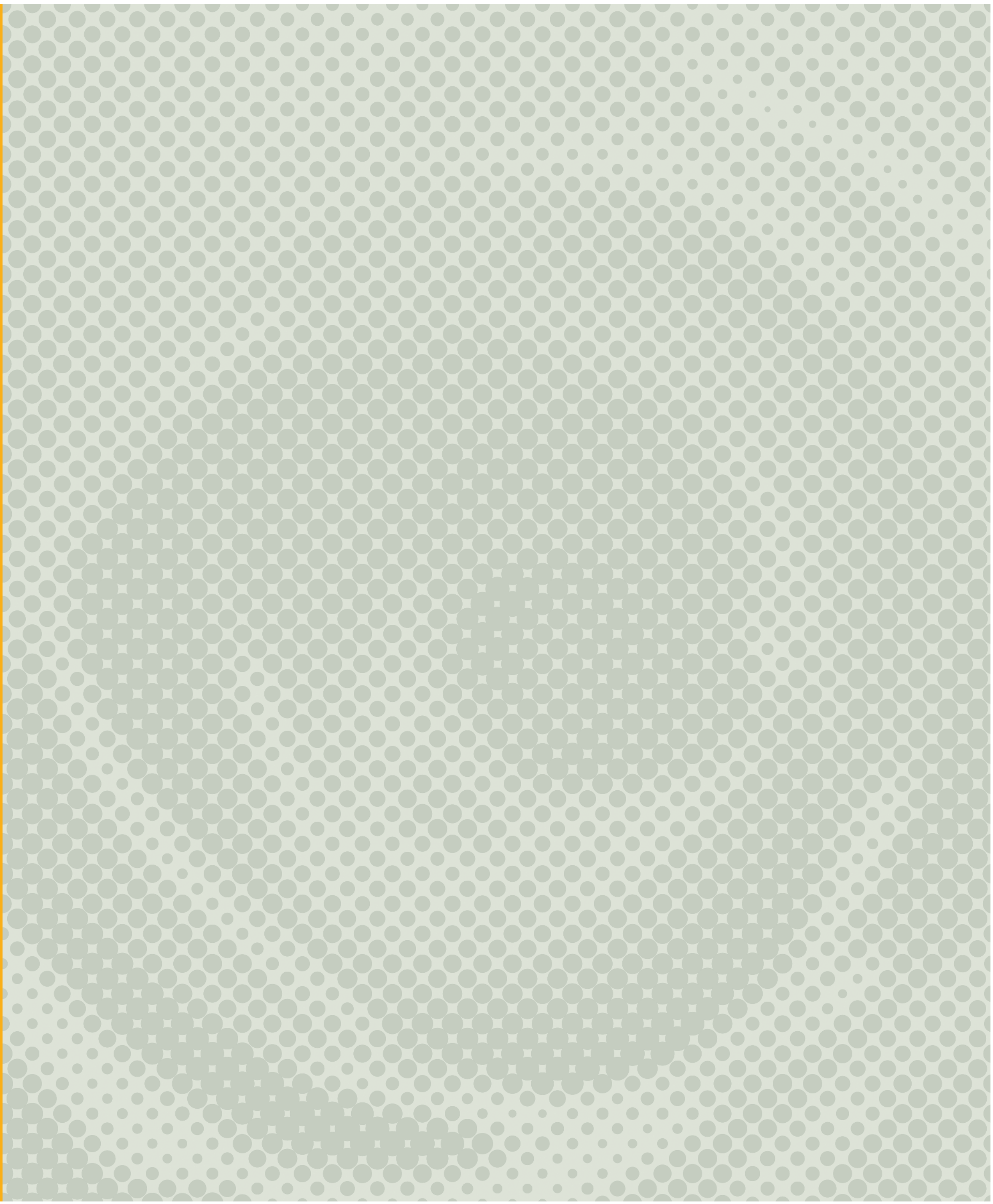
The power of independence - increasing self-sufficiency on a small island state

Marie Loe Halvorsen



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Preface

It is now more than two years since Dr. Ilan Kelman, at the Center for International Climate and Environmental Research in Oslo (CICERO), approached me, asking if I was interested in travelling to a tropical island. It was in the middle of the winter, and we were at a climate conference in northern Sweden, where the sun had nearly been up for months. It was not a hard choice.

This thesis is written as part of the international Many Strong Voices (MSV) programme, which seeks to increase knowledge sharing on sustainability and climate change between Small Island Developing States (SIDS) and isolated arctic communities. The programme is coordinated by CICERO and GRID-Arendal, and cooperates with more than 20 organisations from Small Island Developing States (SIDS) and the Arctic. The goal is act on climate change by building stronger networks in international negotiations, raising awareness about the effects of climate change to their regions and by working to understand more of their adaptation needs, solutions and measures (1). The programme includes several student theses, both on the master and PhD level (2). This thesis addresses the island Mauritius, an African SIDS. It explores the opportunities and challenges for the island for increasing the share of renewable energy in their electricity grid and becoming less dependent on fossil fuel imports.

I would like to thank my supervisors, Petter Heyerdahl and Ilan Kelman for always being there when I needed help. From Mauritius, a special thanks to Maja Zidov and Xavier König, for their friendship, help and support; Dr. Dinesh Surroop, Dr. Khalil Elahee, Dr. Romeela Mohee and Dr. Anwar Chutoo at the University of Mauritius, who helped us get in touch with the right people and found the data we were missing; Sanjay Sookhraz from the Central Electricity Board, for setting up meetings and giving a guided tour of two hydro power plants; Rajiv Ramlugon for a fantastic tour of the Omnicane power plant; Dr. Sanju Deenapanray from Ecoliving in Action who made me question everything I wanted to write; and everyone else we met for always being so friendly and helpful. A big thank to Norad and Tekna for financial support for the field trip. To my parents, and my friends Sindre, Gaute, Ragnhild, Andreas and Thomas for comments, support and constructive critique. But most of all I wish to thank Synnøve Lill Paulen, my travel partner, friend and fellow student who wrote about the transportation system on Mauritius. She has made this work so much more fun than if I had done it alone, and she has been my main discussion partner throughout this work.

With this thesis, I conclude my master's degree in Environmental Physics and Renewable Energy at the Norwegian University of Life Sciences (UMB). It is my hope that my work can be of use not only to the Mauritian people, but also to other islands facing the same challenges. Mauritius is a good example to study because their challenges today might become global challenges in the future as we move from an energy system based on fossil fuels towards one based on variable renewable energy sources.

Ås, May 13 2013

Marie Loe Halvorsen

Abstract

Fossil fuels constitute 21% of import costs and are the basis for 76% of electricity generation on Mauritius. The volatility and unpredictability in fossil fuel prices and supply are incentives to reduce dependency on these fuels. This thesis explores the possibilities for the main island of Mauritius to reduce future fossil fuel dependency, with a focus on the electricity sector. A field trip to the island was conducted in August 2012, to collect data and broaden the understanding of challenges and opportunities in the Mauritian energy system. The implications of implementing solar panels, electric vehicles and gas power plants as alternatives to a planned 100 MW coal power plant are studied. In this scenario, the balance between the need for peak and base capacity is considered. It is shown how solar panels can meet daytime peak demand, while utilizing storage capacity of electric vehicle batteries to meet evening peak demand. Natural gas generators provide backup capacity and flexibility for cloudy days and evening demand. The solutions are scalable, and could be deployed separately or as a combination. Together, they could replace the coal power plant and thereby reducing the expected growth in fossil fuel imports by 28%. Implemented on a larger scale, they could also reduce overall fossil fuel imports. Solutions like this will also be relevant for other small island states and even for larger states as they try to convert their own energy systems towards one based on renewable energy.

Sammendrag

Fossil energi utgjør 21% av importkostnader, og 76% av strømproduksjonen på Mauritius. Svingningene og uforutsigbarheten på både prisene og tilførselen av fossile brensler utgjør en insentiv for å redusere avhengigheten av disse brenslene. Denne oppgaven utforsker muligheten for hovedøya på Mauritius til å redusere sin avhengighet av fossile brensler, med fokus på elektrisitetssektoren. En ekskursjon til Mauritius ble gjennomført i august 2012, for å samle data og utvide forståelsen av utfordringer og muligheter i energisystemet på øya. Konsekvensene av å implementere solcellepaneler, elbiler og gasskraftverk som et alternativ til et planlagt kullkraftverk på 100 MW er studert. I dette scenariet er balansen mellom behovet for topp- og baseeffekt vurdert. Det pekes på hvordan solcellepaneler kan møte den høye etterspørselen på dagtid, mens lagringskapasiteten i elbil-baterier kan brukes til å møte toppen av etterspørsel om kvelden. Gasskraftverk gir backup-kapasitet og fleksibilitet for overskyede dager og den økte etterspørselen om kvelden. Disse løsningene er skalerbare, og kan implementeres hver for seg eller kombinert. Sammen kan de erstatte kullkraftverket, og dermed redusere den forventede økningen i import av fossile brensler med 28%. Dersom de implementeres på en større skala, kan de også redusere den totale importen av fossile brensler. Denne typen løsninger vil også være relevante for andre små øystater, og til og med for større land etter hvert som de forsøker å endre sine egne energisystemer mot et basert på fornybar energi.

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Acronyms

BP	British Petroleum
CCGT	Closed Cycle Gas Turbine
CEB	Central Electricity Board
CEL	Consolidated Energy Limited
CICERO	Centre for International Climate and Environmental Research – Oslo
CPP	Continuous Power Producer
CSO	Central Statistics Office
CTBV	Compagnie Thermique de Belle Vue
CTDS	Centrale Thermique du Sud
CTSav	Centrale Thermique de Savannah
FSPG	FUEL Steam Power Generation
GMT	Greenwich Middle Time
HFO	Heavy Fuel Oil
IEA	International Energy Agency
IPP	Independent Power Producer
LFG	Landfill Gas
LPG	Liquid Petroleum Gas
MID	Maurice Ile Durable (Mauritius Sustainable Island)
MSV	Many Strong Voices
Norad	The Norwegian Agency for Development Cooperation
OCGT	Open Cycle Gas Turbine
PV	Photovoltaic (solar panels)
SIDS	Small Island Developing States
SIPP	Small Independent Power Producer
SWH	Solar Water Heater
Tekna	The Norwegian Society of Graduate Technical and Scientific Professionals
toe	tonne of oil equivalent
TPES	Total Primary Energy Supply
UMB	Universitetet for miljø- og biovitenskap (Norwegian University of Life Sciences)

Nomenclature

G	Solar irradiation
G_{max}	Maximum solar irradiation
θ	Angle of incidence
ω	Hour angle
δ	Declination
ϕ	Latitude
β	Tilt of a solar panel
t_{zone}	Local time
ω_{eq}	Equation of time
ψ	Longitude
ψ_{zone}	The longitude where the sun is directly overhead at noon local time
n	Number of the day
δ_0	The tilt of the Earth’s axis to the normal to the plane in its orbit around the Sun
γ	Orientation of a plane
SH	Solar Hour
E_{sun}	Total energy from the solar irradiation on a square meter in a given time period
t	Time
A	Area
$\mathrm{W_p}$	Watt peak – the maximum power delivered by a solar panel
r	The average range of an EV battery
$E_{EV\ transport}$	The annual electricity demand of an EV fleet used only for transportation
E_{EV}	The electricity consumption for one EV when used only for transportation
N_{EV}	The number of vehicles in the entire fleet
l	Average grid losses
E_d	Average electricity consumption per km for one EV
d	Average annual distance travelled for one EV
$P_{EV\ total}$	The power available from EV batteries at any given time
P_{EV}	The maximum power available from one EV battery
s	The share of EVs available for feeding electricity back to the grid
$P_{EV\ average}$	The average power available from EV batteries
$E_{battery}$	The total energy storage capacity of an EV battery
b	The share of one EV battery available for feeding electricity back to the grid
$\Delta t_{discharge}$	The length of the period where extra power is needed in the grid
$E_{EV\ additional}$	Annual additional electricity demand when batteries deliver power to the grid
$P_{EV charge}$	The average power needed to recharge EV batteries
Δt_{charge}	The daily time available for charging
$P_{EV\ max}$	The total power needed to charge all EV batteries at once
$E_{EV\ total}$	Total EV electricity demand
P	Desired capacity from EV batteries
E_K	Kinetic energy
η	Efficiency
$E_{gasoline}$	Energy consumption of a gasoline vehicle

1 Introduction

1.1 Background

1.1.1 Global energy situation

Global fossil fuel consumption is steadily rising. In 2010, 81% of total primary energy supply (TPES) came from fossil fuels like coal, oil and natural gas, as indicated in Figure 1 (3). At the same time, two thirds of energy supply for electricity generation came from fossil fuels (3). Figure 2 shows the growth in consumption of these fuels.

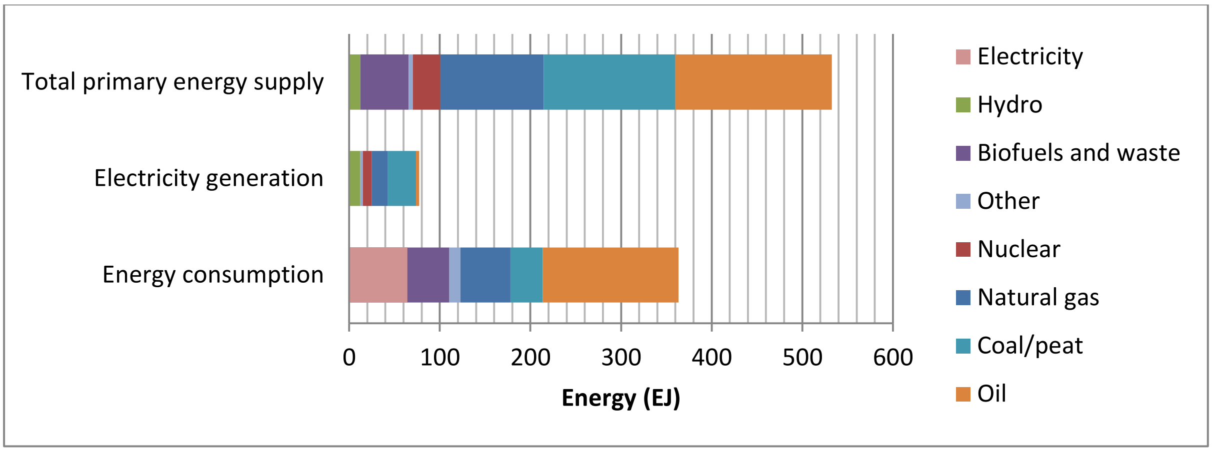

Figure 1 – Global TPES, electricity generation and final energy consumption in 2010 (3)

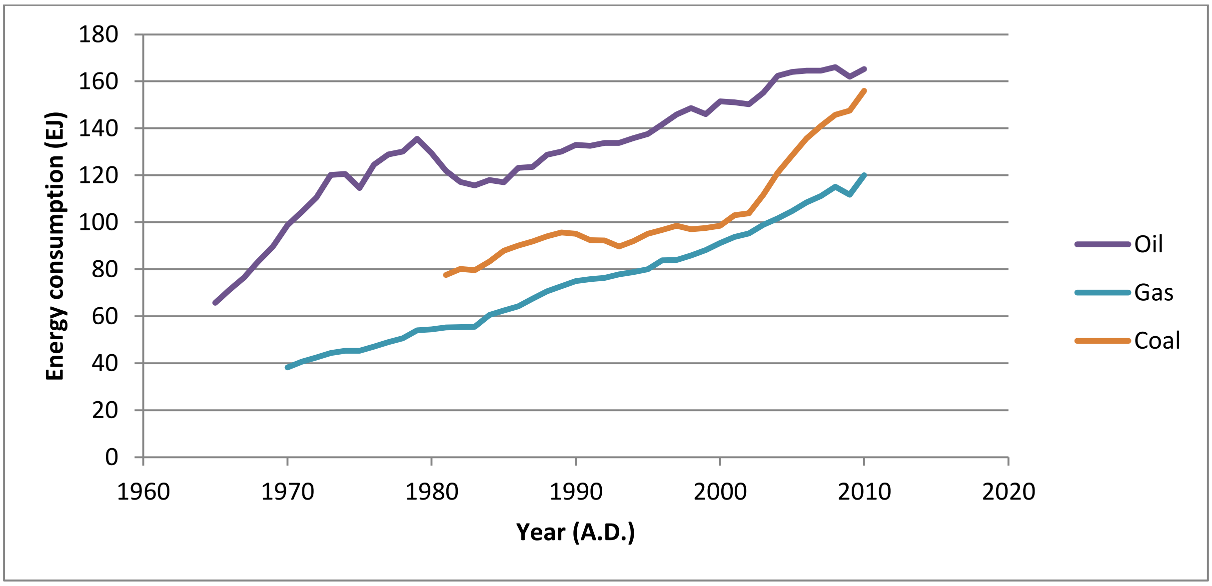

Figure 2 - Historical fossil fuel consumption (3)

After a relatively steady price on oil for all of the 20th century, the last two decades have seen soaring fossil fuel prices, as indicated in Figure 3. The price for a barrel of oil rose from USD 40 in 2003 (4) to an average of USD 112 in 2012 (5), with a peak of USD 147 in July 2008 (6). Coal has followed a similar development path (7), while natural gas prices vary between different regions, as shown in Figure 4. In the USA, natural gas prices have decreased and are currently lower than the average global coal price, while it is about three times as high in Japan.

