 5.8% of Ecuador's energy electric power demand was met by imports. We projected that this level would linearly rise to 15% by 2025, provided that oil prices increase or remain stable. All other parameters were maintained as they were in Scenario 3. The simulation shows that this change further decreased fossil fuel consumption used in electricity generation and per capita electricity demand (32 million Btu/person/yr) relative to baseline levels (Figure 9). It also further reduced greenhouse gas emissions, although not enough to produce a significant decline. The observed emissions were only 2.5% less than Scenario 3 in 2025 (Figure 10).



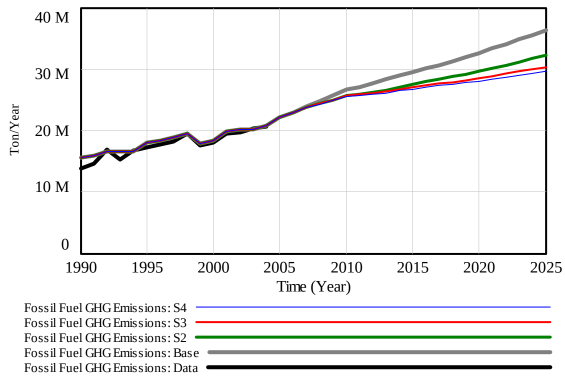


Figure 9 and 10: Scenario four, projection of per capita energy consumption and GHG emissions for the period 1990-2025.

Conclusions

While each of these scenarios provides its own benefits and disadvantages, the most effective policy recommendation to reduce energy consumption and curb emissions should take into account the context of each intervention with respect to the spheres that comprise society, economy and environment. Thus, the political reality that President Correa will seek popularity with voters must be taken into consideration as well as the environmental goal of reduced emissions and the economic targets set by the government. This study proposes an integrated approach to policy formulation and evaluation aimed at reducing GHG emissions that takes all of these factors into consideration and provides an analysis of the present, near future, and long-term benefits and challenges associated with each of the described interventions.

For the short term, President Correa should increase subsidies for electricity. As discussed, this will decrease energy prices and increase disposable income for the citizens of Ecuador. If this measure works as intended, it will provide President Correa with another term in office and more political stability for Ecuador. With respect to emissions, the danger of increasing subsidies for energy is that it will increase energy consumption, and thus increase fossil fuel emissions. However, results of the simulation show that the increase in emissions from this measure was negligible overall.

In order to address lowering emissions, the authors analyzed the implementation of investments into energy efficiency and renewable energy generation. These are increasing consumer energy efficiency through increased investment in technology, and decreasing production of electricity with fossil fuels by investing in renewable energy sources. In order to increase consumer energy efficiency, the authors simulated investing 1% of GDP in energy efficient technology, with resources provided by the Government. Other possible means of securing this investment include taxes, private investment, and attracting industry through incentives, such as modifying interest rates. Once secured, these funds would increase technology availability, thus increasing efficient use of electricity, which would decrease demand. This decreased demand for electricity then represents a near-future decrease in fossil fuel consumption and carbon emissions. Because technology to increase efficiency is available in the market, this measure could be adopted soon, and would have an impact on carbon emissions in the near future.

In order to effect a long-term reduction of emissions, the role of fossil fuel in the energy profile must be drastically reduced. To do so, the authors simulated the capping of the use of fossil fuels for energy production at 50%, which is its current level. The other half of energy production would come from increased investment in renewable energy production capacity. Because increasing capacity requires years of development of infrastructure, this policy is intended to take effect in 5-10 years. Possible sources of funding for this measure were not addressed in this research work.

The present study indicates that the combination of these comprehensive policy recommendations would stabilize carbon emissions generated by the electric sector around 2010 levels. It is worth noting that these measures, while they would reduce emissions, only stabilize them for the electricity sector and do not lead to an overall decrease in national emissions, for which a larger investment would be needed. This conclusion stems from the observation of the characteristics of non-electric sectors. In fact, when looking at transportation or industrial sectors, capital is characterized by a long lifetime and its replacement value is higher than appliances in the electric sector. In other words, a car lasts longer and costs much more than a refrigerator or TV. Investing in the electricity sector does not put a heavy load on the citizens, while acting in non-electric sectors requires a strong and active participation (investment) of households that are facing poverty issues. On the other hand, the overall results in reducing emissions may be more encouraging when investing also in non-electric sectors. Thus, this research work indicates that a greater investment than the Stern Report's suggested 1% of GDP will be necessary to achieve quick significant reductions in greenhouse gas emissions in Ecuador and that the representation of the context, through the creation of an integrated computer simulation model based on System Dynamics, such as MCM-Ecuador, can provide valuable insights to policy makers dealing with energy and climate policy formulation and evaluation.

