A System Dynamics Model of the Mauritian Power Sector

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Abstract

Mauritius, a Small Island Developing State and one of the most successful economies in Africa, has experienced sustained economic growth during the past three decades. Mauritius' power sector has evolved considerably during this period to cater for increases in electricity demand following such growth. The island has continuously invested in additional capacity to meet such increases in demand in the medium term. Approximately 78% of Mauritius' electricity needs are met through imported energy sources, mainly oil and coal. However there are increasing concerns about price volatility and security of supply from such sources. Policymakers are thus committed towards a sustainable energy development plan for the country. In this line, authorities have embarked into elaborating a comprehensive energy policy for Mauritius. Threshold-21 (T21) is a tool that applies system dynamics to aid in policy making in an integrated manner. This paper documents the first iteration in the development of a power sector model for Mauritius based on T21 models. The aim is to provide a description of the Mauritian power landscape and translate the same into a systems dynamics model. Future work includes expansion of the model to cover the whole of the Mauritian energy system and to do policy analysis.

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Introduction

Volatility of fuel prices, growing demand, deficiency of rainfall and the quest towards ensuring a sustainable future poses serious challenges to Mauritian policymakers as far as energy is concerned. Energy is central to our quality of life and is an essential ingredient to the commercial and industrial development of a country. The emerging economic model and reforms have underpinned the incumbent Mauritian government's policy. Tourism, information technology, seafood hub, sugar production and textile manufacturing are envisaged to become the main pillars of this economic model. Such a model is energy intensive and requires thorough planning.

There is growing awareness in the need for sustainable development; the concept of "Maurice Ile Durable", meaning "Mauritius Sustainable Island", has become a major focus on the island. The aim is to make Mauritius a proof of concept in sustainable development. Energy is the central theme within the concept and its planning is an essential step towards the goal of achieving sustainability. Since independence in the late sixties, the island has never implemented an integrated energy policy. Mauritius has thus embarked in drafting its first long term energy policy (Ministry of Public Utilities 2007).

System dynamic methods have been applied to complex systems modeling since its inception in the mid-1950s. The method has been widely applied to energy planning and policy analysis since the 1970s; starting with as part of Forrester's WORLD1 model and his subsequently refined WORLD2 model (Forrester 1970). FOSSIL2 is a U.S energy supply and demand model that was used by the U.S Department of Energy to prepare projections for energy policy analysis (Naill 1992). John Sterman then worked on a systems dynamics model that captured energy-economy interactions (Sterman 1981). Identification of cross sector interactions has urged researchers to build integrated and comprehensive system dynamics models.

Threshold 21 (T21) is a dynamic simulation framework designed to support comprehensive, integrated long term national planning with strict adherence to causality (Barney, et al. 1995). T21 provides ability for comparative analysis of policy options and thus allows the user to identify the policy options best contributing towards their goals. It incorporates a country's economic, social and environment dimensions into a single framework. Each dimension is composed of modules and sub modules. The Energy module is an important part of the overall framework (Bassi 2006). The model has been customized for developing countries, such as Mozambique, Malawi and Bangladesh, as well as developed countries, for example United States and Italy.

There has been keen interest amongst the Mauritian research community and policy makers to explore the development and use of integrated tools as an input to the energy planning needs of the country (Mauritius Research Council 2008). This study documents the findings in the development of a model for the power sector of Mauritius based on existing T21 models. The model is derived from a bottom up approach and is the first step towards the ultimate goal of developing a comprehensive and integrated tool to support policy analysis of the energy sector of the country.