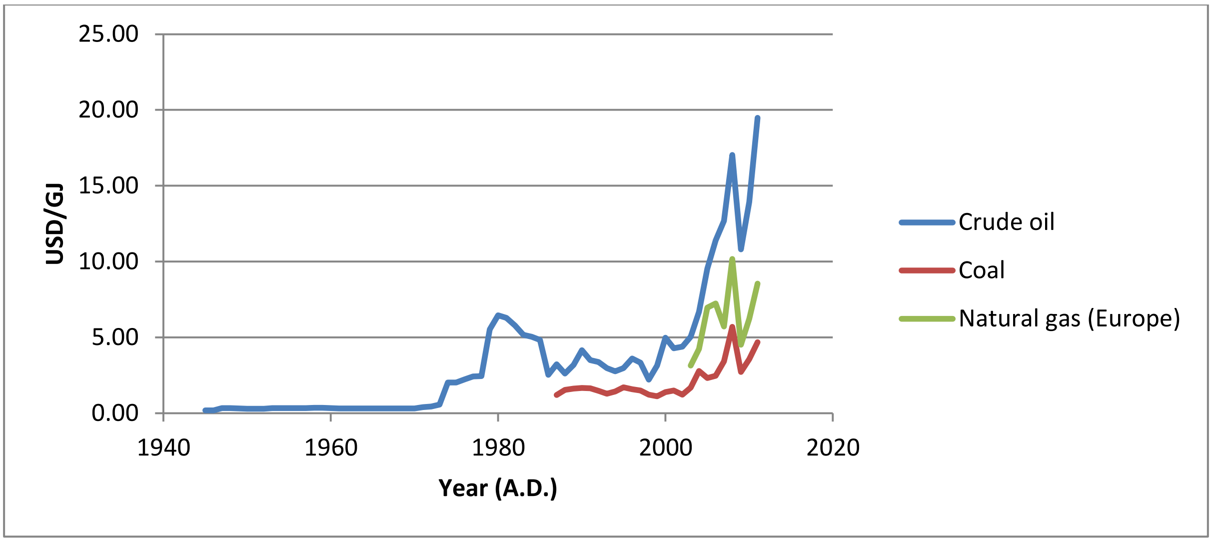

Figure 3 - Historical oil coal and gas prices (10) (5)

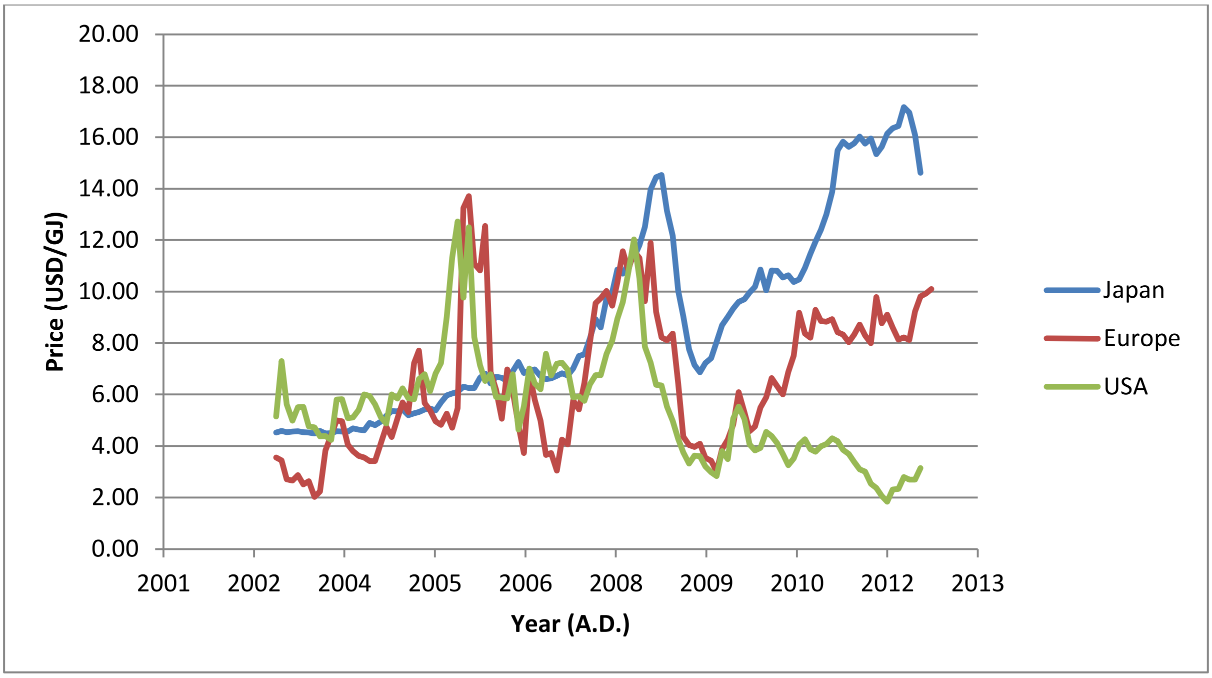

Figure 4 - Historical gas prices in different regions (5)

Most experts agree that the growth in oil extraction will be reversed sometime this century (8). The rise in oil price might signal that the global oil market has in fact already entered a phase of depletion (7), even though extraction and consumption still grows. The increased demand from emerging states like China and India, combined with an expected decrease in supply, give reason to believe that the price on fossil fuels might also stay high in the future (4) (7). In addition, the political situation in many petroleum exporting states results in a high unpredictability and variability of the price. In the future, some suggest, there might be more frequent examples of states choosing to protect their petroleum finds and restrict exports for economic and political reasons (8). Three states; Saudi Arabia, Russia and the USA, alone provide about one third of crude oil supply (3). Similarly, Russia and the USA extract 40% of natural gas in the market, while China alone extracts almost half of global coal supply (3). As the remaining fossil fuel reserves are controlled by few states, geopolitical issues might reduce the access to fossil fuels significantly should any of these states choose to keep it for themselves, or extract less than today. These decisions might have a large influence on both prices and supply of fossil fuels (9).

Although renewable energy technologies still constitute a relatively small share of global energy supply, some have a massive relative growth. Global photovoltaic (PV) solar panel capacity grew with 42% and wind capacity with 19% from 2011 to 2012 (5). At the same time, capital costs for PV panels fall rapidly (5). In areas with peak demand in the summer, generation costs start approaching peak market prices (5). Figure 5 shows the most recent increase in global installed PV and wind capacity.

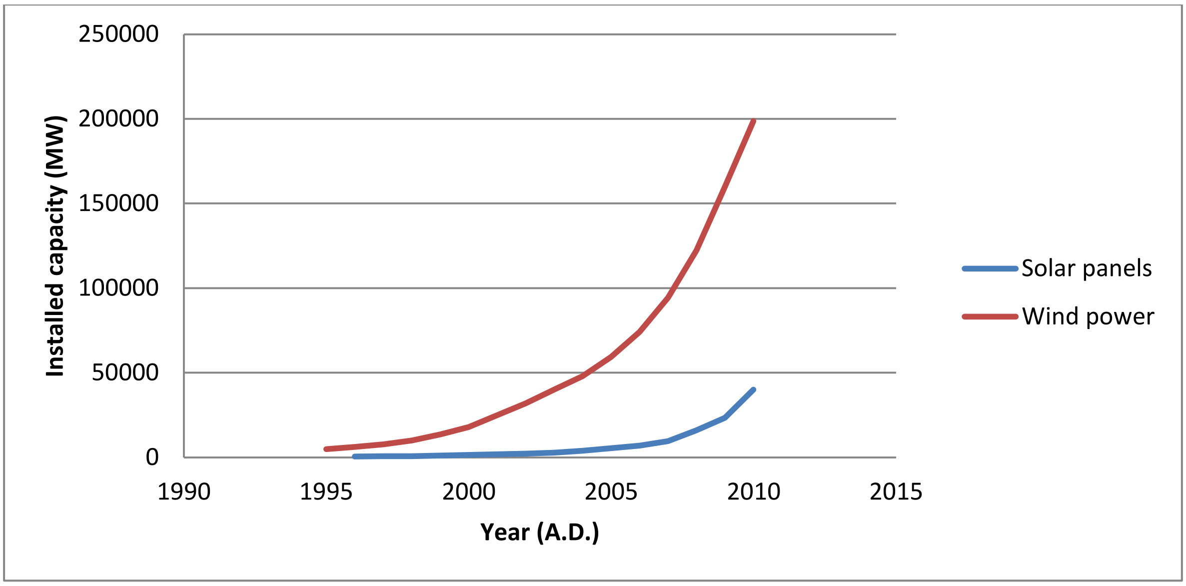

Figure 5 - Historical global installed PV and wind capacity (10)

With the lack of distribution of fossil fuel extraction, most states end up relying on the willingness of a few other nations to continue their supply of fossil fuels at steady prices. By reducing dependency on fossil fuels for energy supply, states can reduce this insecurity. Fossil fuel dependency can be reduced in two ways: By reducing overall energy consumption, or by converting to other energy sources, like renewable energy. As renewable energy resources like solar and wind energy are available domestically in all states, at varying magnitudes, these technologies could increase a state’s control and predictability of energy supply and prices.

1.1.2 Small Island Developing States

Small Island Developing States (SIDS) are a group of low-lying island states that often have extra challenges related to their economic and social development (7). SIDS face a double stress on their economy and people from climate change and rising and volatile global oil prices (7). At the same time, SIDS have the potential to become early markets for renewable energy technologies (11). Fossil fuels are often slightly more expensive than in other states, as they have to be transported far (11), and because the island lacks the economy of scale.

Most SIDS are rich in renewable energy resources like wind, sun and waves. They could prove valuable testing grounds for implementation of a high share of renewable energy penetration, and for deployment of storage and demand side solutions (6). This is of use for the rest of the world in the years to come, as larger states make the transition to a low carbon energy system (7).

As small and isolated systems (7), variable renewable energy supply can give abrupt and unpredictable changes in the overall power supply. Therefore, SIDS must pay special attention to backup capacity as variable energy supply is introduced to the system (6).

1.1.3 Mauritius

Mauritius is an African SIDS in the Indian Ocean, east of Madagascar (12). With ith 1.3 million inhabitants (13) and an area of 2,040 km^2, Mauritius has a high population density (14). It shares many of the same attributes as other small island states (15), like no known petroleum reserves and a heavy reliance on fossil fuel imports (11).

On Mauritius, imported fossil fuels constitute about 76% of energy resources for electricity generation (16). Import price variations therefore affect the profitability and cost of the electricity sector, which could also influence the price on electricity.

The total import price on fossil fuels to Mauritius more than tripled between 2004 and 2011 (17). Fossil fuel imports now constitute about 21% of total import costs for the Mauritian society as a whole (18). This makes the whole economy vulnerable to both the growth and volatility of fossil fuel prices, especially oil (19). With an increasing demand for energy, the island would have a special interest in becoming less dependent on fossil fuels (11).

1.2 Scope of the thesis

As SIDS are especially exposed to the effects of climate change (15), it could be argued that they should lead the way on reducing their own greenhouse gas emissions. While this might be true, large changes should not be based solemnly on the willingness of the population, politicians and businesses to do good. Rather, this analysis will look for a path that is both economically sound and increases independence. Emissions from fossil fuel combustion will naturally go down as a result of the decreased imports.

Likewise, the thesis will only look at consequences of different energy sources within the borders of the island of Mauritius. Coal mining, for example, cause hundreds of deaths every year, and pose major environmental threats in the area where it is done (9). However, as the mining is not on Mauritius, these factors are not considered in the thesis. This is not because they are not important, but because they should not be the sole reason for a state to turn away from coal.

As a small island, the economy might be vulnerable to abrupt changes. Thus, heavy investments in pilot projects and technologies should be left to larger states. The thesis will therefore focus mainly on well tested technologies that are already in place on the island, but with alterations that might require components and competencies from other states.

While the analysis will focus mainly on the electricity sector, a brief description of overall energy resources and consumption will be given, to search for comprehensive solutions than can reduce overall fossil fuel dependency.

The potential for wind power on the island of Mauritius could be high, and some wind farms are already established on the smaller island of Rodrigues (20). However, the wind farms require special designs because of the hard cyclones that sometimes hit the island (11). As the extra requirements to meet this challenge are beyond the scope of this thesis, wind power in general will therefore not be discussed in depth.

As the Central Electricity Board currently assumes an installation of a 100 MW coal power plant in the next few years, this analysis will mainly focus on alternatives to this new investment, instead of replacing existing power plants.

The state of Mauritius consists of more than one island, with separate electricity grids. This analysis will focus on the main island of Mauritius.

1.3 Thesis question

This thesis will explore the possibilities for the island of Mauritius to become less dependent on fossil fuel imports and try to answer the following question:

How can the island of Mauritius reduce future dependency on fossil fuel imports for electricity generation?

2 Theory

2.1 Definitions

This section defines some of the expressions as they are used in the analysis.

Primary energy resources are defined as the energy products that only need to be extracted or captured, not transformed from something else. The primary energy resources needed to cover final energy consumption is called *primary energy requirement*. *Final energy consumption* is the energy needed to provide the end user services such as lighting, air conditioning and transportation. This differs from primary energy requirement, as some of the primary energy resources have been converted to energy carriers such as electricity and charcoal, which causes losses.

The *capacity* of a generator or set of generators defines the maximum power it is able to deliver. The nameplate capacity, called *installed capacity*, is normally slightly higher than the *effective capacity*, which is the actual power delivered. The *capacity factor* of a power plant is a measurement of how much of the time the plant operates. It is found as the ratio of average power to effective capacity for the power plant.

$$Capacity\ factor\ = \frac{Average\ power}{Effective\ capacity} \qquad \text{Equation 1}$$

Power plants can be separated into three categories, after how fast they can be regulated. *Base capacity* plants operate around the clock, with none or little variation in power output (19). These will normally be thermal power plants with a capacity factor of between 70%-90% (21). *Semi base capacity* plants provide some variable output, but are generally run at constant output for long periods of time (19).*Peak capacity* plants can be switched on and off at short notice to meet variable demand (19). Peak capacity plants normally have a capacity factor of 10%-15%, but it could also be even lower (22). A *Spinning reserve* consists of backup capacity that is synchronised to immediately deliver power to the grid if needed, normally from turbines generating below effective capacity, where power output can be increased fast. A *blackout is the* loss of power in parts of or the entire electricity grid.

In this text, the terms *demand* and *load* both refer to the total power consumption of the entire electricity system at a given time. *Base load* is the constant, lowest power demand in a system. Base load normally equals night time load. *Semi base load* is the demand fluctuating around the normal demand level. *Peak load*, or *peak demand* are both expressions for the periods where power demand is significantly higher than the average. The *load factor* shows the difference between average load and peak load in a system.

$$Load\ factor\ = \frac{Average\ load}{Peak\ load} \qquad \text{Equation 2}$$

The *capacity margin* denotes an electricity system's effective capacity to the maximum peak demand:

$$Capacity\ margin\ = 1 - \frac{Maximum\ peak\ demand}{Effective\ capacity} \qquad \text{Equation 3}$$

2.2 Solar irradiation

The maximum solar irradiation on a surface changes with latitude, time of day, time of year and the orientation and tilt of the surface. The maximum solar irradiation is reached when the sun is directly above a horizontal plane, so the rays are parallel to the normal to the plane and the rays go through as little atmosphere as possible. This value is about 1000 W/m^2 (23). The irradiation reaching the surface is reduced as the solar rays angle away from the normal to the plane increases:

$$G = G_{max} cos\theta \qquad \text{Equation 4}$$

Where G_{max} is the maximum solar irradiation, and θ is the angle of incidence away from the normal to the plane. θ is dependent on the hour angle ω, declination δ, latitude ϕ, and the slope β of the plane.

The hour angle, ω, is the angle that the sun has moved across the sky since it was directly overhead. ω is therefore negative in the morning and positive in the evening. The hour angle can be calculated by:

$$\omega = (15^\circ\,\mathrm{h}^{-1})(t_{zone} - 12\mathrm{h}) + \omega_{eq} + (\psi - \psi_{\mathrm{zone}}) \qquad \text{Equation 5}$$

Where t_{zone} is the local time, $\omega_{eq}$is the equation of time, ψ is the longitude and ψ_{zone} the longitude where the sun is directly overhead at noon local time. The equation of time corrects for changes in the length of the day over the year. These changes are small (23), so ω_{eq} will be neglected in this thesis.

The island of Mauritius is located at $\psi = 57.55°\mathrm{E}$ and in the GMT + 4 time zone. The Earth turns 15° every hour, which means that $\psi_{zone}$for this time zone is

$\psi_{zone} = 4\mathrm{h} \times 15°\mathrm{h}^{-1} = 60°$

$\psi - \psi_{zone}$ can now be calculated:

$\psi - \psi_{zone} = 57.55° - 60° = -2.45°$

This gives a simplified hour angle equation for Mauritius:

$$\omega = (15^\circ\,\mathrm{h}^{-1})(t_{zone} - 12\mathrm{h}) - 2.45^\circ \qquad \text{Equation 6}$$

As the Earth moves around the Sun, the angle between the solar rays and the equatorial plane changes. Thus, the declination changes over the year, and can be calculated for each day as (23):

$$\delta = \delta_0 \sin(360^\circ \frac{284 + n}{365}) \qquad \text{Equation 7}$$

Where n is the number of the day (January 1st = 1) and δ_0 is the tilt of the Earth's north-south axis to the normal to the plane in its orbit around the Sun, which is 23.45° (23).

The angle between the solar rays and collector, θ, can be calculated using the following formula (23):

$$\cos\theta = (A - B)\sin\delta + (C\sin\omega + (D + E)\cos\omega)\cos\delta \qquad \text{Equation 8}$$

Where:

$$A = \sin\phi\cos\beta$$
$$B = \cos\phi\sin\beta\cos\gamma$$
$$C = \sin\beta\sin\gamma$$
$$A = \cos\phi\cos\beta$$
$$B = \sin\phi\sin\beta\cos\gamma$$

Here, ϕ is the latitude of Mauritius, β is the slope of the selected plane and γ is the orientation of the plane. γ is 0° for a plane facing south, 180° for a plane facing north, 90° for a plane facing westwards and 270° for a plane facing eastwards.

2.2.1 Solar hours (SH)

As most hours of sunshine have an irradiation of less than 1000 W/m^2, solar hours are used as a more exact measurement of how much solar energy reaches an area. A solar hour is a unit defining the number of hours with solar irradiance of 1000W/m^2 on a horizontal surface. Hours with less irradiation will thus be counted as less than a full hour:

$$SH = \frac{E_{sun}(\mathrm{kWh/m^2})}{1000\ \mathrm{W/m^2} \times t(\mathrm{h})} \qquad \text{Equation 9}$$

Here, E_{sun} is the total energy from the sun on a square meter in the given time period, and t is the number of hours in the same period.

Knowing the annual solar hours in a region, the total energy from the sun can be calculated for the entire region:

$$E_{sun} = SH \times 3600\ \mathrm{s/h} \times 1000\ \mathrm{W/m^2} \times A \qquad \text{Equation 10}$$

Here, A is the area of the region.