Appendix A: MCM Model Attributes

The Minimum Country Model (MCM) (Pedercini et al., 2008) is a Systems Dynamic model primarily developed by Dott. Matteo Pedercini at the Millennium Institute on a Vensim software platform (Ventana Systems, Inc. Harvard, MA). MCM, a simplified version of MI's flagship model Threshold21 (Millennium Institute, 2005), is a quantitative tool for integrated, comprehensive national planning utilizing an integrated modeling approach to policy development. Its purpose is to support the overall process of national, regional and global strategic planning by facilitating information collection and organization. A key attribute to MCM is that the model architecture is based on T21, which is designed to function as a tool for decision support. It provides an analysis of the projected results of proposed alternative policies that address complex development issues across a vast array of dynamic variables by measuring impacts on environment, economy and society from single or multiple input(s) endogenous or exogenous to the model.

As mentioned above, MCM is a simplified version of the T21 model that has been developed over the last 24 years and applied to over 25 country models. MCM is constructed on a software platform which allows for the interaction of a complex network of feedback loops within a generic structure representative of the development mechanisms common to developing and industrialized countries. T21 and MCM architecture simulates the interaction of a large number of feedback loops. Spheres contain sectors and sectors contain modules that are constructed in to be in continuous interaction with other modules in the same sector, across sectors, and across spheres. The starting model construction of MCM contains 12 sectors divided among three spheres – society, economy and environment, as shown in Figure 1 below, and 12 modules. MCM-Ecuador is largely focused on energy, which is considered to be the fourth sphere represented and accounts for 20 modules, 8 of which belong to the energy sphere (Figure A2).

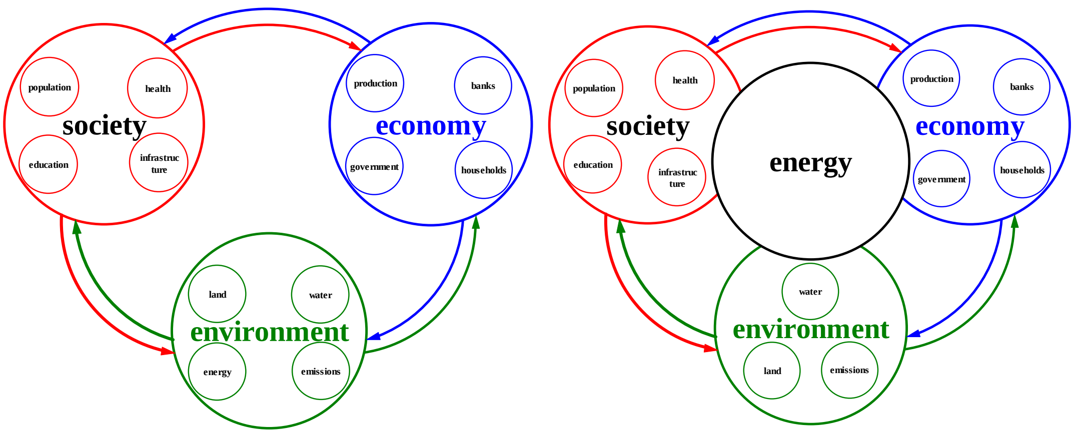


Figure A1 and A2: MCM Model Structure: Base MCM model construction consists of three dynamic spheres of influence consisting of a minimum of 12 sectors. MCM-Ecuador focuses on energy and accounts for four spheres and 20 modules.

MCM model customization to the Republic of Ecuador begins with the implementation of the so-called "Starting Framework." A Starting Framework is a customization of the generic MCM model structure consistent with conditions imposed by historical trends and current polices governing the dynamics of long-term issues governmental entities encounter in the development process.

The structure and content of individual modules is based upon accepted peer reviewed research within its designated field and targeted to a specific governing dynamics isolated by the research inquiry. By example, modules in the economy sphere are based upon the Social Accounting Matrix and Cobb-Douglas production functions. Module structure and content are then translated into stock and flow models and integrated with ad-hoc research and/or national policy determinants. The distinctive characteristic of T21 and MCM is the manner in which various determinants are linked together forming a complex link of feedback loops in which ad-hoc research and/or policies can then be analyzed and weighted as driving or limiting a country's development agenda.