Background

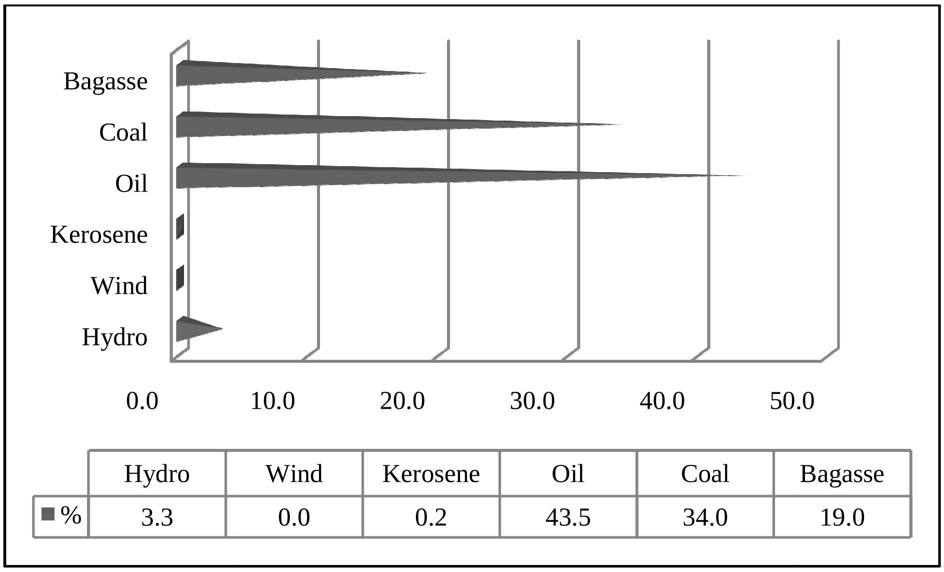
Mauritius is a tropical island situated in the south-west Indian Ocean about 855km east of Madagascar with a surface area of 1,864km^2. The Republic of Mauritius is composed of the main island of Mauritius and several outlying islands. The population of Mauritius is approximately 1.2 millions. Rodrigues, with an area of 108km^2, is the second largest island and situated 560km east of the island of Mauritius. It has a population of about 35,500 and its economy is based on fishing, cattle rearing and Tourism. Agalega Islands are located 1000km north of Mauritius and have a population of 300 inhabitants engaged into coconut exploitation. St Brandon comprises of sand banks, shoals and islets and is located some 430km north east of Mauritius. It is used as a temporary fishing base.

Since independence, Mauritius has progressed from a low income, agriculture based economy to a middle income diversified economy. During the past three decades, annual growth has been of the order of 5% to 6% (Sacerdoti 2005). Mauritius has one of the highest Gross Domestic Product (GDP) per capita in Africa and a relatively high standard of living.

Mauritius is Small Island Developing State (SIDS) and shares similar sustainable development challenges with other member states. SIDS are defined as low lying coastal countries that share similar sustainable development challenges: small population, limited resources, remoteness, susceptibility to natural disasters, vulnerability to external shocks and excessive dependence on international trade. Energy dependence is seen as a major source of economic vulnerability for many small island developing states. Assessments of current and future patterns of energy use, form part of a broad list of strategies identified by the SIDS members to face energy challenges. (United Nations 2005).

Power production in Mauritius

Mauritius has no known oil, coal or gas reserves and is heavily dependent on imported sources of energy. More than 70% of the country's electricity requirements were met from oil in the 80's. With the volatility of the price of oil and instability in the middle-east, there has been increasing concerns about the vulnerability of the Mauritian economy as a result of its dependence on oil. The strategy of decision makers has been to diversity the sources of energy with the introduction of coal and bagasse in the power production mix.



	Hydro	Wind	Kerosene	Oil	Coal	Bagasse
■ %	3.3	0.0	0.2	43.5	34.0	19.0

Figure 1 Energy Mix for the electricity sector in 2007 (Central Statistics Office 2008).

The power landscape is characterized by the Central Electricity Board (CEB) and the Independent Power Producers (IPPs). The CEB, a semi-governmental body, had the responsibility to produce 40.7% of the countries' electricity requirements in 2007 and as per legislation has the monopoly over the transmission, distribution and commercialization of electricity. CEB's production is fired by fuel oil and kerosene, and the balance is met from hydro and, to a minimal extent, wind. Hydropower potential has been nearly fully tapped in Mauritius. There are nine hydro plants and only three are able to generate all year round during peak hours. IPPs are private power generators of the Sugar Industry who produced the remaining 59.3% of the electricity requirements of the country in 2007. This electricity is produced by burning bagasse (a by-product of sugar production) and coal. The IPPs have base load plant, operating 24 hours a day. IPPs can be classified as continuous producers, burning from bagasse only in the crop season, and firm producers, burning bagasse and coal all year round.