As the irradiance is less than 1000W/m^2 for most hours of sunshine, due to factors like the angle of incidence to the surface and cloud cover, solar hours are more exact when estimating the electricity that would be generated from a solar panel.

2.3 Electric vehicles (EV)

Electric vehicles get their energy from a battery rather than diesel or gasoline. Knowing the energy content of a fully charged battery and the average range on one battery, the electricity consumption per km, E_d , can be estimated:

$$E_d = \frac{E_{battery}}{r} \qquad \text{Equation 11}$$

Where $E_{battery}$ is the total energy storage capacity of an EV battery and r is the average range.

The annual electricity demand of an EV fleet, $E_{EV\ transport}$, can be estimated using the following equation:

$$E_{EV\ transport} = E_{EV} \times N_{EV} \times l = E_d \times d \times N_{EV} \times (1 + l) \qquad \text{Equation 12}$$

Where E_{EV} is the electricity consumption for one EV, N_{EV} is the number of vehicles in the entire fleet, l is the average grid losses, E_d is the average electricity consumption per km for one vehicle and d is the average distance travelled per EV.

The power, $P_{EV\ total}$, available from EV batteries at any given time can be estimated as:

$$P_{EV\ total} = P_{EV} \times N_{EV} \times s \times (1 - l) \qquad \text{Equation 13}$$

Where P_{EV} is the maximum power available from each EV battery or charging station and s is the share of EVs plugged in to a charging station capable of feeding electricity back to the grid. As most charging stations will be in private homes, the capacity of the local grid will normally define the maximum power available from each battery.

As the main purpose of EVs is transportation, batteries should never be fully discharged. For a given time period, the average power available from all batteries can be estimated:

$$P_{EV\ average} = \frac{E_{battery} \times b \times N_{EV} \times s \times (1 - l)}{\Delta t_{discharge}} \qquad \text{Equation 14}$$

Where b is the share of the battery that can be discharged and $\Delta t_{discharge}$ is the length of the time period.

Due to grid losses, charge and discharge of a battery will consume some energy. If the available power of batteries is utilized to its full potential, the annual additional electricity demand would be:

$$E_{EV\ additional} = E_{battery} \times b \times N_{EV} \times s \times 365 \times (1 + l) \qquad \text{Equation 15}$$

Given that cars consume the energy estimated in Equation 12 for transportation and in Equation 15 for delivering power back to the grid, the average power needed to recharge, $P_{EVcharge}$, can be estimated:

$$P_{EVcharge} = \frac{E_{EV\ total} \times (1 + l)}{\Delta t_{charge} \times 365} = \frac{(E_{EV\ transport} + E_{EV\ additional}) \times (1 + l)}{\Delta t_{charge} \times 365} \qquad \text{Equation 16}$$

Where $E_{EV\ total}$ is the total electric energy needed both for transportation and for grid capacity. Δt_{charge} is the daily time available for charging.

If all EVs charge at the same time and charge with the same maximum power as they can deliver, the total power needed will be:

$$P_{EV\,max} = P_{EV} \times N_{EV} \times (1 + l)$$ Equation 17

To calculate the total number of EVs needed to provide a given capacity, the following equation can be used:

$$N_{EV} = \frac{P}{P_{EV\,max} \times s}$$ Equation 18

Where P is the desired capacity.

Knowing the efficiency of electric vehicles and gasoline vehicles, the potential fossil fuel savings for switching from gasoline to electricity fuelled vehicles, can be estimated by calculating the share of energy consumption that is converted to kinetic energy. With a 25% efficiency, for example, 25% of energy consumption is converted to kinetic energy.

$$E_K = E_{EV} \times \eta$$ Equation 19

Where E_K is the kinetic energy and η is the efficiency of the vehicle. The equivalent energy consumption from a gasoline vehicle can then be found:

$$E_{gasoline} = \frac{E_K}{\eta}$$ Equation 20

2.4 Energy resources

This chapter gives a brief overview of energy resources considered, with their characteristics and qualities.

2.4.1 Fossil fuels

These carbon rich materials have been produced through exposure to heating and pressurizing of biological remains in the ground over hundreds of millions of years (18) (9). Thus, fossil fuels are basically solar energy carriers, with the energy fixed in hydrocarbons in the ground. All liquid petroleum products are made from crude oil (18).

Coal

Coal is the world’s main resource for electricity generation (9), and the growth in coal power plant installations is faster than any renewable energy technologies on an absolute basis (5). Still an abundant resource, coal supply could last for more than 200 years with today’s usage rates (9). It can be used for energy purposes through steam generation, gasification or liquefaction (9). Coal power plants with steam generation normally serve best as base capacity.

Heavy Fuel Oil (HFO)

These oils are mainly produced from the residues of crude-oil distillation, and can be used for steam boilers in power plants, on ships and in industrial plants (24) (18). HFOs available on the market are normally blended with other petroleum fractions to achieve the right qualities (24). HFO generators are relatively slow and therefore work best as base capacity.

Gasoline
Gasoline is a liquid petroleum fuel, consisting of a mixture of different volatile, flammable hydrocarbons (25). It is mainly used for fuelling internal-combustion engines in vehicles (25). The average efficiency of internal combustion engines in cars is about 25% (22).

Diesel
Diesel is another liquid petroleum fuel mainly produced from less volatile fractions of crude oil than in gasoline production (26). There are several types of diesel – the lightest and most volatile are for high-speed engines with variable load and speed, like trucks and cars (26), while heavier distillates are for low- and medium-speed engines with little variations, like stationary engines (26). These generators are best used as semi base capacity.

Kerosene
Kerosene is a light, oily liquid (27). Some kerosene types can be used as aviation fuel, while others are used for electricity generation or domestic purposes such as in lamps (18). In electricity generation, kerosene turbines work well as peak capacity.

Liquefied Petroleum Gas (LPG)
LPG is derived from oil, and consists mainly of propane and butane (18). Although a gas under atmospheric pressure, LPG is normally pressurized to a liquid under storage and transportation (18).

Natural gas
Natural gas is a fossil gas consisting mainly of methane and some ethane, with some other hydrocarbons such as propane and butane and nonhydrocarbon gases such as carbon dioxide and hydrogen (28). Electricity generators fuelled with natural gas can function both as base, semi base and peak capacity (29).

2.4.2 Renewable energy
There are three sources of renewable energy: Solar irradiation, the moon's pull, and energy radiating from the centre of the Earth. Solar irradiation gives rise to several renewable energy resources through vaporization of water, photosynthesis and wind and ocean systems.

Hydropower
Hydro power is energy derived from the potential and kinetic energy in water that has been vaporized and brought to a higher altitude. Water can be stored in dams, and turbines are easy to regulate. These power plants can therefore provide peak capacity. Alternatively, turbines are placed directly in the stream of the river, where generation is dictated by the run of the river.

Bagasse
Bagasse is a fibrous, cellulosic material that is left after sugar extraction from sugar cane (30) (12) (18), a plant grown on most of the arable land on Mauritius. Bagasse can be combusted for steam generation, and in turn electricity generation. These plants provide base capacity.

Photovoltaic solar cells
Photovoltaic electricity generation differs from all other electricity generation. While all other power plants include an engine or turbine, solar cells generate electricity directly from the electromagnetic energy in solar rays through the separation of positive and negative charges in a semiconductor (23).

They thus generate direct currents instead of alternating currents. Output from a solar cell varies with solar irradiation, and the capacity factor of solar cells is therefore relatively low.

Landfill gas

Landfill gas is produced by anaerobic fermentation of waste, and consists mainly of methane and carbon dioxide (29). The gas can be combusted in a gas turbine, and can be easily regulated and shut on and off, thus providing good semi base and peak capacity.

3 Methodology

3.1 Calculations and sources

The background material on the global energy situation was mainly based on the International Energy Agency (IEA)'s Key World Energy statistics, in combination with statistics on fossil fuel prices from British Petroleum (BP). Based on energy statistics from the Mauritian Central Statistics Office (CSO), a basic overview of energy requirement, energy conversions and energy demand was made. A deeper insight into the electricity generation system and power plants was provided by annual reports and electricity plans from the Mauritian Central Electricity Board (CEB).

Solar irradiation over the day and year for different angles was estimated using the method explained in chapter 0. Data from the Nissan LEAF electric vehicle was used to estimate the number of electric vehicles needed to provide peak capacity in the evening, following the steps explained in chapter 2.3. Scenarios for an electricity system with solar panels combined with electric vehicle batteries for storage and backup peak capacity from natural gas was then developed. All calculations have been done in Excel.

3.2 Assumptions

The suggested measures have been compared to a scenario where a planned coal power plant caters for all new electricity demand. Some other projects are under development, but these are considered small in comparison and therefore neglected. Projected future electricity and power demand is based on the base scenario from the Central Electricity Board. The efficiency of the planned coal power plant is set to 45%.

Maximum capacity factor of thermal power plants is generally assumed to be 80%.

Solar irradiation on Mauritius is set to an average of 1600 solar hours per year. Solar panels are assumed to have an efficiency of 15%, based on the typical efficiency of a solar panel from Renewable Energy Corporation (31).

The maximum capacity provided by a battery when connected to a local, low voltage grid is assumed to be 3 kW, the typical capacity of a household circuit. To cater for different usage patterns of electric vehicles, a share of the cars are assumed to be unavailable each evening. For the same reason, only a fraction of the battery is assumed available for evening discharge, to allow for driving later the same evening. As an estimate, therefore, half the cars are assumed plugged in at any given time, with only 25% of the energy available for discharge. The charge and discharge of batteries could result in some additional grid losses, which throughout the analysis are set to 10%. For simplicity, evening peak demand is assumed to last for three hours and have the same magnitude as daytime peak demand. To estimate energy consumption of a typical car, the average daily travel distance is set to 20 km, which is about the same as the radius of the island (32). Assumptions on storage capacity, power and mileage of electric vehicles are based on data from the Nissan LEAF. Engine efficiency, however, was not available from the Nissan web page. Based on the Tesla Roadster, an engine efficiency of 88% is therefore assumed, while the efficiency of a gasoline engine set to 25%, based on data on internal combustion engines from the International Energy Agency.

When dimensioning the needed capacity of photovoltaic solar panels and natural gas generators, it has been assumed that peak power demand could happen on a densely clouded day, but that no electric vehicles charge at that time. Lastly, it is assumed that no additional spinning reserve is needed, so that the increased need for peak capacity equals the increase in peak demand.

When estimating the overall differences in fossil fuel imports between a coal power plant and the suggested solutions, it is assumed that natural gas generators provide the additional electricity needed to charge electric vehicles at night.

3.3 Data collection

Information was gathered mainly through public statistics and a literature study. A trip to Mauritius deepened the understanding of the subject and helped requiring data and statistics.

Statistics for Mauritius were collected through annual energy statistics from the CSO and annual reports from the CEB. As these are both governmental bodies, they are likely the most reliable sources for information. However, as the CEB has an economic interest in the electricity system of Mauritius, they might not be fully objective on issues regarding the development and investments of generation plants in the future. Although most information was available on the internet, a visit to the CSO was conducted to get copies of energy statistics from before these were published online. In the end, these historical data were not used in the thesis. Analyses on the global energy situation are based on statistics from the International Energy Agency (IEA) and British Petroleum (BP), available online.

A literature study on the energy and electricity system on Mauritius was conducted, including both scientific articles and governmental and CEB reports and long term energy strategies. Articles on solar irradiation, variability issues and on the energy situation for other small islands and isolated areas was conducted to provide a background for the suggested changes in the energy system.

Two months before the thesis deadline, the CEB released an integrated electricity plan for the next ten years. This has provided some more data on the expected development of electricity demand, peak demand, and planned new installations and grid upgrade. The calculations have been altered to better support this new information.

As part of the preparations, a one month trip to the island of Mauritius was conducted in August-September 2012 together with Synnøve Lill Paulen, a fellow student. With few contacts on the island, it was hard to predict on beforehand what the best method for information gathering would be. However, with a relatively small island, most people working in the field of energy and electricity generation know each other and where to get information. Meetings with some of them therefore opened the door to new contacts that in turn offered new information and contacts. In the end, most people recommended had already been contacted, which suggests that the coverage of key persons was relatively good.

To get a broad picture of the situation, questions were prepared for each meeting, adapted to get most information about the person's field of expertise. Claims from one source were often tested in later meetings to control their validity, and to broaden the understanding of the different facets of the topic. The one month stay included meetings with representatives from the CEB and the sugar industry, professors at the University of Mauritius (UoM), a journalist from one of the main newspapers, government advisors and environmental groups. In addition, several informal conversations with people on Mauritius helped test ideas and getting a better overview of popular opinions and what solutions might be politically feasible. The CEB also provided field trips to the Midlands dam while it was under construction, and gave a tour of the Champagne hydro power plant. Another field trip was taken to the sugar factory and power plant in La Baraque, owned by the sugar and energy company Omnicane. On the return to Norway, a last meeting with a social anthropologist specializing on the society of Mauritius helped preventing possible systematic cultural misunderstandings. None of the information gathered during meetings or conversations are quoted directly in the thesis, but are used as a background to understand the challenges of the Mauritian electricity and energy system, and ensure that the suggested alternatives are viable.

4 Analysis

4.1 Primary energy resources

This chapter creates an overview of some primary energy resources currently available on the island of Mauritius.

4.1.1 Imported energy

The imported energy resources are all fossil fuels. In 2011, Mauritius imported a total amount of 66 003 TJ of different fossil fuels (16):

Table 1 Fossil fuel imports on Mauritius in 2011 (16)

Fuel source (TJ)		Fuel type (TJ)	
Fossil	66,003	Coal	17,137
		Gasolene	5,276
		Diesel	13,105
		Dual purpose kerosene	10,029
		Heavy Fuel Oil	17,477
		LPG	2,979

4.1.2 Solar energy

The Mauritian government estimates that the island has an average of 2900 hours of sunshine per year (4). According to the solar panel company SFER, Mauritius has somewhere between 1400 and 1800 solar hours per year (33). With a total area *A* of 2040 km^2 (12), the total energy delivered by the sun in an average year can be estimated roughly using Equation 10:

Table 2 - Annual solar energy reaching Mauritius

Solar Hours (h)	1 400	1 600	1 800
Energy (PJ)	10 000	12 000	13 000

Table 2 shows a low, high and medium estimate of solar energy available on Mauritius. In other words, about 0.6 % of the area of Mauritius receives the same amount of energy in one year as the energy in the annual imports of fossil fuels. This does not mean that all of the Mauritian energy requirements could be covered by installing photovoltaic (PV) solar panels, but it indicates that in theory there are enough energy resources available to become independent on fossil fuel imports.

4.1.3 Energy from waste

According to the Ministry of Environment, 4.20 x 10^8 kg of waste was collected on Mauritius in 2009 (17). Mohee (34) has estimated that the calorific value of the waste on Mauritius is about 18 800 kJ/kg dry matter, with a moisture content of 48 %. Assuming that energy from vaporization of water can be recovered, the annual energy available from waste can be estimated. A 48 % moisture content means that 52 % has a calorific value of 18 800 kJ/kg, while 48 % of it is water, which will give no net energy when combusted.

$$4.20 \times 10^8 \text{ kg} \times 52 \,\% \times 18\,800 \text{ kJ/kg} = 4.69 \text{ TJ}$$

4.1.4 Other renewable energy resources

As Mauritius is a small island, a lot of the weather comes from the oceans surrounding it. Situated within the path of the South East Trade Winds, the island enjoys steady and good wind conditions for most of the year (19). Wind, waves and currents around the shores of Mauritius can be considered separate energy resources, created in other areas than the actual island. The same can be said about some of the rain, although cloud formation also happens on land. The weather systems give a small island like Mauritius one advantage, compared to larger states, or states with fewer coasts: Some of the solar energy reaching the oceans around Mauritius, which would otherwise be hard to collect, is concentrated and transported to their shores. The wind and waves transfer kinetic energy that can be used directly for electricity generation in turbines, while the rain provides both potential energy when it falls on high ground and the osmotic potential difference between fresh and salt water. In addition, the hot surface ocean water contains huge amounts of energy that could be extracted through Ocean Thermal Energy Conversion. In addition to solar energy, some geothermal heat radiates through the island from below, and tidal changes in ocean levels could also be a source of energy. These resources are harder to quantify than direct solar energy, but might still contribute significantly to the island’s energy supply.

4.2 Primary energy requirement

The rough estimates above give some indication as to how much energy is really available on the island of Mauritius. Not all of this is used for energy purposes, however.

In 2011, 83.3% of primary energy requirement was met with imported fossil fuels (18), and the rest with domestic renewable energy, with bagasse constituting 94% of renewable energy (18). Total primary energy requirement on Mauritius was 59 746 TJ, or 16.6 TWh, in 2011 (18). This is only the primary energy that has somehow been on the market, such as imported fossil fuels or electricity generation, and data are for the state Mauritius, including islands like Rodrigues.

Table 3 - Primary Energy Requirement on Mauritius in 2011 (16)

Fuel type	Primary energy requirement (TJ)	Percentage
Coal	16,650	27.81%
Heavy Fuel Oil	10,387	17.35%
Bagasse	9,133	15.25%
Diesel	8,931	14.92%
Aviation fuel	5,625	9.39%
Gasoline	5,444	9.09%
LPG	2,979	4.98%
Fuel wood	320	0.53%
Hydro power	203	0.34%
Kerosene	182	0.30%
Landfill gas	11	0.02%
Wind power	10	0.02%

As Table 3 shows, coal accounts for the largest part of primary energy requirement, followed by Heavy Fuel Oil (HFO). Most of the biomass used for energy purposes is bagasse from sugar production, in addition to some fuel wood. The reason why fuel wood is so little widespread is that consumers have easy access to Liquid Petroleum Gas (LPG), which is the main source for cooking (30), and that the island has very little need for spatial heating because of its climate. The wind power is from turbines on the island of Rodrigues and is therefore not part of the rest of this analysis.

4.3 Energy conversions

Some of the primary energy resources are converted into more convenient energy carriers before consumption. Most important is the conversion to electricity, which will be elaborated in more detail in the following chapters. In addition, some fuel wood is converted to charcoal (16).