The MCM starting framework is a medium sized systems-wide model. Given the size and the dynamic complexity of the model, its structure is organized into modules. These are a relatively small pieces of the MCM structure in which internal mechanisms can be understood in isolation from the rest of the model. This architecture allows for the customization of the starting framework for the development of country specific models.

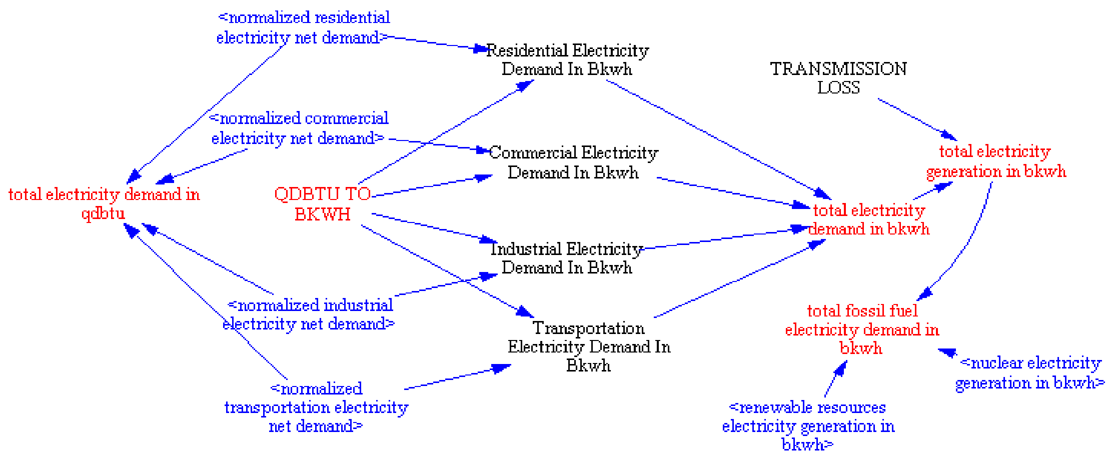


Figure A3: T21 Module Structure: T21 Modules are based on existing sectoral studies and represent the causal structure of the system analyzed.

Model logic within the MCM-Ecuador model is driven by national, or as in the case of global climate change, international policy objectives. MCM-Ecuador provides a platform for evaluating policy intervention strategies in order to move a nation's development agenda towards a desired outcome(s), and it serves as a monitoring tool to assess the impact of policy implementation over time in order to plan corrective actions.

A large number of models with unique attributes are available for either analysis of energy or integrated national planning. Two categories of energy-economy models are commonly accepted: i) market and behavior-oriented models and ii) bottom-up optimization models (Bunn and Larsen, 1997). Examples of the first category are POLES (LEPII-EPE, 2006) and PRIMES (NTNUA, 2005 and 2006). These models rely on adaptive expectations to simulate the dynamics of energy systems. They take into account the introduction of new technologies and attempt to represent their adoption process. Agent Based Modeling (ABM) is becoming increasingly used for this purpose.

Examples of the second category are MARKAL (MARKet ALlocation) (Fishbone et al., 1983; Loulou et al., 2004) and MESSAGE (Model of Energy Supply Systems Alternatives and their General Environmental Impacts) (Messner et al., 1996; Messner and Strubegger, 1995). These models operate under perfect foresight and optimize energy flows given demand and an objective function. NEMS (National Energy Modeling System) (EIA, 2003), proposed by the Energy Information Administration (EIA), and WEM (World Energy Model) (IEA, 2004), built by the International Energy Agency (IEA), belong to this category. These models are much more detailed than T21; however, given their focused use for energy-economy related projections, many feedbacks among society, economy, and the environment are not constructed into the model dynamics. In fact, even such crucial variables as economic growth, population dynamics, employment, technology, and prices are treated as exogenous inputs to the models. Therefore, the projections shown in the Annual Energy Outlook (EIA, 2007) and in the World Energy Outlook (IEA, 2006) are limited to energy and a few economic indicators, and they derive much of their output from the exogenous assumptions concerning society and the economy.