From Figure 1, the performance of the island in terms of renewable sources of electricity i.e. 22% in 2007 is above many developed countries. The totality of the bagasse produced is burned for electricity production and more electricity from this source is envisaged mainly through increases in boiler efficiencies in the IPPs and the use of more fibrous varieties of sugarcane (Ministry of Public Utilities 2007).

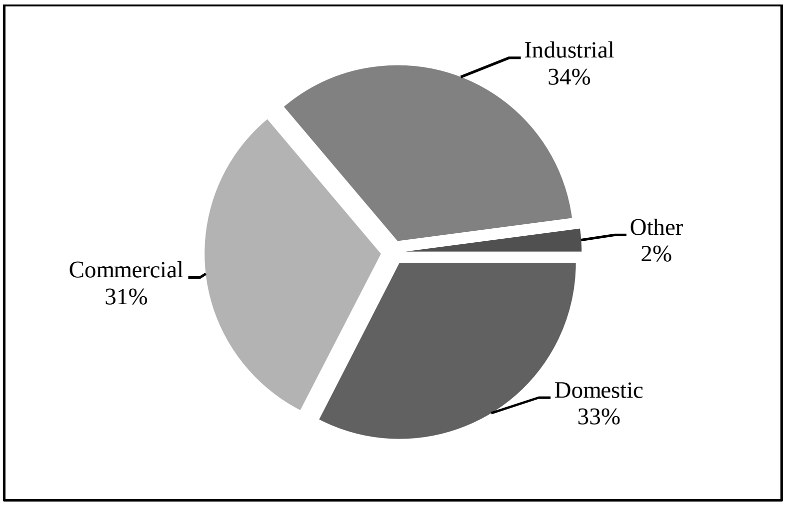


Figure 2 Electricity consumption in 2007 by type of tariff (Central Statistics Office 2008).

In 2007, the Industry consumed 34% (673 GWh) of electricity followed by Domestic sectors which consumed 33% (643 GWh) and the Commercial sector which used 31% (618 GWh). Others comprising of street lighting and temporary electricity sold stood at 2% (41 GWh) [see Figure 2 above]. The total electricity consumed was 1,975 GWh in 2007.

In the absence of an energy policy, a number of power generation projects have been approved by the Mauritian Government: A letter of intent has been issued to the promoter of a 20MW waste-to-energy generation plant for Mauritius as part of the solid waste management policy of the government. Construction is expected to start on the fourth quarter of 2009 and it should start to operate in 2011 (Prime Minister's Office 2008). A wind turbine is to be added at Grenade, Rodrigues and a wind farm is to be constructed in Bigara, Mauritius. Two hydro stations of low capacity are to be installed at La Nicoliere and Midlands dam in Mauritius. A grid code is also being drafted with a view to enable small power producers to integrate the power generation system. Legislation to enforce energy efficiency standards for appliances, vehicles and buildings are also planned (Ministry of Public Utilities 2009).

Causal relationships

The power sector model developed as part of the study can be broadly described as a balancing relationship between the demand and the supply of electricity. Both are calculated endogenously. The causal loop diagram in Figure 3 depicts an abstract overview of the intended interrelationships within the model.