Table 4 shows the different primary energy sources used to generate electricity on Mauritius. In the process, about 70% of the energy is transformed into other forms than electricity, and therefore considered losses in the electricity generation. However, the combustion of bagasse is done in power plants connected to sugar factories. The generated heat is used in the production process, and is therefore not an overall loss. Note that about 158 TJ, or 1.6% of the electricity, is used as input for new electricity generation.

Recently, some photovoltaic (PV) panels have been introduced to Mauritius. As they are so new, the CSO has not yet any data on their annual power generation.

Table 4 - Energy requirement for electricity generation on Mauritius in 2011 (16)

Fuel	**Energy requirement**		**Total energy requirement**	**Result**			
	TJ	%	**TJ**		**GWh**	**TJ**	%
Coal	16,025	48.93%	32,751	**Electricity**	2,731	9,832	30%
Diesel	64	0.20%					
Kerosene	159	0.49%					
Heavy Fuel Oil	8,623	26.33%		**Losses**	6,366	22,919	70%
Bagasse	7,497	22.89%					
Hydropower	203	0.62%					
Wind power	10	0.03%					
Landfill gas	11	0.03%					
Electricity	158	0.48%					

4.4 Final energy consumption

Figure 6 shows the total primary energy requirements on Mauritius in 2011, the energy used to generate electricity and the final energy consumption, and how it is divided between different fuels, while Table 5 shows how these fuels are consumed by sector. The difference between the primary energy requirement and final energy consumption is mainly because some primary energy is converted to electricity, which causes losses (18).

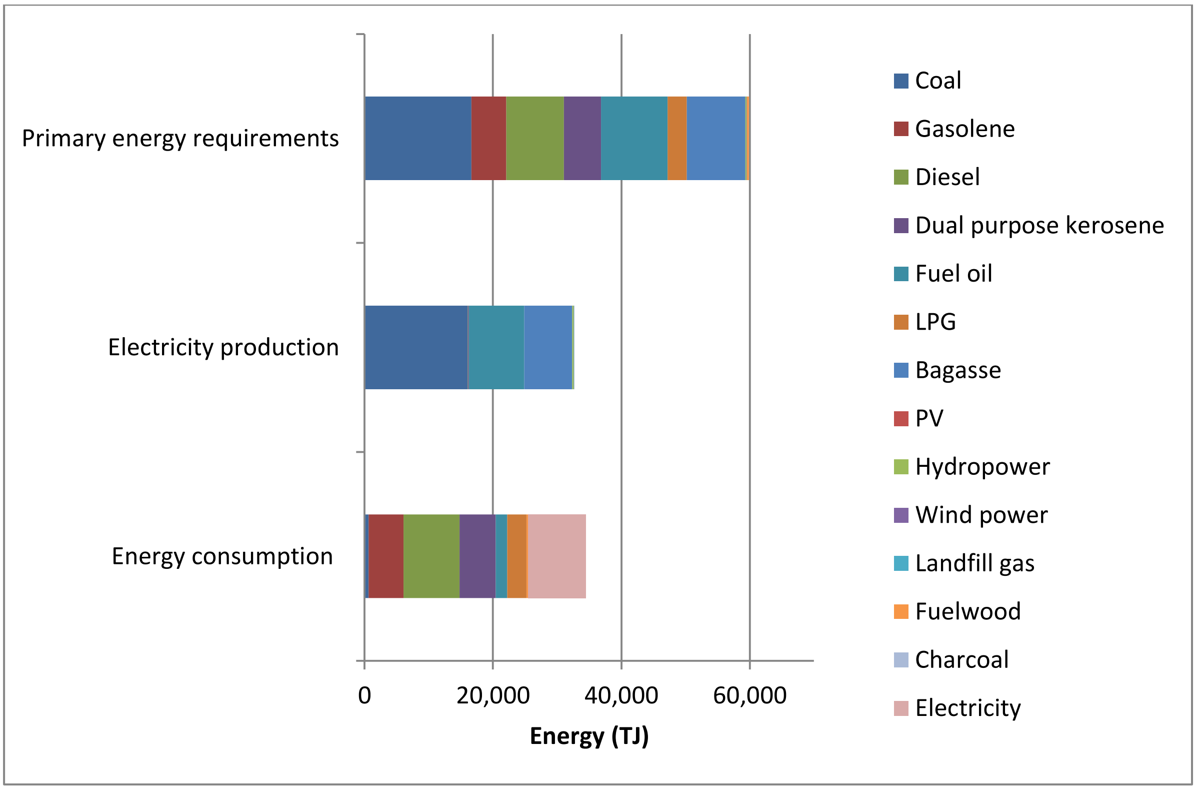

Figure 6 - TPES, electricity generation and final energy consumption in 2011 (16)

The Mauritian Central Statistics Office (CSO) divides energy usage into different sectors, as shown in Table 5. *Agriculture* is energy used for irrigation and by other agricultural equipment (18). *Commercial and distributive trade* is energy consumed by the commercial and business sector (18). *Residential* is the energy consumption by the residential sector (18), *manufacturing* is the energy consumption in industry and construction, and *transport* is energy consumed by land vehicles, ships and local aircrafts (18). In addition, some primary energy is converted to other energy carriers, mainly electricity.

Table 5 - Final energy consumption on Mauritius in 2011 (16)

Fuel	Final energy consumption per sector and fuel		Sector	Total final energy consumption per sector	
	TJ	%		TJ	%
Gasolene	5,444	29.88%	**Transport**	18,221	50.47%
Diesel	6,810	37.37%			
Aviation fuel	5,625	30.87%			
Heavy Fuel Oil	139	0.76%			
LPG	204	1.12%			
Coal	625	6.73%	**Manufacturing**	9,286	25.72%
Diesel	1,822	19.62%			
Heavy Fuel Oil	1,626	17.51%			
LPG	237	2.55%			
Fuelwood	23	0.25%			
Sugar cane	1,637	17.63%			
Electricity	3,317	35.72%			
LPG	509	15.07%	**Commercial and distributive trade**	3,378	9.36%
Electricity	2,854	84.49%			
Charcoal	15	0.44%			
Kerosene	22	0.45%	**Household**	4,916	13.62%
LPG	2,019	41.07%			
Fuelwood	260	5.29%			
Electricity	2,612	53.13%			
Charcoal	4	0.08%			
Diesel	99	55.00%	**Agriculture**	180	0.50%
Electricity	81	45.00%			
Electricity	111	90.98%	**Other**	122	0.34%
LPG	11	9.02%			

As shown in Table 5, the transport sector is the most energy consuming sector on Mauritius, with 50.5% of final energy consumption (18). Table 5

Table 5 - Final energy consumption on Mauritius in 2011 (16) shows how much of the different fuels are used. Aviation fuel, HFO and LPG are only used for planes and ships, while gasoline and diesel is used for land transportation (18). Land transportation alone constitutes about 67.3% of energy needs for transportation, or 34.0% of total final energy consumption. Electricity provides a large share of energy supply in all other sectors than for transportation.

4.5 Electricity

The following chapter provides a more detailed description of the Mauritian electricity system.

4.5.1 Legal system

The Electricity Act (1939) gives the Government responsibility for distribution, transportation and sales of electricity (19). Through Central Electricity Board Act (1964), these responsibilities are executed by the Central Electricity Board (CEB), a state owned enterprise reporting to the Ministry of Renewable Energy and Public Utilities (19). The CEB has contracts with Independent Power Producers (IPPs), sugar factories that burn coal and bagasse to generate electricity and steam for own production. The contracts allow them to sell a certain amount of electricity to the national grid at a set price. In most of the contracts, the CEB pays for the available capacity, and then generation is adjusted after electricity demand at that time. If demand is lower than expected, the CEB will still have to pay the same as if the full capacity of the plant was used to generate electricity (20). A National Grid Code regulates a somewhat similar system between the CEB and Small Independent Power Producers (SIPPs) with power plants of less than 50 kW capacity. The CEB is obliged to accept all electricity from SIPPs. This project is called the *Small Scale Distributed Generation* (SSDG) project, and includes both wind, solar and small micro hydro power (19), with a maximum total installed capacity of 20 MW. A feed-in tariff is established to encourage people to join the scheme (26). Wind turbines on Rodrigues are owned by the CEB (19). Wind farms and large scale PV plants built on the island of Mauritius, however, will follow a *Build Own Operate* scheme, where private enterprises sell electricity to the CEB (19).

Electricity tariffs are set by the government, through the CEB. Customers are divided into three main groups: Residential, commercial and industrial (20). In addition, smaller groups include public lighting, traffic lights and irrigation (20). The residential sector consumes about 32% of total electricity sales, while the commercial sector represents about 36% and the industrial sector 30% in 2011 (20).

4.5.2 Demand

This section explores both electric energy and power demand on the island of Mauritius.

Electric energy demand

On average, electricity demand grew with 4% per year between 2003 and 2011 (18). This is a reduction from in the 90s, where it grew by 5% annually (19). This was mainly caused by a diversification of the economy towards more industry and exports (20). Historically, demand has increased because of the economic development, matched by on-going investments in electrification (20). In the summer, from December to February, electricity consumption is generally higher than in the winter, mainly because of the use of air conditioning.

Power demand

So far, only the total annual energy flows have been analysed. But *when* energy is available and consumed is essential for a well-functioning energy system. Power is the rate at which work is done, and power demand varies throughout the day and over the different seasons in a year. In general, demand is higher in weekdays, in the summer and during the day, due to activities in the commercial sector and air conditioning. On workdays, demand is normally high between 9:00 and 16:00, mainly because of the commercial and industrial customers (20). After a drop at around 18:00, demand rises to almost the same level between 18:00 and 21:00, mainly caused by the residential sector (20). In the weekend and in the winter, demand is relatively low all day. However, the evening peak stays almost the same all year (20). Demand is at its lowest at night.

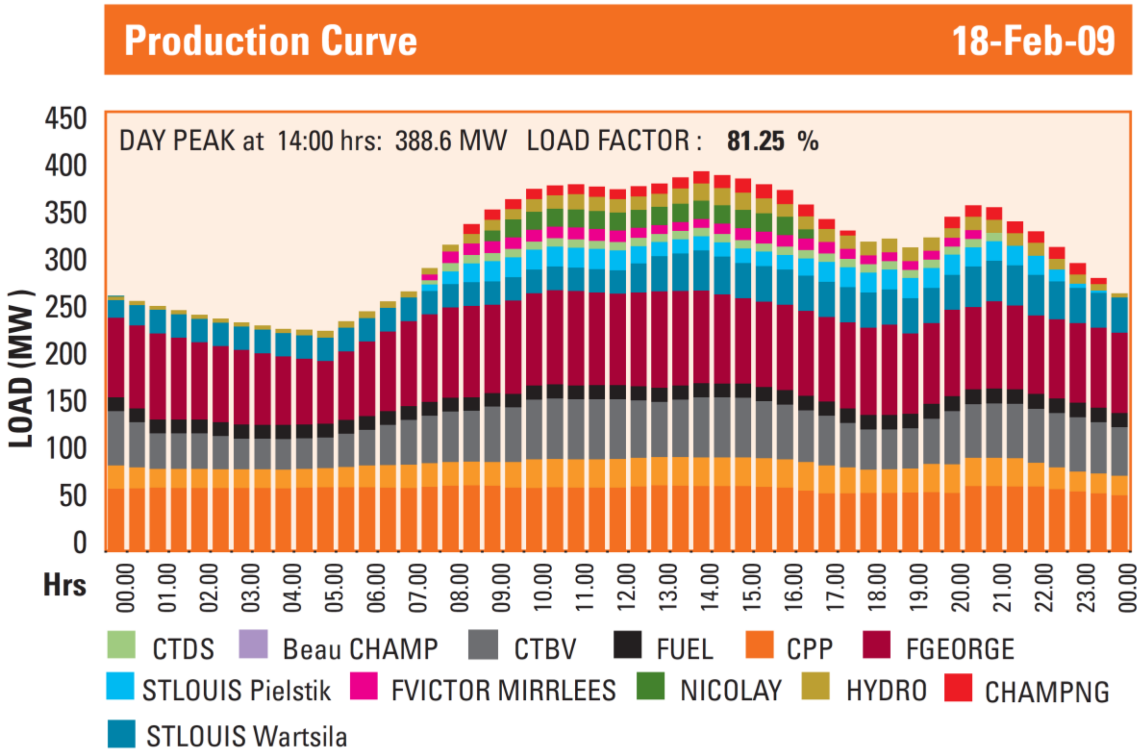

Figure 7 - Generation curve on the island of Mauritius, February 18 2009 (19)

Figure 7 is from the Central Electricity Board’s Annual Report in 2009, and shows generation pattern on the day with highest peak demand in 2009. As generation always follows demand, this gives also gives a representation of the variations in power demand throughout the day. The different colours represent the generation from each power plant. These are listed in section 4.5.3.

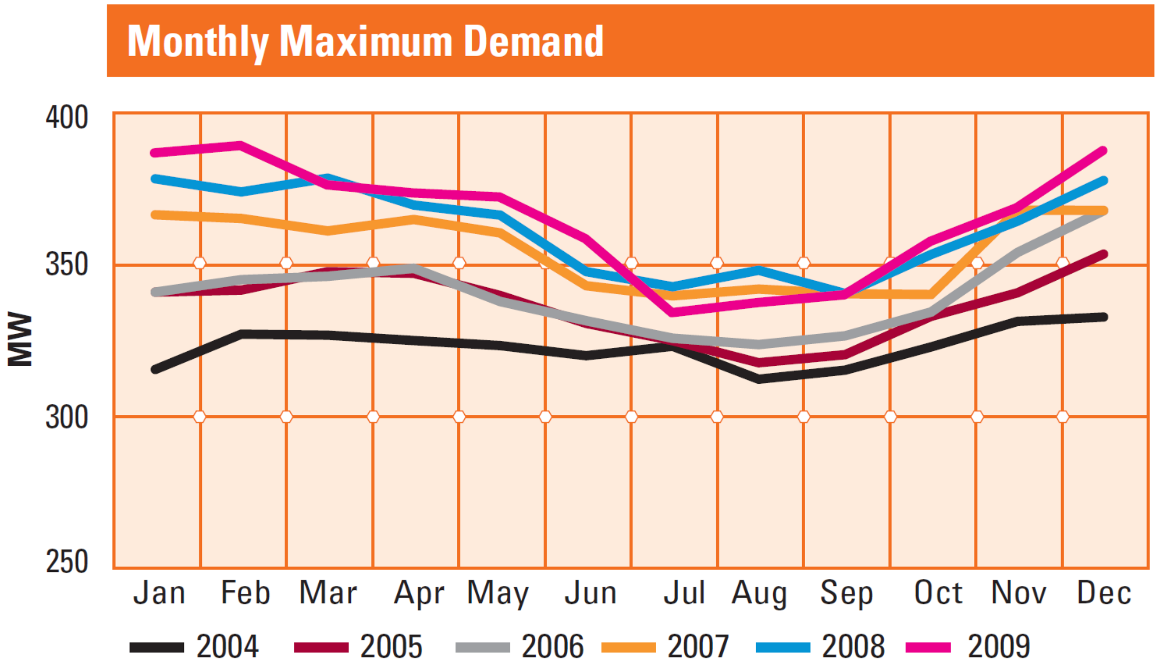

Figure 8 - Monthly Maximum Demand, from the Central Electricity Board Annual Report 2009 (19)

As Figure 8 shows, power demand varies from season to season. Power demand is higher in the summer, from December to March, mainly because of air conditioning.

Peak demand

Peak demand is the highest power demand over a set period. Peak demand is growing at about the same rate as overall electricity demand on the island of Mauritius (18). As Figure 7 shows, there are typically two peaks during a normal day. In Figure 7, peak demand was 388.6 MW at 14:00, with another peak in the evening. The sharp evening peak is normally between 19:00 and 20:00. It has traditionally been the highest, but the growth of the commercial sector has increased the daytime peak so that it is sometimes higher than the evening peak (20). The morning peak in the summer grows especially fast, due to the increased use of air conditioning (35). The latest years have seen a rise in summer temperatures and shorter winters, which will increase this effect (35). On Mauritius, temperature is one of the largest factors affecting electricity demand. Badurally, Dauhoo and Elahee (35) have estimated that 70-80% of variations in peak electricity demand are due to the temperature. Peak demand is normally in early summer, in November or December.

As a small, isolated system, peak demand management is key on Mauritius. Mismatch in demand and supply may lead to supply shortage, which could lead to blackouts of the entire electricity grid (19) because of voltage or frequency problems. While most other states can import and export electricity to manage fluctuations, the Mauritian electricity grid is not connected to any other grid. Figure 9 shows the development in annual peak power demand and effective and installed plant capacity on the island of Mauritius.