Computable Global Equilibrium (CGE) models, as in the case of PRIMES (NTNUA, 2005 and 2006) and MESSAGE (IIASA, 2002) represent the economy and energy through an iterative process based on econometrics and linear optimization (Loulou et al., 2004); consequently, they do not capture medium and long-term trends dynamically (Bunn and Larsen, 1997; Sterman, 1998). Rather, their projections (extended to 2030) are adjusted according to the latest data available on technology, investment, etc.

System Dynamics energy-related models include the IDEAS model (AES Corporation, 1993), an improved version of the FOSSIL models originally built by Roger Naill (Backus et al., 1979), the Energy Transition Model (Sterman, 1981), the Petroleum Life Cycle Model (Davidsen, Sterman and Richardson, 1988 and 1990), and the Feedback-Rich Energy Economy model (Fiddaman, 1997). However, these models do not encompass the interactions between energy, society, economy, and environment, which constitute one of the major innovations introduced by the Millennium Institute (for what concerns society, economy and environment) and the present study, which focuses on energy. In fact, FOSSIL, IDEAS and the Life Cycle models consider energy in isolation, Sterman's model includes only energy-economy interactions, and Fiddaman's FREE model exclusively focuses on economy-climate interactions. Nevertheless, both FOSSIL and IDEAS models made important contributions, notably their use by the Department of Energy for policy planning during 1980s.

T21, MCM and Vensim, the software used, combine these two categories into one holistic framework. They offer a complementary approach that allows for optimization flows while simultaneously simulating the interaction of a large number of feedback loops with the major factors embedded in the dynamic feedback of environment, economy and society.

Model Description

The core of the Economy sphere of MCM-Ecuador is represented by GDP, as one aggregated item, which is characterized by a Cobb-Douglas production function with inputs of labor and capital, but also technology, infrastructure (roads), energy prices, literacy (education) and life expectancy (health). A Social Accounting Matrix (SAM) (Drud et al., 1986) is used to elaborate the economic flows between the main actors in the economy: government, households, producers and banks. The government sector collects taxes based on economic activity and allocates expenditures by major category, which then impacts the delivery of public services, subject to budget balance constraints. Standard International Monetary Fund (IMF) (IMF, 2001) and Banco Central del Ecuador (BCE) (BCE, 2007) budget categories are employed, and key macro balances are incorporated into the model.

The Social sphere contains detailed population dynamics by sex and one-year age cohort, health and education programs. These sectors take into account, for example, the interactions of family planning, health care and adult literacy on fertility and life expectancy, which in turn determines population growth. Population determines the labor force, which shapes employment. Education, health levels, and other factors influence labor productivity. Employment and labor productivity affect the levels of production from a given capital stock. And these factors all affect the levels of saving for investment and consumption expenditures.

The Environment sphere tracks pollution impacts on the environment. It estimates the consumption of natural resources – both renewable and non-renewable – and can estimate the impact of the depletion of these resources on production and prices. Energy demand and supply are calculated endogenously. Particular attention is devoted to electricity generation, especially when fossil fuels need to be utilized. More specifically, the energy sources considered in the model are oil, natural gas and electricity (which in Ecuador is generated from oil, natural gas and renewable energy sources, mainly hydro) (CNCE and Cenance Corporation, 2005; CNE, 2006). Energy demand is calculated for oil, natural gas and electricity (Figure A4). The factors influencing demand are population, GDP, technology and energy prices. Energy consumption is assumed to equal demand given the large availability of oil and natural gas in Ecuador. Energy prices and costs are based on projections made using Threshold21 customized to the United States, which largely focus on the national and global energy sector and where world demand and supply are calculated to obtain global fossil fuel prices (Bassi et al., 2007). Energy technology addresses energy efficiency and it is calculated based on the field study carried out in the Galapagos by SolarQuest (Fonseca, 2007). Air Pollution includes emissions (CO_2, CH_4, N_2O, SO_X, and total greenhouse gasses). Pollution is based on fossil fuel consumption only.