The demand side is broken down into different sectors so that they can be analyzed in isolation and can match the partitioning of data used by the power industry and the national statistics office. GDP is favored as the main driver for the different sectors due to the bidirectional causality between Mauritius' GDP and electricity demand (Neeliah and Deenapanray 2009). Significance of the drivers with respect to sectoral electricity demand has been assessed by the authors in previous studies (Balnac and Bokhoree 2009). Household demand is driven by per capita income. Per capita income in turn is driven by GDP and Population. The commercial, manufacturing and others (Street lighting & Temporary demand) form a reinforcing loop with population, as well as GDP since these sectors (Poinen, et al. 2009) contribute to GDP through goods and services they provide on consuming electricity. The agricultural demand is driven by the population and land under cultivation, it also contributes towards GDP. In practice however GDP, disposable income, population and land under cultivation have been treated as exogenous variables and are thus assumed to have a one way interaction with the demand at this early stage of the study. The ultimate step being the implementation of an integrated model with these variables being calculated endogenously to close the feedback loop.

The different demand variables form balancing loops with the electricity supply. The different sources of generation are constrained by capacity. Generation from imported sources of energy reinforces the energy imports bill which in turn has a negative effect on GDP. Again this effect on GDP in not modeled since GDP is assumed to be exogenous at this stage of the study. The different generation sets affect electricity price which in turn affects the demand variables.

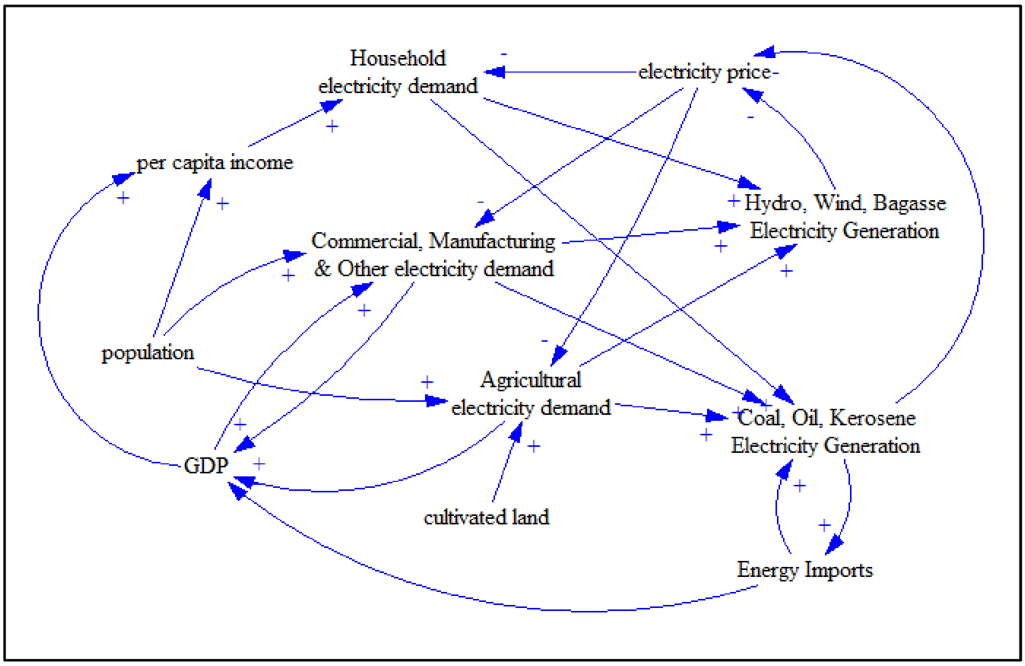


Figure 3 Causal loop diagram

Demand View

Electricity demand (see supporting document: Illustration 1 – Electricity Demand) is partitioned according to the standard structure of energy data favored by the statistics office (Central Statistics Office 2007). Energy data is segregated into Household, Commercial, Manufacturing, Agricultural and Others. The data further distinguishes between Mauritius island and Rodrigues. Electricity data as provided by CEB is partitioned according to type of tariff, i.e. Domestic, Commercial, Industrial (General & Irrigation) and Others. Given this distinction and in an effort to make the model easily adaptable and pluggable to future energy models a mapping was done between the different data partitioning schemes. CEB data broke the demand sectors into number of consumers and average number of units consumed. Such a structure added the possibility of using distinctive drivers to separate components of particular demand sector. For example, efficiency measures would affect the average number of units consumed rather than the number of consumers.