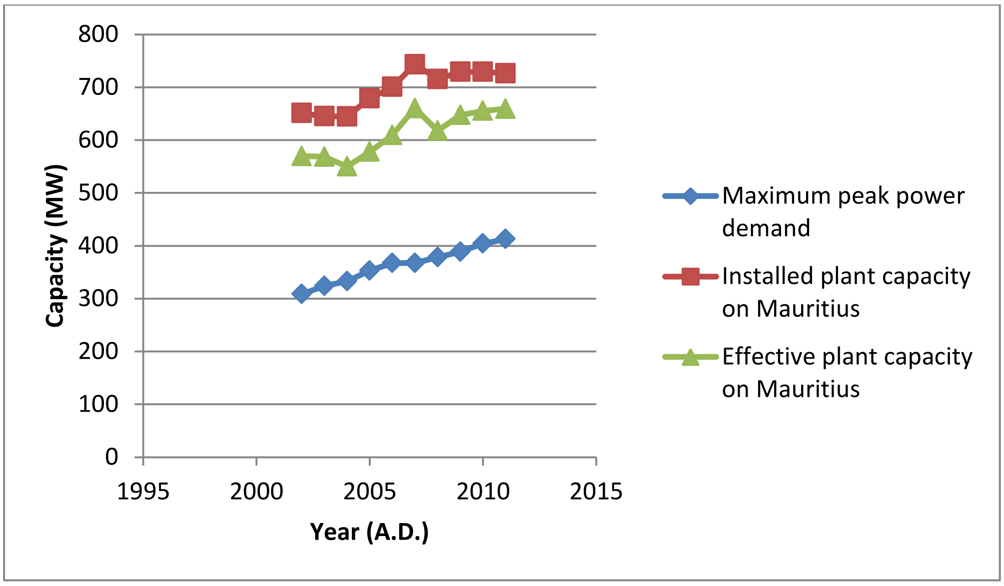

Figure 9 – Maximum peak demand and capacity changes on the island of Mauritius (18)

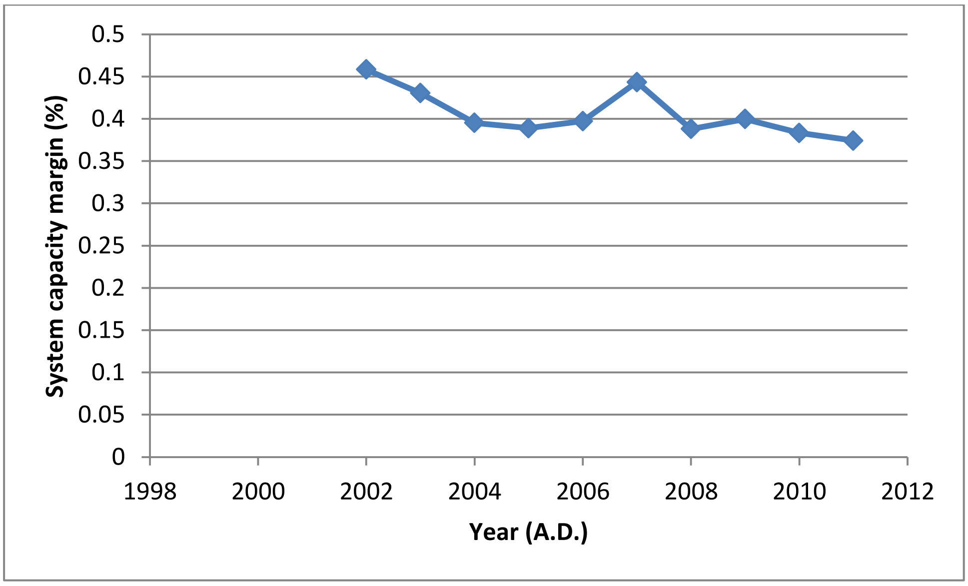

Figure 10 - Margin between effective plant capacity and maximum peak power demand (18)

Demand has to be met even under scheduled maintenances or forced outages (20). Peak demand partly defines how high the total capacity of all power plants together needs to be, as this is the point when most of them have to be on at the same time. Figure 10 shows the system capacity margin of the electricity system on the island of Mauritius.

This system capacity margin has decreased from 46% in 2002 to 37% in 2011, which means that a larger share of the power plants will have to operate at the same time to meet peak power demand, which increases the chance of blackouts if a large power plant is, for some reason, out of service at that time.

Load duration curve

A load duration curve is a histogram showing the number of hours with each load in a year, sorted with increasing number of hours along the x axis. Figure 11 shows the load duration curve for the island of Mauritius in 2009. From this, base load can be defined as approximately everything up to 140 MW, as there are no hours with less generation than that. Semi base load could be defined as between 140 and 300 MW, with the relatively few remaining hours with a load above 300 MW defined as peak load. The maximum peak demand is almost three times as high as the lowest demand. Base load also varies throughout the year. As could be seen in Figure 7, about 230 MW was required around the clock one summer day, while Figure 11 shows that about 140 MW is the most common load. With 8760 hours in a year, no loads can last longer than that. Hence, the sudden drop to the right of the graph.

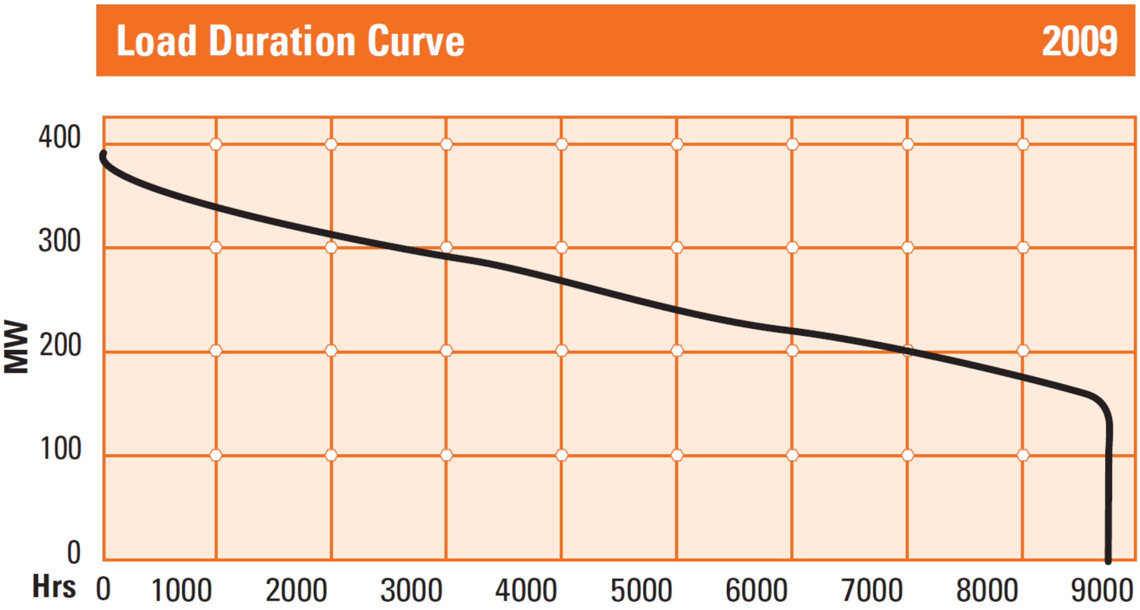

Figure 11 - Load Duration Curve 2009, from the Central Electricity Board Annual Report 2009 (19)

The Central Electricity Board estimates an average system load factor of 82.8% in the summer and 68.6% in the winter (20). A low load factor means that a power plant, on average, is used less, which increases the cost of electricity per generated unit.

4.5.3 Supply

As there is no means of storage in the Mauritian grid, supply has to match demand at all times. This means that there has to be enough capacity installed to generate enough power for peak demand, and enough electricity has to be generated to meet overall demand.

Capacity

Power plants can be divided into four different categories after their generation pattern: Slow generators in thermal plants provide base capacity, and generate around the clock. Other, faster thermal generators provide semi base capacity, operating at longer periods of time. Peak capacity is provided by fast thermal generators and hydro power, and can be regulated to match variable demand. The last category accounts for capacity that provides a variable output with little or no means of regulation, such as run-of-river hydro power, solar panels and wind turbines.

At night, demand is so low that peak and semi base capacity is shut down, and the base capacity plants are run at a lower output (20). This gives a lower efficiency and is therefore more expensive for the operator (20). In addition, it sometimes makes it hard for the CEB to buy as much electricity from the IPPs as is contracted (20).

In the case of a breakdown of one of the main power plants, there should always be enough of backup power to immediately replace the power plant's capacity. Demand is not only variable, but also to a certain degree unpredictable. For these reasons, the CEB operates with a spinning reserve of 10 % of peak load (14).

As Figure 12 shows, 51% of electric energy and 40% of power is provided by IPPs and the rest is provided by the CEB. The IPPs provide base and some semi base capacity, while the CEB cater for the rest of semi base capacity, peak capacity and both spinning reserve and other backup reserves for breakdowns and maintenance. As the CEB plants run less on full capacity, they provide less of the total electric energy. Figure 13 shows how the base capacity IPPs provide a higher and higher share of total electricity generation. The lower share of flexible capacity in the system makes it harder for the CEB to cater for all fluctuations in demand.

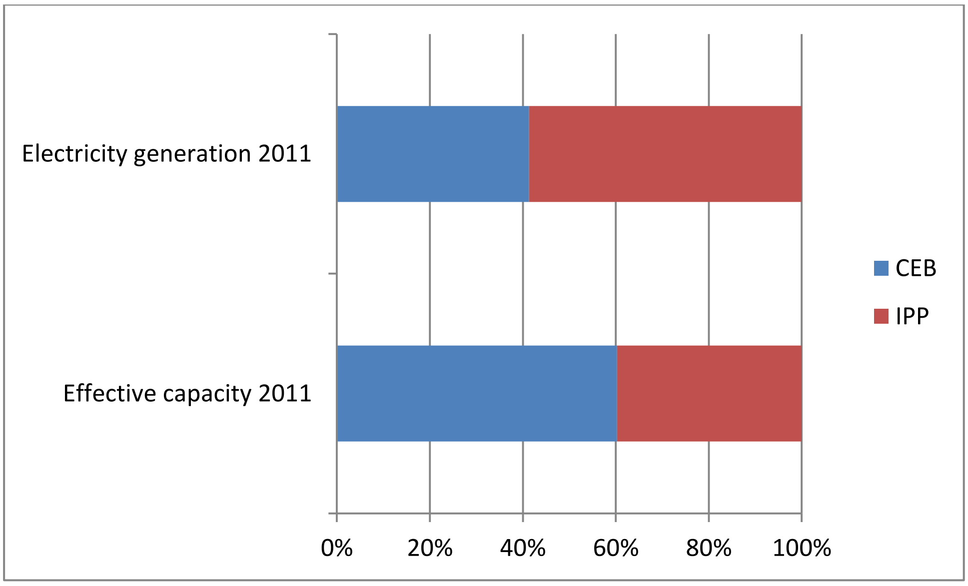

Figure 12 - Electricity generation and effective capacity from the CEB and IPPs in 2011 (18)

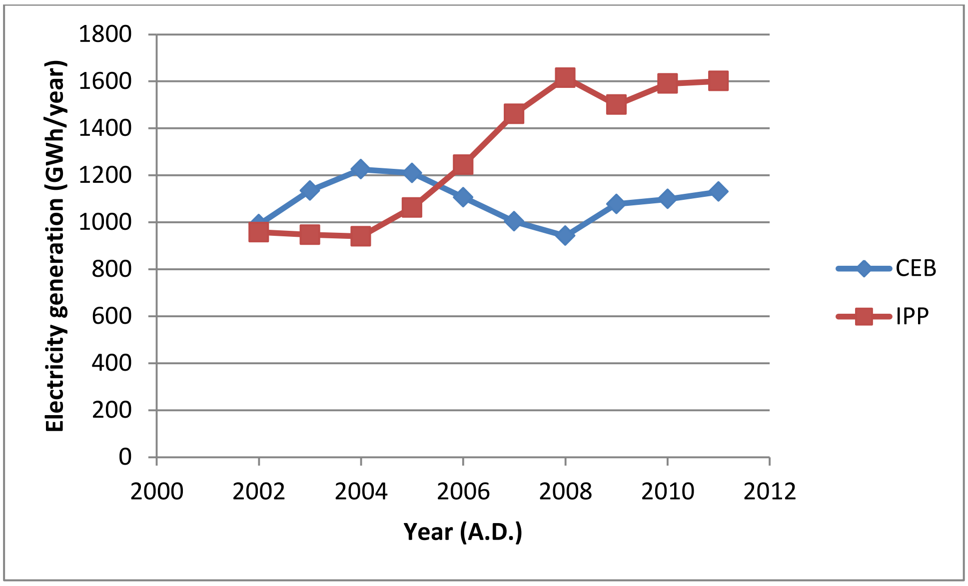

Figure 13 - Historical development in annual electricity generation from the CEB and IPPs (18)

Figure 14 shows the different power stations in Mauritius, and how electricity is distributed through the electricity grid. The double circuit 66 kV transmission lines are red on the map, but blue in the list of labels.

Power stations and grid

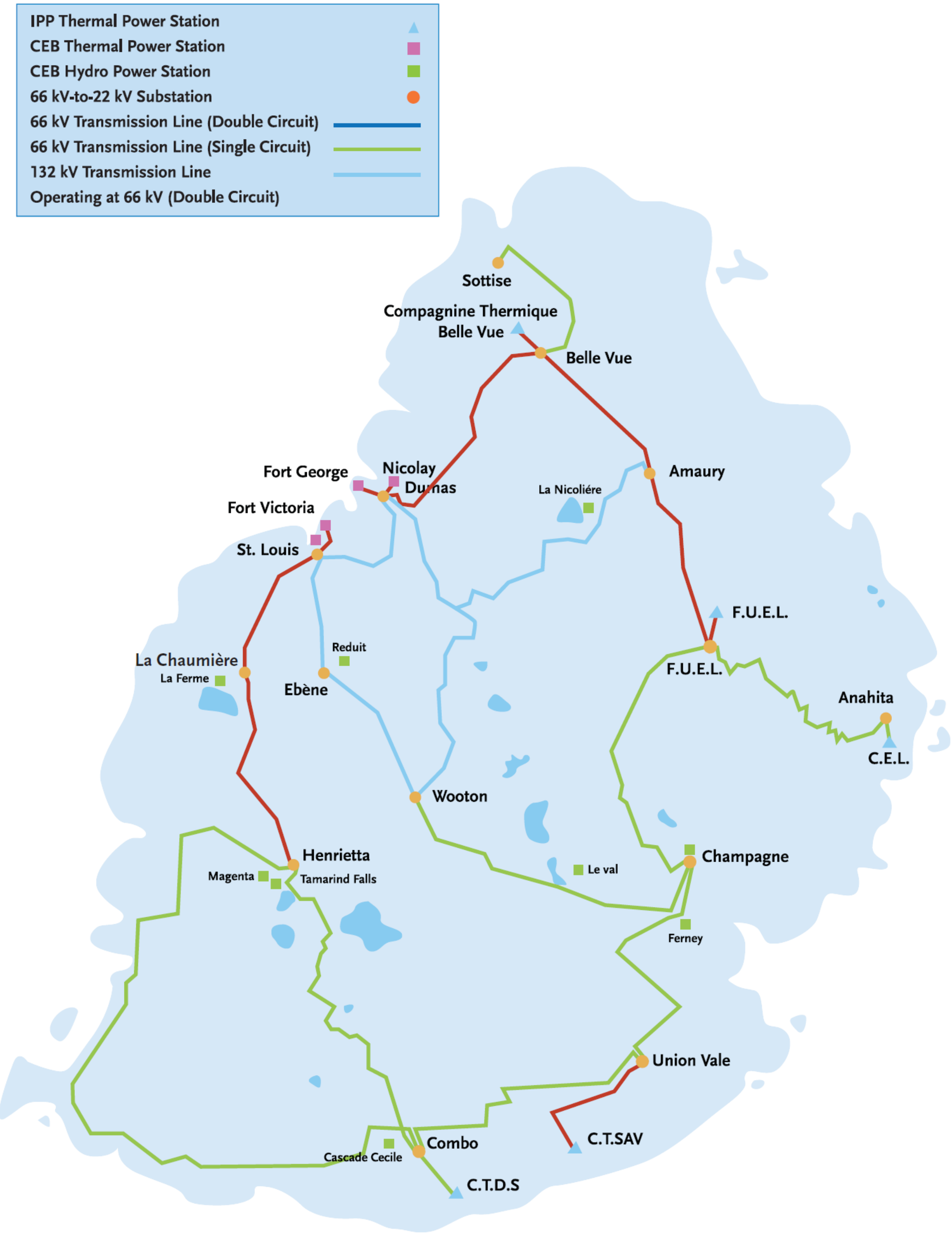

Figure 14 - Power stations and grid system on the island of Mauritius (20)

Liquid fossil fuels

Table 6 shows the current power plants on the island of Mauritius generating electricity from liquid fossil fuels. All of them are owned by the CEB and located in the capital, Port Louis.

Table 6 - Diesel, HFO and kerosene power plants on the island of Mauritius (18) (20) (19)

Name	Fuel	Effective capacity (MW)	Electricity generation in 2009 (GWh)
Fort George	HFO	134	636.6
St Louis	Diesel	75	239.4
Fort Victoria	Diesel	107	31.8
Nicolay	Kerosene	76	15.3
Total		**332**	**923.1**

Fort George

Fort George has 18% of total effective capacity on the island of Mauritius, and its five turbines generated about 28% of all electricity in 2009. The slow speed engines, catering for base load, are run both day and night, but at a lower output at night. They have an efficiency of between 44.5% to 45.8% and an average capacity factor of 55% (18) (20).

St Louis

The St Louis plant consisted of eight old medium speed diesel engines that were scheduled for retirement one generator per year from 2008. The plant was supposed to only be used for peaks from 2009 and retired in 2014.The plant was redeveloped with three medium speed diesel engines with a capacity of 13.8 MW each in 2006 (20). It now constitutes 10% of effective capacity on the island. The plant is considered semi base capacity and normally generates between 07:00 and 21:00, and it has a capacity factor of 30% (18) (20)

Fort Victoria

The Fort Victoria plant consisted of two different kinds of medium speed diesel engines that were old and with low efficiency, and they were scheduled for retirement in 2009. The plant went through a redevelopment in 2012, where the old engines except two were replaced with six 15 MW medium speed diesel engines (20). It now constitutes 15% of effective capacity on the island. The plant is considered semi base capacity and normally generates between 07:00 and 21:00, and is expected to have a capacity factor of 35% (18) (20).

Nicolay

The Nicolay plant consists of three open cycle gas turbines (OCGT) that are flexible enough to meet variable demand. They are generally used only for emergency purposes and some peaking (18), which results in a capacity factor of 3% (20).Fuelled with kerosene, electricity generation from Nicolay is substantially more expensive than from other plants (14).

Coal and bagasse

Since the eighties, more and more of electricity generation has come bagasse (4) (36) (15). Sugar mills are self-sufficient in both electricity and steam for the sugar production during crop season (30) (18), and feed excess electricity to the grid. Centralisation reforms of the sugar industry have resulted in fewer, regional, sugar factories, and the shutdown of some small Continuous Power Producers (CPPs), bagasse power plants that only operate during harvest season (20). As the regional factories receive more sugar cane, the efficiency of the power plants increases (36).