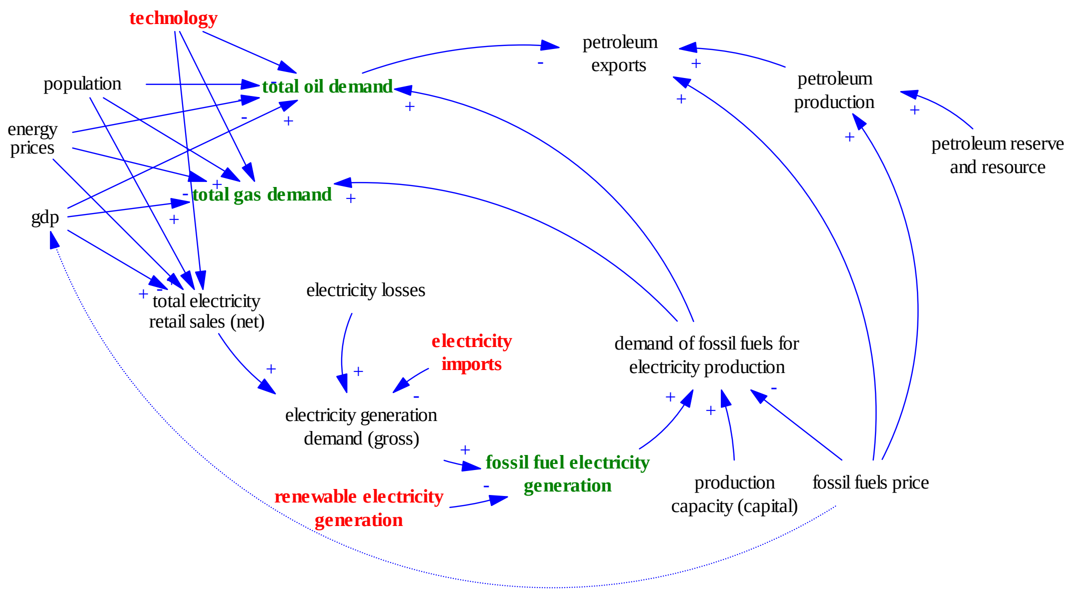


Figure A4: MCM-Ecuador, conceptual overview of the energy sector, highlighting main output variables (in green) as well as policies and assumption simulated (in red).

Under the leadership of the Millennium Institute and in collaboration with a group of students from Middlebury College, the team created the following causal loop diagram to determine which factors affect electricity use and greenhouse gas emissions, and what feedback loops exist among them (Figure A5).

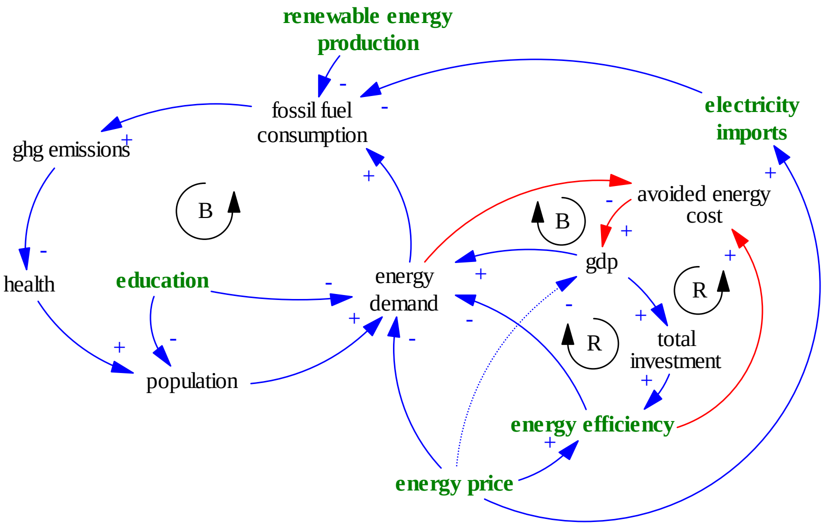


Figure A5: MCM-Ecuador, causal loop diagram representing the linkages between the power sector and the rest of the model.

Being fossil fuels consumption the main cause for the generation of greenhouse gas emissions, emphasis has been put on what determines energy demand. Energy demand is correlated, and causal related, with GDP, energy prices and energy efficiency as well as population and education. While GDP and population are positively related to energy demand, with the latter being reduced by emissions in the longer term (balancing loop), increasing energy efficiency, prices and education curb it. Specifically, education tends to decrease energy demand, both by influencing behavioral change as well as by decreasing fertility and therefore population growth. Energy price and energy efficiency also tend to decrease energy demand, but energy efficiency, under certain circumstances, may allow the main actors in the economy to save enough resources to push demand further up (balancing loop). In fact, high avoided costs have a positive effect on GDP, through increased consumption and investment, which in turn increases energy demand and total investment (reinforcing loop). On the supply side, renewable energy production and electricity imports, when high oil prices justify it, decrease fossil fuel consumption for domestic electricity generation.