Curve fitting through Matlab's cftool (Dierckx 1993) was favored to identify relationships between demand components and potential drivers. Relative GDP was used as the driver for most of the demand sectors except for Domestics and Industrial Irrigation (see Table 1). *Population* was favored to drive *Domestic number of electricity consumers* since a linear correlation was found between these two variables. *Relative disposable income* also showed good correlation with the *domestic average number of units per customer*. *Industrial Irrigation* was more challenging to model with its varying patterns; the maximum best fit was found when it was driven by relative land cultivated but the correlation remained low.

Table 1 Drivers of Electricity Demand

Demand Sector	Component	Driver	R^2 value
Domestic Electricity GWh Sold	Domestic number of electricity consumers	Population	0.9985
	Domestic electricity average No of Units Per Customer	Relative disposable income	0.9795
Commercial Electricity GWh Sold	Commercial number of electricity consumers	Relative GDP	0.9898
	Commercial Electricity Average No of Units Per Customer	Relative GDP	0.9952
Industrial General Electricity GWh Sold	Industrial General number of electricity consumers	Relative GDP	0.9572
	Industrial General Average No of Units Per Customer	Relative GDP	0.9902
Rodrigues Island Electricity GWh Sold	Rodrigues Island Electricity Number of Consumers	Relative GDP	0.9727
	Rodrigues Island Electricity Average No of units per customer	Relative GDP	0.9365
Other Electricity GWh Sold	Other number of electicity consumers	Relative GDP	0.9847
	Other Average No of Units Per Customer	Relative GDP	0.9427
Industrial Irrigation Electricity GWh Sold	Industrial Irrigation number of electricity consumers	Relative Land Cultivated	0.5653
	Industrial Irrigation Average No of Units Per Customer	Relative Land Cultivated	0.2901

The demand sector variables are then aggregated to obtain the *Total Electricity use in GWh* which in effect represents the quantity of electricity on demand. *Losses* and *power sector own use* are functions of this figure. *Total Electricity to be Generated in GWh* is the sum of quantity of electricity on demand, losses and electricity for power sector's own use.

The demand sector variables are also mapped to the statistics office format after conversion from Gigawatt hour (GWh) to thousand tonnes of oil equivalent (ktoe) (Central Statistics Office 2007).

Supply View

The electricity supply system broadly aims to cater for the *Total Electricity to be Generated in GWh* aggregated in the demand view. The supply model (see supporting document: Illustration 2 – Electricity Supply) assumes a least-cost-first rationale for the allocation of demand to the generation sets. The order of preference is: Hydro, Wind, Bagasse (Continuous producers), Bagasse/Coal (Firm producers), Oil and finally Kerosene. The generation sets are assumed to be constrained by a function of effective capacity and running time. The electricity generated at a generation set is the minimum between the amount required to be generated and the constraints (i.e. capacity). Any extra electricity to be produced beyond the capacity available is passed on to the next generation set in line. Any extra electricity left to be produced beyond the last generation set is the deficit, i.e. the supply cannot match the required electricity production. Such a situation generally implies exercising spinning reserves or in the worst case load shredding before investing in additional capacity.

Generating set capacity

The capacity sub models compute the effective capacity coupled with running time of generating sets. The capacity sub models of the generating sets are similar to the bagasse capacity sub model (see supporting document: Illustration 3 – Bagasse Capacity). Installed capacity is modeled as a stock with an initial capacity predefined. Capacity construction is an inflow which increases the installed capacity stock whereas the capacity depreciation is an outflow decreasing the installed capacity stock.

The construction of capacity is modeled as a lookup table and is a policy variable which users can use to do scenario analysis. The depreciation of capacity is modeled as alternate functions; normal depreciation or user induced depreciation. Normal depreciation is the installed capacity in stock divided by the life of the generating set. Also users have the possibility to intervene by setting values in the depreciation table which then overrides the normal depreciation at that specific point in time.