The island of Mauritius has four firm power plants in sugar factories (IPPs) (36). These boilers are fired with coal to deliver electricity to the grid outside of harvesting season (30) (36). The cogeneration of coal and bagasse has several advantages. Bagasse, a residue from sugar production, is used to provide electricity and heat for the sugar production itself, and the excess electricity is sold to the CEB, helping them meet the increasing electricity demand. In addition, while all other main power plants are situated within the capital, IPPs are distributed throughout the island, relieving pressure on the electricity transmission system and reducing line losses (20). In 2000, it was normal to get about 60 kWh/tonne of cane (36), and the efficiency of the plants were around 45% for electricity generation (36), but 90% when also taking the useful generated heat into account (36).

In addition to the firm power plants, two Continuous Power Producers generate electricity from bagasse throughout crop season, and one firm power plant runs solely on coal all year (20).

Table 7 - Bagase power plants on the island of Mauritius (36) (19)

Name	Fuel	Effective capacity (MW)	Electricity generation in 2009 (GWh)
FSPG	Bagasse/Coal	33	161
CTBV	Bagasse/Coal	62	320
CEL	Bagasse/Coal	26	108
CTSav	Bagasse/Coal	90	423
CTDS	Coal	30	177
Medine	Bagasse	10	6.4
Mon Loisir	Bagasse	14	16
Total		**264**	**1211**

FUEL Steam and Power Generation (FSPG)

The FSPG plant operates on bagasse during crop season and coal the rest of the year. Effective capacity is 5% of overall effective capacity on the island, and in 2009 it generated 7% of electricity.

Compagnie Thermique de Belle Vue (CTBV)

The CTBV plant is the largest of the IPP plants and operates at a pressure of 82 bar, which makes it more efficient than the other plants (36). It is fuelled with bagasse during crop season and coal the rest of the year (18). Effective capacity is 9% of overall effective capacity on the island, and in 2009 it generated 14% of electricity (18).

Consolidated Energy Limited (CEL)

The CEL plant operates on bagasse during crop season and coal the rest of the year. Effective capacity is 4% of overall effective capacity on the island, and in 2009 it generated 5% of electricity (18).

Compagnie Thermique de Savannah (CTSav)

Following the shutdown of some small Continuous Power Producers (CPPs), CTSav, a more efficient IPP, was set up in 2007 (20). It is fuelled with bagasse during crop season and coal the rest of the year (18). Its effective capacity is 13% of overall capacity on the island, and it generated 19% of electricity in 2009 (18) (20).

Compagnie Thermique Du Sud (CTDS)

CTDS was established in 2005, and runs solely on coal all year (20). Constituting 4% of overall effective capacity, it generated 8% of electricity in 2009 (18) (20).

Medine and Mon Loisir

Two small CPPs still generate electricity for the grid during crop season. Together , they make up 3% of overall effective capacity and generated 1.3% of electricity in 2009 (18).

Hydro power

All hydro power plants are owned by the CEB. Generation depends on rainfall, and therefore varies from year to year. In a normal year, generation is about 100 GWh (37). There are eight plants, with half of them operating year round as peak capacity. The rest generate electricity when water is available, mostly in the rainy season from January through March, due to small reservoirs (30).

La Nicoliere Feeder Canal was finished in 2010, and the Midlands Dam in 2012. Electricity generation from these plants is not available yet, but is estimated by the CEB (20). Information on generation pattern is currently not available.

Table 8 - Hydro power plants on the island of Mauritius (18) (20) (19)

Name	Effective capacity (MW)	Electricity generation in 2009 (GWh)	Generation pattern
Champagne	28	48	All year, peaking
Le Val	4	6	All year, peaking
Ferney	10	34	Run-of-river
Réduit	1	4	Run-of-river
La Ferme	1.2	4	Run-of-river
Cascade Cécile	1	4	Run-of-river
Magenta	1	2	All year, peaking
Tamarind Falls	7	21	All year, peaking
Midlands Dam	0.4	2	-
La Nicolière FC	0.4	2	-
Total hydro	**54**	**126**	

Landfill Gas

From August 2011, electricity was generated from landfill gas (LFG) at Mare Chicose sanitary landfill from a 2 MW plant (18).

Solar power

There is no exhaustive overview of all PV installations on the island of Mauritius, or how much electricity they have generated. Table 9 shows some of the largest installations and their peak capacity.

Table 9 – Some PV plants on the island of Mauritius (38)

Owner	MW_p
CEB	0.002
International Financial Services	0.022
Total	0.004
Mauritius Commercial Bank	0.400
University of Mauritius	0.003

4.6 Measures already taken to reduce fossil fuel dependency

The Mauritian Government and the CEB have taken some measures to decrease electricity demand, and especially peak electricity demand (19). In August 2008, the CEB started a campaign to switch from incandescent light bulbs to compact fluorescent lamps, and one million of these were sold to private households at a discounted price (14) (19). There was also a pilot project on daylight saving time. It was considered successful by the CEB, but was nevertheless considered not to help meeting demand during peak hours (14). A feed in tariffs for SIPPs encourage the installation of small scale renewable energy (19). In addition, the Government has some subsidies for solar water heaters (37). Solar Water Heaters (SWHs) are used for hot water generation for bathing, cooking and cleaning (7). In 2008, it was estimated that about 25 000 out of 330 000, or 7.6 % of households in Mauritius have SWHs (37). As some household heat water with LPG instead of electricity, this will not always reduce electricity demand, but still reduce dependence on imported fossil fuels.

4.7 Demand forecast

The Central Electricity Board has made an Integrated Electricity Plan for 2013-2022 (20) that describes the expected developments in electricity demand, as shown in Figure 15. With the on-going economic development, the CEB expects a continued growth in electricity (20). They expect demand in the residential sector to grow at a rate of 3.01% per year, but staying at about 30% of total electricity demand (20), which means that the evening peak will stay at current levels relative to overall demand. Further, they expect the industrial sector to be reduce relative demand to about 28% of total electricity demand in 2022 (20), which represents an annual growth of about 2.60 % per year (20). The commercial will see the highest growth in demand, of about 4.31% per year (20). Overall, the CEB expects electricity demand to grow with about 3.43% per year. They expect a lower demand growth than in earlier decades due to energy efficiency and saving measures, fuel switching, rising energy prices, saturation in development of commercial buildings and structural changes in the economy towards sectors that are less energy intensive (20).

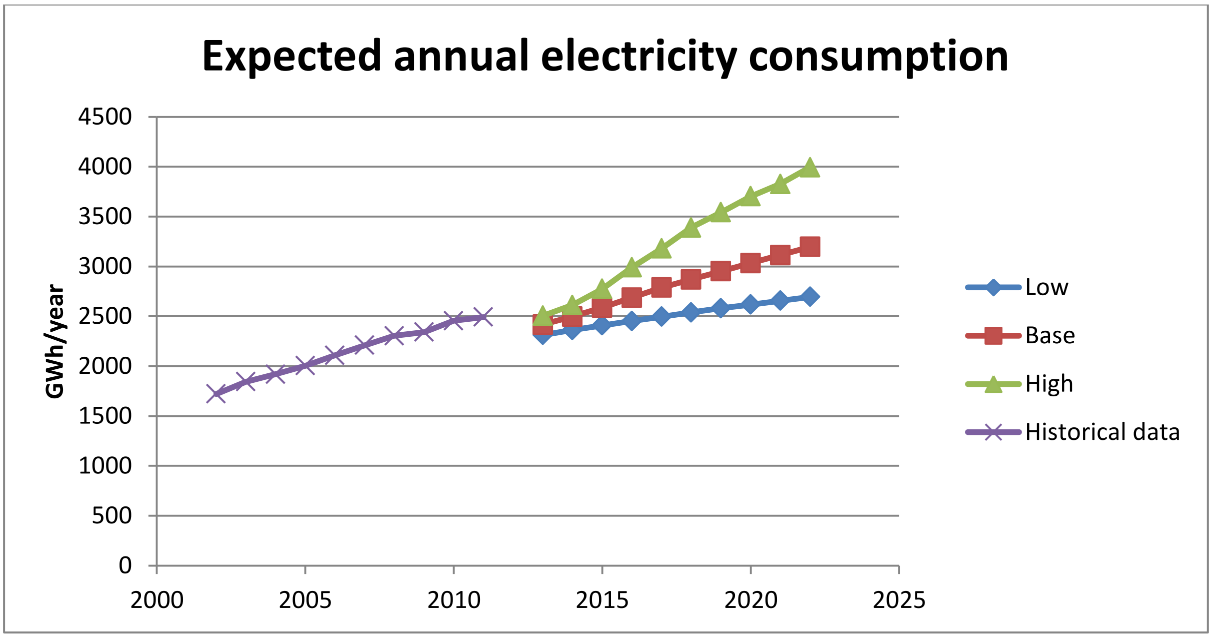

Figure 15 - Electricity scenarios, forecast from the Central Electricity Board (20)

In Figure 15, historical demand between 2002 and 2011 is added for comparison. Table 10 shows the annual increase in demand and the cumulative increase in demand from 2013, based on assumptions in the base scenario in the CEB Integrated Electricity Plan

Table 10 – Assumed increase in electricity demand, forecast from the Central Electricity Board (20)

Year	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Demand (GWh)	2416	2497	2587	2686	2787	2869	2951	3033	3113	3196
Annual increase in demand (GWh)		81	90	99	101	82	82	82	80	83
Cumulative increase in demand (GWh)		81	171	270	371	453	535	617	697	780

As peak demand depends heavily on weather and climate conditions, forecasting requires long term weather forecasts that are hard to make. Peak demands are therefore especially difficult to predict (20). Figure 16 shows what the CEB expects as maximum annual peak demand from 2013 to 2022.

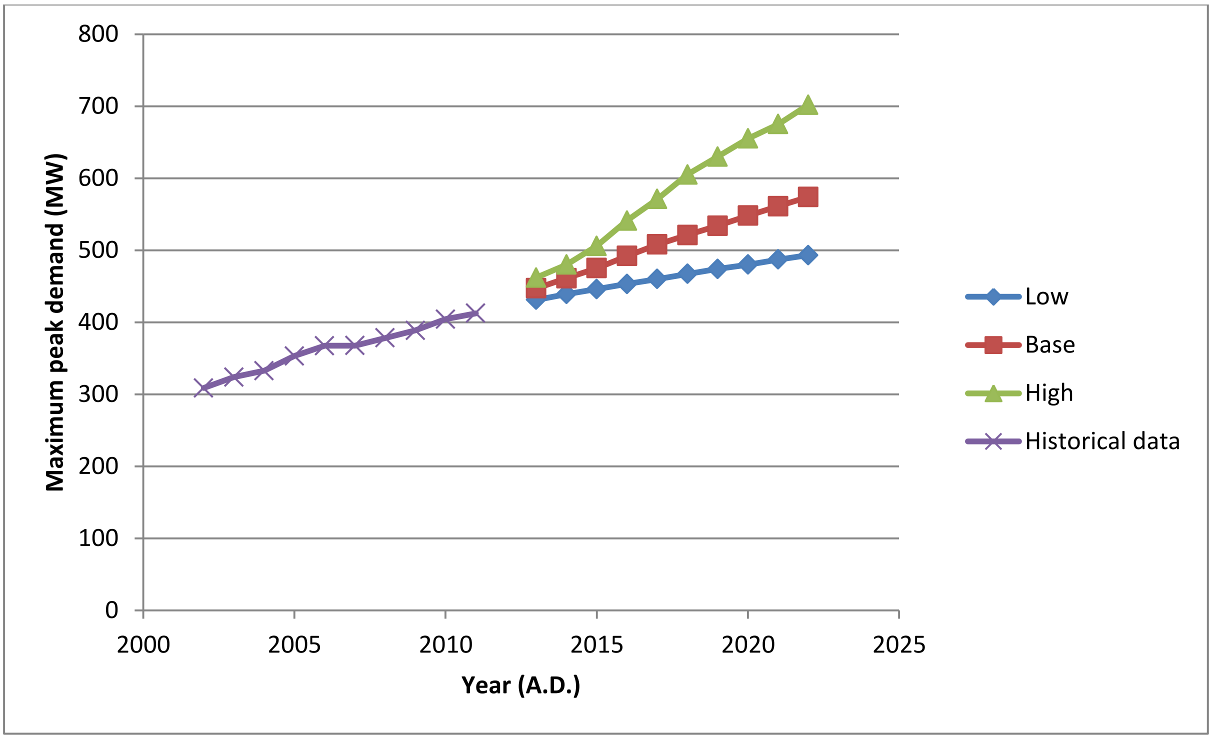

Figure 16 - Peak demand, forecast from the Central Electricity Board (20)

Table 11 – Assumed increase in maximum peak power demand, forecast from the CEB (20)

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Demand (MW)	447	461	475	492	508	521	534	548	561	574
Annual increase in demand (MW)		14	14	17	16	13	13	14	13	13
Cumulative increase in demand (MW)		14	28	45	61	74	87	101	114	127

4.8 Plans

The Mauritian government is proposing to install a new coal power plant, using pulverized coal (20). These installations could have an efficiency of up to 45%, leading to a lower electricity cost than that from a coal-bagasse power plant (4) (22). One 100 MW plant is considered generating electricity from 2016 (20) and another 100 MW power plant of unknown fuel is planned between 2017 and 2021 (20). These would be operated by IPPs that have generation contracts with the CEB.

Some mini and micro hydro power plants are considered wherever that is economically feasible (37), in addition to the construction of new reservoirs (17). One wind farm is underway, and some other wind farms are also under consideration (19).

To better reflect the different generation costs at day and night, a time of use (ToU) tariff is considered, in combination with smart meters that record when and how much electricity is consumed (20). With a lower price of electricity at night than day, some consumption could be shifted from day to night.

4.9 Alternatives to coal power

In this chapter, the CEB baseline scenario is assumed for growth in both peak power demand and annual electricity demand.

The 100 MW coal power plant currently under consideration will mostly provide base capacity. Assuming an 80% capacity factor, as is typical for the IPP power plants (20), the plant will generate 701 GWh/year from 2016 if all goes after the plan. With the expected levels of demand growth in the baseline scenario, this much additional electricity will not be needed until 2022. The capacity factor of the plant would be as low as 31% in 2016, and would have reached 80% in 2021, but at that time there are plans to install another 100 MW plant, which would reduce the capacity factor of the power plants combined to 40%, only half of what is normal for a thermal power plant.

In 2011, the effective capacity of the IPPs and CEB's heavy fuel oil plants combined was 557 MW, as shown in Table 12. In a scenario where the two largest plants are not operating, due to maintenance or breakdowns, available capacity would be 316 MW, which is still more than night time demand in Figure 7. As mentioned in chapter 4.7, annual electricity demand is expected to increase with 4.31% in the commercial sector, but only 3.01% and 2.60% in the residential and industrial sector respectively (20). As the commercial sector mainly drives day time demand, meeting peak demand during the day will likely be a bigger challenge than meeting demand at night.

Table 12 - Effective capacity of base load plants (18) (20)

Name	Fuel	Effective capacity (MW)
FSPG	Bagasse/Coal	33
CTBV	Bagasse/Coal	62
CTDS	Coal	30
CEL	Bagasse/Coal	26
CTSav	Bagasse/Coal	90
Fort George	HFO	134
St Louis	Diesel	75
Fort Victoria	Diesel	107
	Total effective capacity (MW)	**557**
	Without Fort George and CTdS	**316**

CEB plants, and to a certain degree IPP plants, currently run at lower output than desired at night, which reduces efficiency (20). Assuming a maximum capacity factor of 80% on these power plants, which would be a conservative estimate, they should be able to deliver 394 MW on average if run at effective capacity. This would generate 3455 GWh per year, as compared to the 2096 GWh they delivered in 2011 (20). The difference of 1359 GWh is almost twice as much as the calculated electricity generation from the planned coal power plant, but the power is far from enough to meet the expected peak demand of 447 MW already in 2013, increasing to 574 MW in 2022 (20). Thus, the projected increase in base load can be covered by tapping unused capacity in already existing plants. Instead, the real challenge will be to meet power demand during day and evening peak hours.

The following sections estimate the implications of a combination of solar panels, electric vehicles and gas power plants to replace the coal power plants.

4.9.1 Photovoltaic solar panels

With solar panels, all power will be generated during the day. The power will vary with cloud cover and with the angle of incidence, as shown in chapter 0. Cosine to the angle of incidence represents the maximum irradiation as compared to an irradiation normal to the plane. Thus, the changes in this value can be used as a measure of how the maximum available solar power varies over the day and year. Note that clouds, air pollution, buildings and trees might reduce this with as much as 90% (23).

The angle of incidence has, as shown in Table 13 – Seasonal and hourly changes in cosθ for a horizontal surface on the island of Mauritiu been calculated for four different days using the equations in chapter 0: Winter and summer solstice, and fall and spring equinoxes. These days represent the extremes – winter solstice the day with the least irradiation, summer solstice the day with the most irradiation and the equinoxes represent the average. Table 13 and Figure 17 show the changes in solar irradiation on a horizontal surface on the island of Mauritius.