Appendix B: Data Collection and Model Customization

A project aiming at analyzing the impacts of national energy policies on the development of a country has to account for social, economic and environmental factors. While the latter are mainly accounted for as energy consumption and generation of emissions in the present study, a few more causal relations are considered in the two remaining spheres. In fact, on the social and economic side, investments in energy efficient technology influence, among others, domestic energy consumption, which in turn has a positive impact on disposable income. Similarly, in the case of the industry the avoided cost for energy consumption can be reinvested in more efficient capital to boost production, while demand for goods increases due to higher households spending. On the public side, lower energy expenditures and increased revenues (stimulated by higher spending and therefore higher GDP) allow the government to increase investments in infrastructure, such as roads, education and health. Better infrastructure and social services increase productivity of labor, by improving health, education and providing adequate infrastructure to stimulate commerce (e.g. roads).

It has to be noted that in the case of energy efficiency, reductions in energy consumption can be immediately seen when new appliances are bought and installed. On the other hand, increases in spending can be seen in the medium term, while improvement in social infrastructure and the impact of education on total factor productivity will be evident in the longer term. Changes in the demographic structure of the country, due to increasing income, literacy and access to basic health care, will be visible as well over the longer term.

Data Collection

The data necessary for the customization of MCM-Ecuador were obtained mainly from the United Nations Population Statistics (UN, 2007), Banco Central Del Ecuador (BCE, 2007), US Energy Information Administration (EIA) (EIA, 2007) and Ministry of Energy and Mines (CNCE and Cenance Corporation, 2005; CNE, 2006). Data on energy efficiency have been estimated by SolarQuest and local Ecuadorian students under a UN and e-8 funded project started in 2003 (Baer, 2007; UNDP, 2007). MCM uses these data to estimate the impact of investments in energy efficiency in Ecuador, with the assumption that appliances and infrastructure are similar to the ones available in the Galapagos.

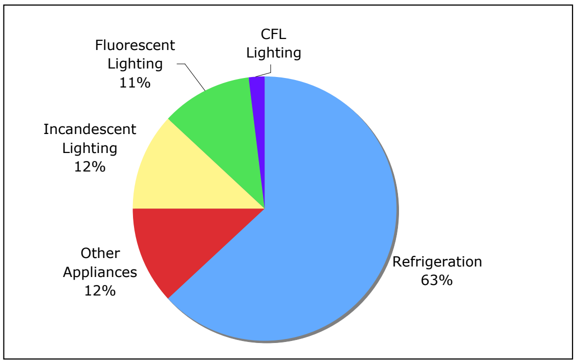
In 2003, Solar Quest, the Ministry of Education and Culture (MEC) and Colegio Tecnico Ignacio Hernandez (CTIH) collaborated on the development of an educational pilot program called: Action, Communications, Technology, and Science (ACTS). ACTS is a productivity-center, service-learning (PCSL) curriculum developed by SolarQuest. The ACTS curriculum was designed to fulfill the community service requirement of the MEC for students in the fifth-level (11th grade by U.S. standards) while strengthening core academics and introducing students to computer sciences. In the ACTS pilot program each student provided 200 hours of community service to monitor and analyze energy consumption on the San Cristobal electric power grid. Students researched the potential for end-use energy efficiency to reduce electricity demand and consumption within the residential and commercial sectors.

As part of this project, students coordinated a public information campaign on refrigerators, radio and television, and distributed audit request forms through the utility administrative office, public schools and commercial shops. The audits concluded that 36% of all tested refrigeration units tested failed to cycle off over a 24-hour test period. Utilizing household census data and survey information, students estimated the number of refrigerators on the four inhabited islands of the Province at 6,000 units. They then calculated that approximately 2,160 refrigerators were consuming energy on a continuous basis. Utilizing the survey results and previous household audits, students estimated the potential to reduce energy demand in the Galapagos by 1.4 megawatts (including lighting measures) at a cost of approximately $3.5 to $4 million per megawatt.