Capacity can be constrained in two ways; by setting the percentage use in a lookup table and/or by capping the number of hours the set may run in a year. This facility serves two purposes first is to provide for spinning reserves and second is to cater for generating sets which do not run throughout the year. For example, Hydro plants may not run due to lack of precipitation or all Bagasse has been burnt by continuous producers for the intercrop season.

Model Validation

Model validation is a continuous process during and after model development. Validation is an essential element during the modeling process. Historical time series data from years 1997 to 2006 was obtained from the Central Statistics Office and the CEB (Central Statistics Office 2007). The data was used to systematically verify and validate the output of the model. Data for years 2007-2008 was incomplete and is to be integrated in the model as soon as it becomes available.

Results and discussion

On the demand side, comparison of historical and model output of electricity demand (*Total Electricity use in GWh*), as shown in Figure 4, reveals an average higher estimate of about 9.4 GWh (0.63%) from the model. An uncharacteristic peak is seen on year 2004 where model demand exceeded historical data by 38.6 GWh (2.26%). This is explained by a peak seen in the commercial demand (*Commercial electricity gwh sold*) in 2004 as projected by the curve fitting functions which produces inconsistency with historical data.

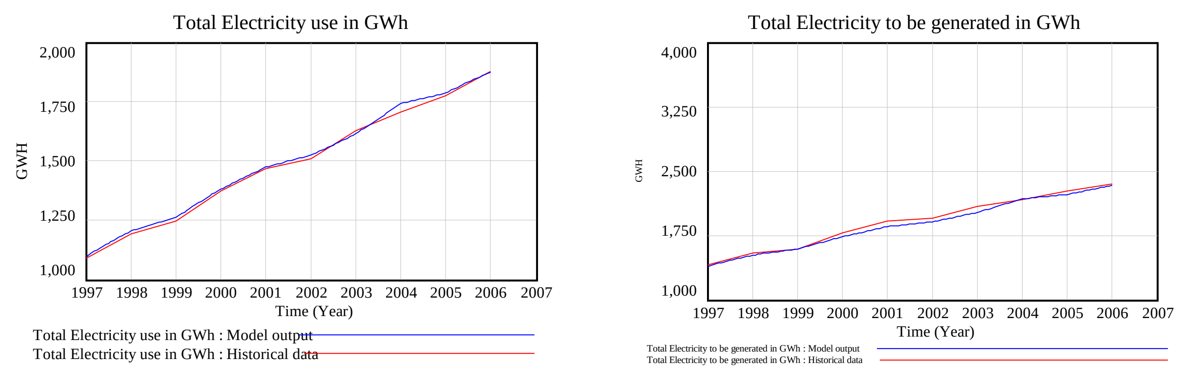


Figure 4 Electricity Demand and Electricity to be produced

In contrast, the total electricity which required to be produced (*Total Electricity to be generated in GWh*), depicted in Figure 4, showed a lower average estimate of about 30.1 GWh (1.58%). This is explained by a declining percentage of losses (*Losses percentage table*) and assumed constant power sector own use percentage (*own use percentage table*). This error would equate to a shortfall of 3.4 MW in generation capacity, which is 0.54% of the effective capacity in 2006.