Table 13 – Seasonal and hourly changes in cosθ for a horizontal surface on the island of Mauritius

	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Fall equinox	0.47	0.67	0.82	0.91	0.94	0.91	0.82	0.67	0.47	0.25
Winter solstice	0.29	0.47	0.61	0.69	0.72	0.69	0.61	0.47	0.29	0.08
Spring equinox	0.47	0.67	0.82	0.91	0.94	0.91	0.82	0.67	0.47	0.25
Summer solstice	0.57	0.75	0.88	0.97	1.00	0.97	0.88	0.75	0.57	0.36

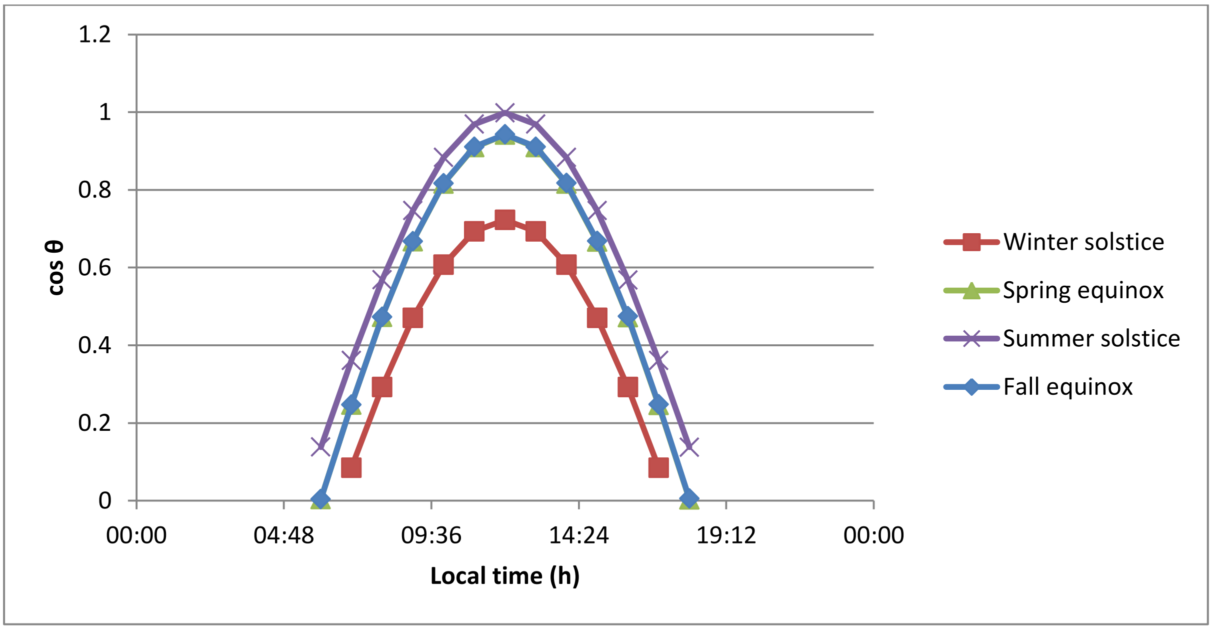

Figure 17 - Seasonal and hourly changes in cosθ for a horizontal surface on the island of Mauritius

Throughout the year, a solar panel will generate most electricity if tilted the same angle as the latitude of its position (23). The island of Mauritius is located at 20.28 °S (32), so panels will give the optimal output if facing north, tilted 20.28 ° up from the horizontal. Figure 18 shows the changes in irradiation throughout the day and year, cos θ, for a panel facing north and with a tilt of 20.28 °.

Irradiation is the same for summer and winter solstices, because the sun is 20.28 ° north of the normal to the panel in the winter, and 20.28 ° south of the normal to the panel in the summer.

Table 14 - Seasonal and hourly changes in cosθ for a northward surface tilted 20.28°

	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Fall equinox	0.50	0.71	0.87	0.97	1.00	0.97	0.87	0.71	0.50	0.26
Winter solstice	0.46	0.65	0.79	0.89	0.92	0.89	0.79	0.65	0.46	0.24
Spring equinox	0.50	0.71	0.87	0.97	1.00	0.97	0.87	0.71	0.50	0.26
Summer solstice	0.46	0.65	0.79	0.89	0.92	0.89	0.79	0.65	0.46	0.24

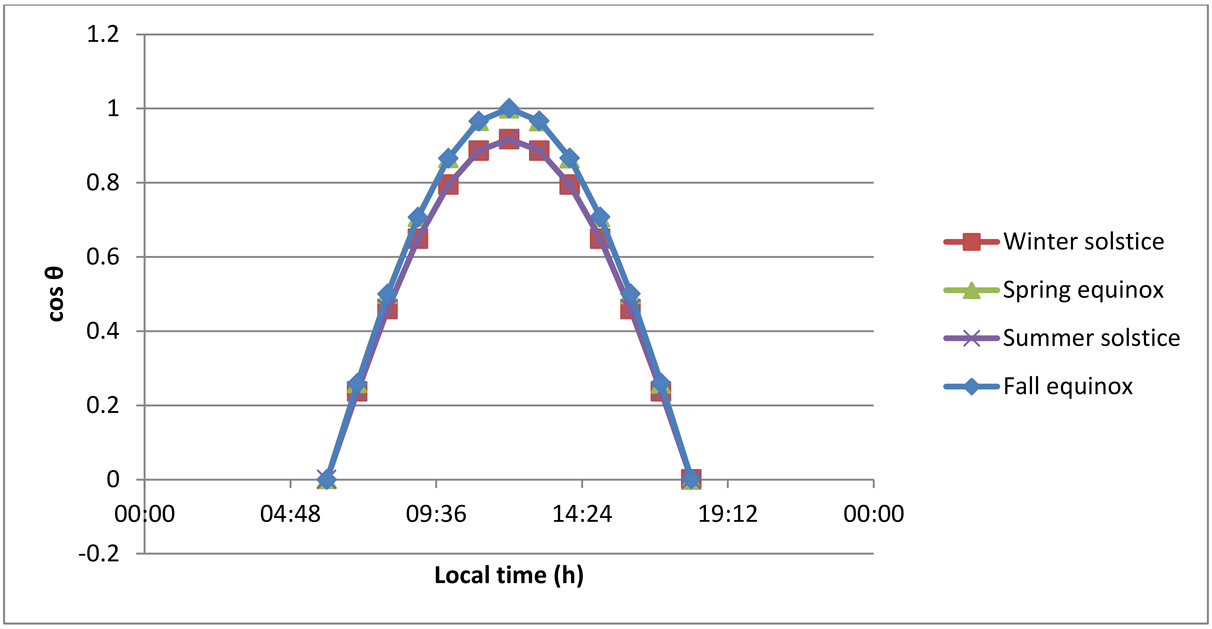

Figure 18 - Seasonal and hourly changes in cosθ for a northward surface tilted 20.28°

As power demand is somewhat higher in summer, panels could be tilted less than 20.28 °, to generate more electricity in the summer than in the winter. The result would then be closer to what is shown in Figure 17. Figure 19 and Table 15 suggest that with some panels facing more to the east and others to the west, the generation curve could smoothen throughout the day, increasing irradiance in the morning and evening. In summer, this will increase total irradiation on a tilted panel, as the sun is lower in the sky in the morning and evening, whereas in the middle of the day the sun would be too high in the sky to provide maximum power on a tilted panel facing north.

Table 15 – Solar irradiation for panels facing north, 45° east and 45° west at summer solstice

Local time	**7.00**	**8.00**	**9.00**	**10.00**	**11.00**	**12.00**	**13.00**	**14.00**	**15.00**	**16.00**	**17.00**
cos θ, facing north	0.24	0.46	0.65	0.79	0.89	0.92	0.89	0.79	0.65	0.46	0.24
cos θ, 45° east	0.62	0.78	0.89	0.96	0.98	0.95	0.87	0.74	0.58	0.39	0.19
cos θ, 45° west	0.05	0.29	0.51	0.70	0.84	0.92	0.95	0.92	0.82	0.67	0.48

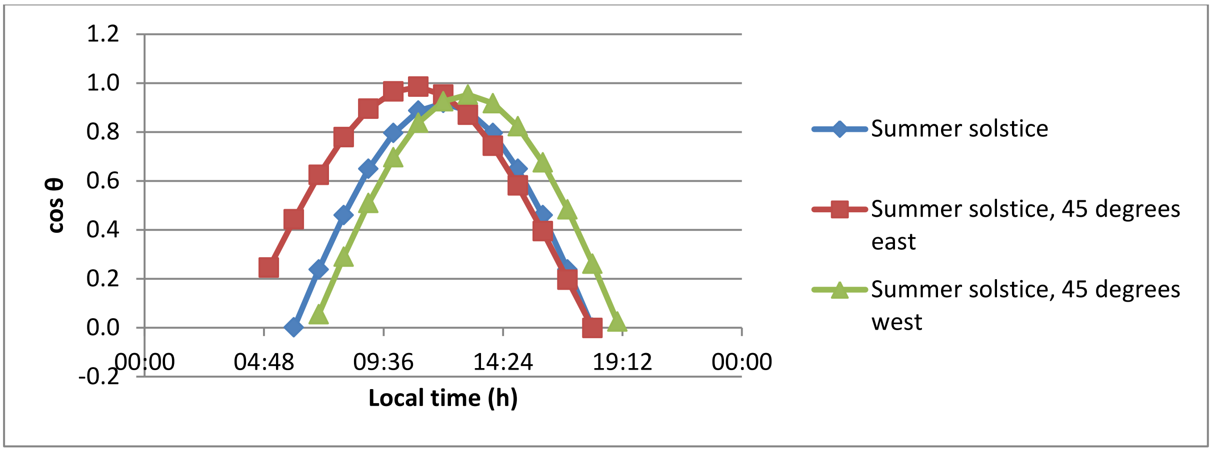

Figure 19 - Changes in irradiance on panels tilted 45° east and west

Dimensioning

Annual maximum peak demand is expected to increase by about 14 MW per year (20), as can be seen in Table 16. The maximum peak will normally occur on a relatively sunny summer day, as this is when most air conditioning is needed. As was shown in Figure 7, daytime demand is high between 09:00 and 16:00, with a peak in the afternoon. With panels facing more to the east or west, daily generation can be at its maximum at the same time as typical peak demand. On a densely clouded day, however, the power from solar panels could still be reduced with as much as 90% (23). This means that only 10% of the solar power can be guaranteed every day. The CEB expects peak demand to reach 574 MW in 2022, which is 127 MW more than what they expect in 2013, as shown in Table 16. Based on these considerations, Table 16 further suggests a scenario where new installed PV capacity matches the expected annual increase in peak demand. The calculations assume 1600 solar hours each year and a 15% efficiency of solar panels (31) to estimate annual additional electricity generation and total required area, using the equations presented in chapter 0. To indicate the range of possible power outputs, maximum morning and evening power and minimum noon power has been estimated.

Table 16 – Solar power scenario with all solar panels facing north

Year	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Annual peak demand growth (MW)	14	14	17	16	13	13	14	13	13
Cumulative peak demand growth from 2013 (MW)	14	28	45	61	74	87	101	114	127
Maximum power at 09:00 (MW)	11	21	34	46	56	65	76	86	95
Maximum power at 16:00 (MW)	8	16	26	35	42	50	58	65	72
Minimum power at 12:00 (MW)	1	3	5	6	7	9	10	11	13
Annual added generation (GWh)	22	45	72	98	118	139	162	182	203
Accumulated area needed (km^2)	0.09	0.19	0.30	0.41	0.49	0.58	0.67	0.76	0.85

The scenario presented in Table 16 would result in a total installation of 127 MW of PV solar panels in 2022. With all panels facing north, the maximum power delivered from solar panels would be 95 MW at 09:00 and 72 MW at 16:00. The minimum power, however, would be 13 MW in the middle of the day and less in the morning and evening.

4.9.2 Electric vehicles (EVs) for evening peak demand

The PV panels can cater for most of daytime demand, but the evening peak is after sunset, when people come home and turn on lights and home appliances. While the cars can charge at night, they could, with the right equipment, feed power to the grid in the evening. A time of use tariff could make this beneficial both for the car owner and the CEB. The delivered electricity would be paid for with day time tariffs, while the battery can be recharged at night with lower electricity prices. In addition to helping meet power demand, electric vehicles could reduce the import of gasoline and diesel if they are partially charged with renewable energy.

Dimensioning

In this chapter, the Nissan Leaf battery is used for calculations. One Nissan Leaf battery can store 24 kWh, and deliver a maximum power of 90 kW (39). The range on a full battery is 160 km (39). Even though range is a major obstacle for EVs in most states, the coastline of Mauritius is only 177 km (40), so it should be possible to reach most destinations on one charge. This also means that most batteries will be far from empty in the evening if fully charged in the morning. For the easiest possible implementation of the system, 3 kW is assumed the maximum possible power delivered by one battery. In one example, 50 000 electric vehicles, or 12% of the vehicle fleet in 2011 (41) is deployed. Assuming that 25% of each battery is available for the grid, that half the cars are plugged in every evening and a 10% loss in the grid, the additional power available for an evening peak of three hours can be calculated, using the equations in chapter 2.3.

Table 17 - Power and energy available for evening peak capacity with 50 000 electric vehicles

Assumptions			
Energy in one battery	$E_{battery}$	24	kWh
Maximum delivered power in one battery	P_{EV}	3	kW
Range with one battery	r	160	km
Average distance travelled for one car in a year	d	7300	km
Number of electric vehicles	N_{EV}	50000	
Grid losses	l	10	%
Percentage of the battery available for the grid	b	25	%
Share of cars available each evening	s	75	%
Hours for night time charging	Δt_{charge}	10	h/day
Hours of evening peak	$\Delta t_{discharge}$	3	h/day

Calculations			
Electricity consumption per car per km	E_d	0.2	kWh/km
Annual electricity demand for transportation	$E_{EV\ transportation}$	60	GWh/year
Maximum power to the grid	$P_{EV\ total}$	101	MW
Average power to the grid	$P_{EV\ average}$	68	MW
Additional annual electricity demand for evening recharge	$E_{EV\ additional}$	90	GWh
Total extra load at night	$P_{EVcharge}$	41	MW
Power needed if all batteries charge at once	$P_{EV\ max}$	150	MW
Total extra electricity demand	$E_{EV\ total}$	151	GWh/year

As shown in Table 17, the power available as extra evening peak capacity would be about 100 MW with 50 000 electric vehicles. Assuming that an average car drives 20 km/day, the additional electricity demand from charging electric vehicles both for mobility and for delivering power to the grid in the evening, would be 151 GWh/year. The total extra load at night would be between 41 and 150 MW.

Assuming for simplicity that peak demand is the same in the evening as in the middle of the day, the amount of cars needed to match the growth in maximum peak demand and the additional electricity this would require has been estimated using the equations given in chapter 2.3.

Table 18 - Cars needed to meet increases in evening demand

Year	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Required power, P(MW)	14	28	45	61	74	87	101	114	127
Required number of vehicles, N_{EV}	6 000	12 000	20 000	27 000	33 000	39 000	45 000	51 000	56 000
Electricity demand, E_{total} (GWh)	19	37	60	82	99	116	135	153	170

For comparison, there were 392 276 vehicles on Mauritius in June 2011, and 131 604 of them were cars (41). If 56 000 cars charged at the same time through 3 kW charging stations, this would lead to an increase in power demand of 186 MW, which would double night time demand.

Fuel savings

Assuming that the efficiency of electric vehicles is 88% (42) and the efficiency of a gasoline engine is 25% (22), the equivalent gasoline demand to provide the same kinetic energy for actually transporting the car can be calculated. This gives an indication of the gasoline savings that the above suggested implementation of electric vehicles could result in.

Table 19 - Potential gasoline savings

Year	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
EV annual electricity demand, E_{total} (GWh)	19	37	60	82	99	116	135	153	170
Demand for transportation, $E_{EV\ transportation}$ (GWh)	7	15	24	33	40	47	54	61	68
Kinetic energy E_K (GWh)	7	13	21	29	35	41	48	54	60
Equivalent gasoline demand, $E_{gasoline}$ (GWh)	26	53	85	115	139	164	190	215	239

Table 19 shows both how much gasoline imports could be saved by implementing EVs, and the huge difference between energy demand of an EV and a gasoline fuelled vehicle. Note that grid losses from when batteries deliver power in the evening and then recharge at night cause the difference between *annual electricity demand* and *electricity demand for transportation*.

4.9.3 Natural gas to provide flexibility

Natural gas generators are more flexible than coal power plants. The flexibility can complement variable demand and the variations in renewable energy supply. They are well suited for peak capacity and backup power in an energy system with an increasing share of variable renewable energy supply (22). Natural gas is more expensive than coal per energy unit, and prices vary a lot from region to region, and over time (5) (22). However, gas turbines can be more efficient than coal power plants and therefore require less energy to generate the same amount of electricity (22). The global average efficiency is 43%, but it can be as high as 60% (22), while the best coal power plants have an efficiency of 45% (22).

Natural gas power plants have lower construction time and lower capital costs than coal power plants (22). As gas turbines can have a much smaller capacity than the planned coal power plant, they can be distributed across the island, and installed one by one as demand increases. They also require less area than coal power plants (22), which is an important feature on a densely populated island like Mauritius.

Establishing a distribution network for natural gas, and installing natural gas generators, might also provide better fuel flexibility than coal. On a short term perspective, natural gas can be used to supply the landfill gas turbines when landfill gas production declines, for an optimal utilization of the already installed capacity. In addition, new generation plants can be installed. Later, imported natural gas might be supplied with locally produced methane from waste and biomass fermentation at these plants as well. With an increasing share of renewable energy, hydrogen production from excess electricity might be an option in the future. Hydrogen can be mixed into natural gas by as much as 20% without any need for significant modifications (22).

There are two main power generation technologies for natural gas. The Open Cycle Gas Turbines (OCGT) has a lower efficiency, but can be used as peak capacity, has a low capital cost and a compact and lightweight design (22). A Closed Cycle Gas Turbine is much the same as an OCGT, but the heat generated by the gas turbine is used to generate steam for a steam generator, providing additional electricity and increasing efficiency to as much as 60% (22). Due to the slower responsiveness of the steam generator, the OCGT is less flexible. Table 20 shows some of the features of the CCGT and OCGT technology, with coal and hydro power for comparison.

Table 20 - Gas Turbine technologies compared with coal and hydro power (22).

Technology	CCGT	OCGT	Coal	Hydro
Start-up time (hot start)	40-60 minutes	<20 minutes	1-6 hours	1-10 minutes
Ramp rate (up or down)	5%-10%/minute	20-30%/minute	1%-5%/minute	20%-100%/minute
Time from zero to full load	1-2 hours	<1 hour	2-6 hours	<10 minutes
Minimum stable load factor	25%	25%	30%-40%	15%-40%

Dimensioning and choice of technology

Natural gas generators can serve as peak capacity in combination with solar panels and EV batteries. They can also provide the extra capacity that might be needed at night if enough electric vehicles are introduced to Mauritius. A scenario is made where natural gas is able to provide all extra peak capacity needed if the maximum peak demand occurs on a densely clouded day, assuming that no cars charge in the middle of that day. It is also assumed that the extra electricity needed to charge the batteries at night is met with natural gas.