The results of the ACTS 2004 program prompted the Ministry of Energy and Mines (MEM) to conduct demand and consumption study on the electricity grid on the island of Santa Cruz in 2005. The MEM study was based upon consumer surveys and standard appliance consumption data rather than on data collection methodology as deployed in the ACTS 2004 pilot project. MEM consultants concluded that refrigeration represented 38% of the electricity demand in the Galapagos residential sector.

ACTS 2006 students were given the task by SolarQuest to verify the results of the MEM study utilizing ACTS 2004 survey data and the methodology for analysis deployed by the MEM contract consultants. After two months of intensive remedial training, students were able to undertake a more comprehensive analysis of ACTS 2004 data in order to assess the conclusions of the MEM study. Their analysis focused primarily on residential electricity end-use appliance demand and consumption. ACTS 2006 student research determined that residential energy consumption represented on average 68% of energy consumption in the residential sector. This is significantly greater than the 38% concluded in the MEM study.

The results of the ACTS 2006 student research were interpolated by ACTS students and SolarQuest staff as shown in Figures B1 – B2, below. Figure B1 represents the average for refrigeration consumption and other end-use loads for a typical household in the Galapagos. Household consumption was then recalculated based on ultra-high efficiency refrigerators and replacement of inefficient incandescent bulbs and standard (T12) fluorescent fixtures with compact fluorescent lighting (CFL), as show in Figure B2.



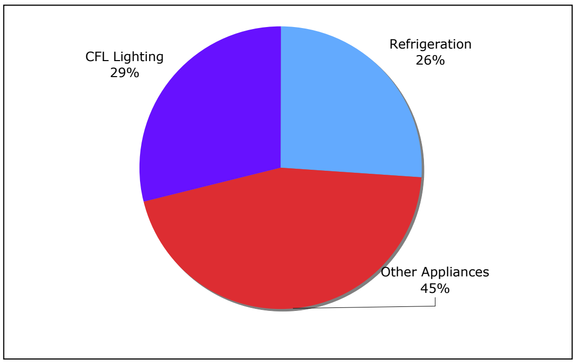


Figure B1: Typical Household (Inefficient). Actual energy end-use representative of the residential sector. (Source: SolarQuest®, based on ACTS 2004 and 2006 student data.)

Figure B2: Efficient Household. Projected energy end-use representative of the residential sector after the installation of energy efficient end-use appliances. (Source: SolarQuest®, based on ACTS 2004 and 2006 student data.) NOTE: Average consumption drops from 146KWh to 48.44 KWh monthly, representing a 66.8% reduction in consumption.

With the aid of SolarQuest staff, advanced students developed comparative grid simulation graphs in order to project a reduced electricity load and consumption profile for San Cristobal over a typical 24 hour period. These are the data sample used as assumptions in the development of the MCM-Ecuador model for what concerns electricity consumption and energy efficiency. The results are shown in Figure B3, as follows:

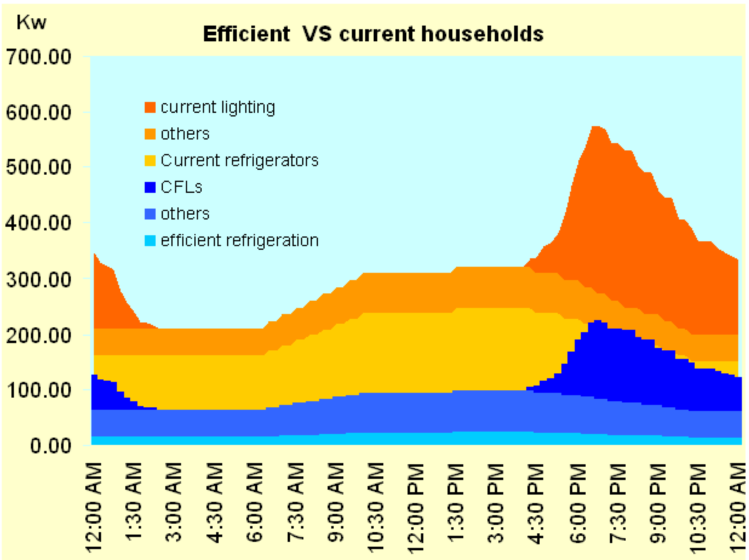


Figure B3: Comparative Grid Profile for household energy demand on the San Cristobal Power Grid. Yellow/Orange Profile equals current profile; Blue equals estimated demand profile with energy efficient appliances. (Source: SolarQuest®)

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