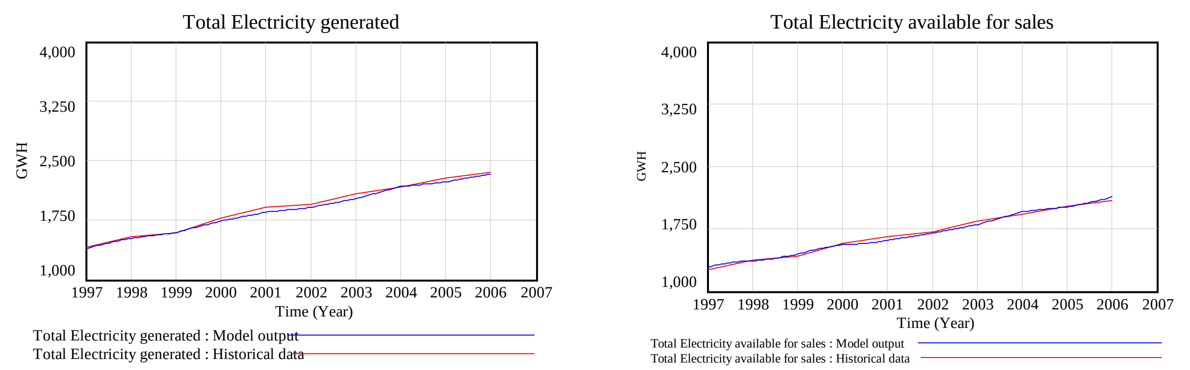


Figure 5 Electricity Generated and Supplied

On the supply side, since effective capacity defined in the model is superior to the total electricity required to be produced, the supply side caters for 100% of the electricity requirements. The resulting electricity generated matches the electricity that was required to be produced (Compare *Total Electricity generated* in Figure 5 and *Total Electricity to be generated in GWh* in Figure 4).

The total electricity available for sales (see Figure 5) is an aggregation of electricity produced by CEB and the amount exported by the IPPs to CEB. This exported amount is defined as a function of the share of electricity exported to CEB by IPPs and the overall production by IPPs. The simulated total electricity available for sales resulted in an average over estimation of about 0.93 GWh (0.06%) when compared to historical data.

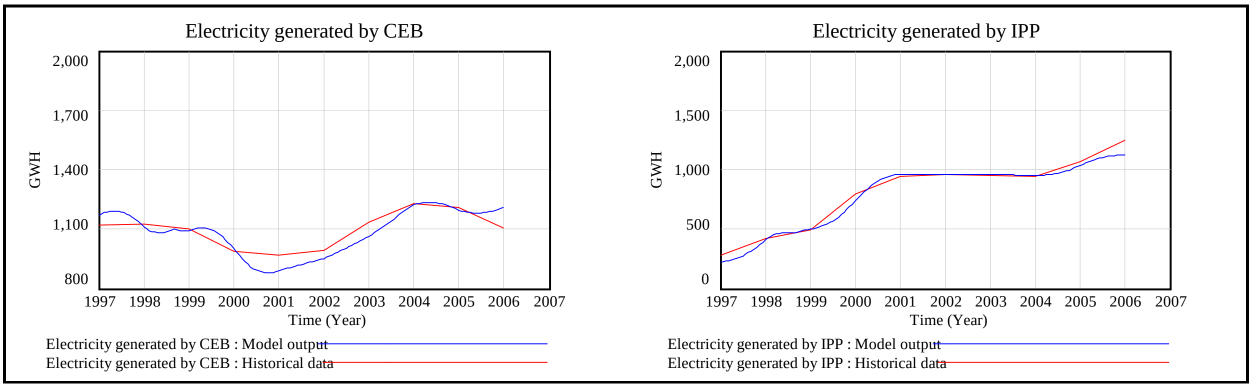
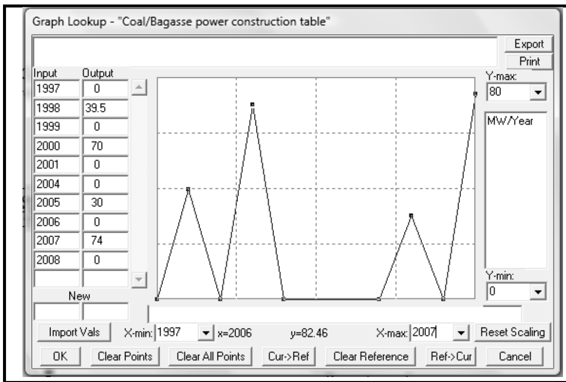


Figure 6 Electricity generated by CEB and IPP

CEB produces electricity from hydro, wind, fuel oil and kerosene, and IPPs burn bagasse and coal. As stated earlier, the model assumes a least-cost-first strategy when allocating demand to generation sets. The level of precedence is as follows: hydro, wind, bagasse, bagasse/coal, fuel oil and kerosene. Demand not produced at a certain level is passed on to the next generating set according to precedence.

Oil and Kerosene made up approximately 90% of the electricity generated by CEB, the remaining being catered for by Hydro (10%) and Wind (less than 1%). Kerosene is generally used during demand peaks. It can be concluded that oil contributes considerably in the aggregate electricity generated by CEB. Since oil is low in the precedence level and kerosene is used during peaks, oil caters for all of the remaining electricity to be produced after bagasse/coal electricity production. The simulated pattern of electricity generated by CEB shown in Figure 6 is defined mainly by the electricity produced from oil. Electricity generated by CEB dipped considerably between years 2000 and 2004 (See Figure 6). This is explained by the gap in demand during this period (See Figure 4 *Total Electricity to be generated in GWh* between 2000 and 2004).

Because oil's capacity caters for any remaining electricity to be produced at its level, no electricity demand was allocated to kerosene generating sets. In practice this is not the case as kerosene capacity is used during demand peaks.



Input	Output
1997	0
1998	39.5
1999	0
2000	70
2001	0
2004	0
2005	30
2006	0
2007	74
2008	0

Y-max: 80
MW/Year
Y-min: 0
X-min: 1997 x=2006 y=82.46 X-max: 2007

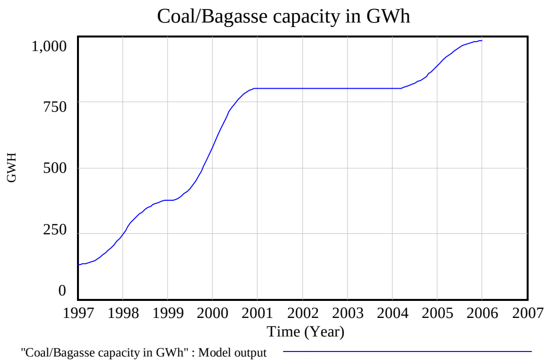


Figure 7 Effect of construction table on capacity

Since the IPPs' generating sets were higher than oil in the level of precedence, their generation of electricity pattern was defined by available capacity. The inconsistencies depicted in Figure 6

(Electricity generated by IPP) are related to the power construction/depreciation tables in the installed capacity stock and flows. There is an area under graph that spreads construction during the year that additional capacity is added, instead of discrete points in time (See Figure 7).This has a smoothening effect on the available capacity patterns of the generating sets. The challenge is to set discrete values on simulated time steps.

Conclusions and future work

Whilst figures were relatively consistent at the aggregate level, it was not the case at the detailed level. The power model ignores peaking demand and the load duration curve since it simulates over large time steps (3.25 weeks). The model assumes a least-cost-first when allocating demand to generating sets. It spreads the demand equally throughout the simulated time step and in so doing flattens any demand peaks. The implication is that least-cost-first fails to allocate demand to generating sets lower in the hierarchy like Kerosene. The model also ignores certain energy to economy interactions and has assumed a one way interaction by treating certain variables exogenously (For e.g. GDP and disposable income). Energy imports, in the form of coal, fuel oil and kerosene, and bagasse production can be modeled as a constraint when defining effective capacity of the generation sets.

Given the socio-economic importance of electricity, its price is regulated in Mauritius. Therefore, price of electricity has a low impact on demand and supply. Further, past increases in the price of electricity have had little effect on the growing demand for electricity. However, Mauritian government’s policy also aims towards ensuring the financial stability of the CEB and it has proposed several measures including a revision of tariffs (e.g. peak and off-peak rates) and investment in costly renewable production capacity. Subsequent models will also investigate policy measures that are being contemplated by the Government of Mauritius.

The study allowed for a better understanding of Mauritius power sector and provided an initial structure for a power model with scope for improvements. Future work will include addressing the issues identified and expansion of the power model to a Mauritius energy model with the ultimate goal of enabling policy analysis.

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