Table 21 – Scenario for meeting peak demand and electricity demand with natural gas

Year	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Peak demand growth from 2013 (MW)	14	28	45	61	74	87	101	114	127
Minimum PV power at 12:00 (MW)	1	3	5	6	7	9	10	11	13
Extra needed capacity (MW)	13	25	41	55	67	78	91	103	114
Annual electricity generation from PV (GWh)	22	45	72	98	118	139	162	182	203
Estimated increase in annual electricity demand (GWh)	81	171	270	371	453	535	617	697	780
Additional electricity demand from electric vehicles	19	37	60	82	99	116	135	153	170
Extra needed electricity generation (GWh)	77	164	258	355	434	512	591	667	747
Electricity generation at effective capacity year round (GWh)	110	221	355	481	583	686	796	899	1001
Capacity factor	70%	74%	73%	74%	74%	75%	74%	74%	75%

Table 21 shows that if all new power generation was met with PV and natural gas, 114 MW of gas power plants would be needed in 2022. Generating about 747 GWh/year in 2022, their capacity factor would be 75%, suggesting that some of the plants could operate as semi base capacity. A mixture of CCGT and OCGT technologies could therefore be deployed, to ensure higher overall efficiency. Another alternative would be to install only CCGT plants, but with the possibility of bypassing the steam engine and running the same generator as a OCGT plant to increase responsiveness.

Imports

Assuming a mix of generator technologies with an average efficiency of 50%, Table 22 shows an estimate of the annual needed imports of natural gas:

Table 22 - Estimated natural gas imports

Year	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Annual electricity generation (GWh)	77	164	258	355	434	512	591	667	747
Natural gas imports	155	327	516	710	867	1024	1181	1334	1494

4.10 Reduction in fossil fuel dependency

Assuming that coal power plants cover all additional electricity demand, and that these plants have an efficiency of 45%, the potential coal import savings can be calculated. Adding in the gasoline savings from replacing some gasoline cars with electric vehicles, and the natural gas imports, the net change in energy imports by substituting coal power plants with solar power, electric vehicles and natural gas can be estimated:

Year	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Gasoline savings (GWh)	26	53	85	115	139	164	190	215	239
Natural gas imports (GWh)	155	327	516	710	867	1024	1181	1334	1494
Coal savings (GWh)	180	380	600	824	1007	1189	1371	1549	1733
Net change in energy imports (GWh)	-52	-105	-168	-229	-279	-328	-380	-429	-479
Relative change (%)	-29%	-28%	-28%	-28%	-28%	-28%	-28%	-28%	-28%

5 Discussion

5.1 Defining the scope

After the trip to Mauritius, it became clear that there were two main obstacles for implementing more renewable energy in the electricity grid. As a developing state with a small economy, the economic mechanisms needed to encourage investments in large scale renewable energy might not be in place. More importantly, fluctuations and unpredictability of renewable energy resources posed a large risk to the security of power supply. Environmental and climate issues were of a concern to most citizens, and some renewable energy installations were planned. Still, growing energy demand had raised discussions about installing a new 100 MW coal power plant, as this was considered the cheapest solution. But by investing in a coal power plant, Mauritius would risk a long term lock in of fossil fuel dependency, in addition to increased local pollution. It became clear that suggestions from this study could not mainly be backed up by environmental or climate arguments. Most of all, they would have to make sense both from an economic and security perspective.

In this setting, three different solutions have been developed with the aim of increasing energy self-sufficiency and at the same time providing flexibility and storage to meet variable supply and demand. Photovoltaic solar power, electric vehicles and natural gas generators offer three different solutions that can be implemented independently or as a whole. If all three are implemented on the suggested scale, however, they could together replace the planned coal plant.

5.2 Challenges and limitations

5.2.1 Costs and benefits

The economic consequences of switching from coal to a combination of solar panels, electric vehicles and natural gas would have to be further explored, examining installation costs and import costs of natural gas, but also the external benefits from a more flexible electricity system. The coal power plant would be built and operated by an Independent Power Producer (IPP) contracted to deliver electricity to the Central Electricity Board (CEB). Natural gas power plants, on the other hand, might be operated by the CEB itself. Thus, costs and benefits might be distributed differently between governmental bodies and private operators in the two scenarios.

The CEB already has problems accepting enough electricity at night from the IPPs, and a new coal power plant could increase this problem, both leading to efficiency losses and extra costs for the CEB.A somewhat similar problem arises from solar panels, even when they are not owned by the CEB. As solar power is variable and only predictable to a certain degree, implementation of solar energy to the grid could add pressure to the CEB's regulation capacity. However, an additional benefit of renewable energy that is sometimes forgotten is the fact that although installation costs may be high, the fuel is often free. This means that it will be possible to deliver electricity at predictable and stable prices, compared to the volatility of fossil fuel prices (6).

These issues have to be factored in when considering the overall cost of natural gas generators, as they would ease the pressure on peak capacity. The CEB could build, operate and own smaller natural gas power plants that are installed one by one as demand rises. As they have shorter installation time, they can be built to match demand forecasts few years ahead, reducing the risk of over or under dimensioning. As natural gas power plants are smaller, they could be built closer to where demand grows, which would ease strain on the electricity grid. This could save grid upgrade costs.

5.2.2 Data sources

The results in the analysis rely heavily on the accuracy of the CEB scenarios. Factors like politics, population growth and the general economic situation of Mauritius that would influence energy demand always have certain unpredictability. Substantial differences between low, base and high scenarios in Figure 15 and Figure 16 give rise to uncertainties to the right scale of deployment of both solar panels, electric vehicles and natural gas generators. However, as solar panels, electric vehicles and natural gas generators are suggested phased in over time, they provide more flexibility to match demand as it develops over the next years.

The Central Statistics Office (CSO) publishes annual energy statistics for Mauritius. These numbers include energy requirements for international flights and shipping, but without energy that is not traded on any market, like the solar energy that heats up water in Solar Water Heaters (SWH). Data on energy requirements for SWHs are not easily available, and have therefore not been considered part of primary energy requirement for Mauritius. This gives the impression of a lower than actual energy demand, as SWHs have replaced what would otherwise have been electricity and LPG use.

As solar panels have only been installed the last couple of years, the CSO did not offer any specific data on total installed capacity or annual electricity generation from solar panels. Detailed data on solar irradiation on the island of Mauritius was not available, so calculations have been made for an assumed total effective capacity on the island, without detailing exactly how large area this would require. The same goes for information on solar irradiation over the year. Estimates for the output from solar panels have therefore been relatively conservative; to cater for the risk of having dense cloud cover on the entire island on days with high peak demand. On days with partial cloud cover, the risk of blocking all panels at the same time can be reduced if panels are distributed around the island.

To check if the suggested solutions will work in all situations, detailed data on electricity demand profiles on different days is key. However, these data were not available for the public. As all scenarios are compared with only one demand profile from 2009, the scale of the suggestions should only be considered as examples, rather than providing absolute numbers.

It has been hard to find consistent data of the current total installed capacity on the island of Mauritius. Some sources operate with more power plants than other. The centralization policy in the sugar industry has led to the shutdown of several Continuous Power Producers (CPPs). The two CPPs in this thesis might have been shut down the latest years. However, they do not contribute significantly to the overall electricity generation. The diesel power plants in the capital currently undergo a renovation process, where some old generators are replaced with new generators. However, in some cases the old ones are also kept, operating together with the new ones. The new generators are well documented, but information about when and how many of the old generators have been retired, has been insufficient, and where nothing else was stated, the old generators are therefore assumed to operate alongside the new ones.

5.2.3 Electric vehicles

There are many possible strategies that could be utilized to decrease the number or use of fossil fuelled vehicles, such as increased public transportation, car sharing and better access for bikes and pedestrians. Plug-in hybrids could also help soften the transition. However, as this analysis focus mainly on the electricity system, these options have not been explored.

An essential challenge when introducing electric vehicles in a small system as the one on Mauritius is the risk of all cars charging at the same time, during peak hours. As EVs become more common, work places might offer charging stations at their parking lots. Cars would then charge in the morning, as workers arrive after driving to work, and after they have been out for lunch. This would normally coincide with the largest daily peaks in the summer, and electric vehicles could thus become part of the problem instead of the solution. Similarly, as people get home from work and plug in their cars in the evening, this could contribute to rising peak demand. Thus, a smart system has to be in place either in the cars or the charging stations, to ensure that cars are not charged during peak hours. Time of use tariffs could reduce this problem, as it would make it cheaper to charge the car at night than in the middle of the day, thus encouraging systems that only let the batteries charge at night. With a time of use tariff that switches from one hour to the other, careful attention should be paid to the eventual development of automatic systems that switch on devices like car charging as soon as the night time tariff starts. This could cause a major peak in just seconds, which would be very hard to predict and cater for.

The amount of cars needed to meet increasing evening peak demand might be overestimated. Calculations assume that the evening peak is as high as in the middle of the day. However, the CEB estimates that most growth in demand will be in the commercial sector, thus mainly driving day time demand. The suggested installation of natural gas could also cater for all or parts of the evening peak, increasing their capacity factor and thereby profitability. However, this would also increase overall fossil fuel demand. Estimates on the percentage of a battery that could be available for the grid, and the share of cars available for evening recharge should be seen as suggestions to illustrate the concept rather than absolutes. More detailed information about Mauritian's car usage would have to be acquired to make an estimate of the number of vehicles needed to cater for the evening peak demand.

5.2.4 Distribution and grids

Mauritius does not currently import any natural gas. Establishing a distribution network for natural gas could offer some challenges compared to just increasing the imports of coal. As methane only becomes a liquid under high pressure, transportation and storage of natural gas would require other equipment than for LPG, which already has a distribution system in place.

As solar panels are already present on the island, an import and distribution network should already be in place. A few electric vehicles have already been sold, but the smart systems needed to ensure night time charging might require technologies that are currently not available on the island.

It could be argued that with more variable electricity supply, there would be an increased need to upgrade the electricity grid. However, with more distributed supply, the opposite might also be the case. In the evening, most demand is domestic. With a good distribution of electric vehicles around the island, batteries would deliver power where it's needed the most. Some of the power from the batteries might never leave the neighbourhood or even the house. From the outside, the only change would be a reduction in power demand from that certain neighbourhood or house, thus reducing the bottle neck effects when peak demand moves from city centres to domestic areas. For the daytime peak, solar panels could be placed in commercial areas, either on office buildings, shopping centres or parking lots. This would also prevent solar panels from taking up agricultural area, and the latter would provide the additional benefit of shade for cars. As natural gas power plants can come in smaller sizes than the planned coal power plant, they could be located closer to densely populated areas with high electricity demand. In comparison, a coal power plant situated far away from Port Louis requires heavy investment in grid upgrades. All in all, distributed electricity generation could potentially lead to less pressure on existing infrastructure. However, this requires careful and coherent planning, taking consumption patterns of different sectors of society into account.

5.2.5 Efficiency and demand reduction

In general, demand dictates the rate of power generation, not the other way around. But the government and other agencies can to a certain degree regulate demand through Demand Side Management (19). This analysis has not looked at any consumption reduction efforts. Energy consumption can be reduced by reducing the demand for energy, and by energy efficiency. These might be the most effective and cheap measures to reduce fossil fuel dependency, as they reduce the overall dependency on energy, instead of increasing domestic energy supply. This would reduce the need to invest in new generation capacity.

The CEB currently has problems accepting enough electricity from the IPPs. By installing semi base or peak capacity from natural gas generators instead of a coal power plant, IPPs would be able to operate at full capacity both day and night, providing more electricity and a slightly higher energy efficiency. Fired by coal for parts of the year, the increased generation could lead to some more coal imports, replacing diesel or natural gas. The exact effect of this is hard to estimate, and has not been included in the analysis.

5.2.6 Dimensioning and placement

As a small and densely populated island, energy solutions should take up as little space as possible. In the solar panel analysis, an area of 0.85 km would be needed to install the suggested solar panels. High efficiency solar panels would reduce the required area, but could also be substantially more expensive. Alternatively, solar panels could shift tilt and position throughout the day or year to increase electricity generation. This would also add costs to the installation and operation, however. Solar panels should therefore to a largest possible extent be installed on existing buildings and parking lots, where there are fewer conflicts with other area usage. Solar panels could also cover water reservoirs and hydropower dams, where they might even reduce vaporization losses. This would have to be further investigated to map costs and physical restraints.

To further reduce fossil fuel imports, the suggested solutions could be scaled up to meet more than the expected increase in demand. Peak demand is currently met with peak capacity plants that can be shut down on short notice without big losses, like hydro power, diesel and kerosene. Thus, the total installed power of PV plants could be higher than only the growth in power demand, to replace some fossil based power on sunny days, but keeping the existing peak capacity as backup power. As long as base capacity generation do not increase significantly, solar panels could be dimensioned to meet all of daytime peak demand without reducing the capacity factor of base capacity plants.

5.2.7 Variability and unpredictability

As a small and isolated grid with no storage capacity, the Mauritian electricity system must be constructed to manage large and sometimes unpredictable variations in supply and demand. Most renewable energy sources, like the sun and the wind, have variations that are beyond our control. Electricity generation from solar panels will vary, with some unpredictability. It could therefore not replace all other capacity even in the middle of the day. A system with high penetration of renewable energy would need backup power. However, this is true for all electricity systems. Output from fossil fuelled power plants also varies, they need maintenance and they could shut down unexpectedly for different reasons. Backup power should also be able to provide power in the case of a failure in the transmission network. Lastly, the unpredictability of electricity demand makes any electricity system variable. As Milborrow (43) argues, these factors remain a bigger threat to an electricity grid until variable renewable energy sources provide a substantial part of electricity supply.

Unpredictability would also be a challenge if the CEB was to follow the initial plan of establishing a coal power plant. On one hand, this plant would be able to provide enough capacity and electricity generation for all scenarios. On the other hand, coal power has little flexibility in generation pattern and a long deployment phase. Thus, Mauritius could end up in a situation where base capacity supply exceeds base load, encouraging growth in demand. With fewer incentives for energy efficiency and consumption reductions, the island could risk a lock-in of low efficiency solutions in larger parts of society than just the electricity providers, increasing long term dependence on fossil fuels.

All power systems will have a way of matching variable supply and demand (43). A higher penetration of renewable energy adds another factor to the variability equation. A one hundred per cent secure electricity system cannot be achieved (43), but the risk of a blackout should be minimized. To achieve this, the degree of uncertainty and reliability of demand patterns, elements of the grid infrastructure and the different power plants, must be mapped.

5.2.8 Expertise and training

Although many renewable energy systems need little maintenance, they often require more specialised knowledge (6). This is a problem on a small island like Mauritius, with limited diversity in both study programs and experienced people from industries. Creating good enough capacity building and training programs within the state might prove difficult. It could, however, also create new jobs and prevent young engineers leaving the island to look for challenges abroad.

5.3 Energy dependence

It could be argued that the suggested changes have little effect on the overall fossil fuel imports. Instead of substituting coal with all renewable energy, a large share of additional electricity generation will now come from a new fossil fuel – natural gas. Natural gas is not just more expensive than coal, prices also vary significantly both geographically and over time. Instead of installing one new coal power plant that would generate more than enough electricity, the extensive and diverse measures require more planning and the societal and governmental costs are hard to estimate. However, these measures not only represent a concrete reduction in imports. They also represent a different way of thinking about energy supply. The coal power plant will require a steady flow of coal imports for its entire operation time. Gas turbines, on the other hand, can be fuelled with locally produced methane, and it might even be possible to mix in hydrogen from excess electricity generation. The flexibility of gas turbines and the storage potential in electric vehicles encourage and ease the transition to a renewable energy based electricity system. These technologies could lay the foundation for a larger change of the electricity system in the future.

5.4 The way forward

Although other renewable energy sources like wind have not been explored in this thesis, they could still be relevant. As the IEA clearly states, wind is already competitive in many areas with good wind resource conditions (5). If the planned wind and PV parks are realized, current semi base and peak capacity plants could reduce generation on sunny or windy days, and the need for natural gas capacity might be reduced slightly. If a coal power plant was installed, enough wind power could further reduce the capacity factor at night.

Nuclear power plants have not been considered at all. A developed technology, this could also be an option. However, as thermal power plants, they would give rise to the same challenges as a coal power plant. There might also be challenges connected to the size and capacity of nuclear power plants, as Mauritius has a relatively small energy system. This would have to be further explored.

On a long term perspective, less mature renewable energy resources like wave and geothermal power could be explored. The neighbour island, Réunion, currently considers the use of solar energy and sea water for air conditioning (7), reducing peak demand on hot summer days. The lower profitability of sugar exports might reduce sugar cane production, in favour of more food production for the home market. With less bagasse for electricity generation, IPPs might generate more electricity from coal. Increased efforts to generate methane from organic waste in food production could be considered. Waste and biomass fermentation could provide domestically produced methane to mix with the imported natural gas.

The planned smart grid implementation should be designed to allow for time of use tariffs that also vary throughout the day, to further reduce demand in peak hours. Variable prices depending on predicted demand from hour to hour could be considered. An electricity market with prices defined by supply and demand could increase electricity generation profitability and change consumption patterns, especially for large electricity consumers. However, this would require a thorough restructuring of the legal system of the electricity sector, and the implications for vulnerable consumer groups depending on predictable electricity prices would need careful investigation.

With changes, new business opportunities could arise. When old EV batteries are replaced, these could be collected and permanently connected to the grid. With variable electricity prices, battery parks like this might prove profitable in the future.

6 Conclusion

A reduction of fossil fuel imports in the island of Mauritius requires more than just increasing the share of renewable energy. The variability and unpredictability associated with most renewable energy sources require higher robustness and flexibility in the electricity system. Solar panels increase self-sufficiency in energy supply, but electricity generation varies with time of day and year, and with cloud cover. Electric vehicles reduce gasoline dependency in the transport sector. With the right mechanisms in place, they could also provide energy storage, which would decouple electricity consumption and generation, storing excess electricity at night and feeding it into the grid in the evening. With a higher efficiency, natural gas plants generate the same amount of electricity with less fuel imports than with coal. Being highly flexible, gas generators can back up renewable energy plants and provide peak capacity when needed. Allowing for a higher penetration of renewable energy in the system, natural gas contributes to further reduce fossil fuel imports.

These solutions can be scaled to needs, implemented separately or as a whole, and are easily combined with other solutions like energy efficiency measures and other renewable energy technologies. Successful implementation, however, requires planning to ensure power supply at the right time and place. A time-of-use tariff could help shift demand from day to night, increase profitability of energy storage and reduce the gap between renewable energy feed in tariffs and electricity prices.

The sustainable island

Mauritius has been called a ‘development wonder’, but the latest decades have put the state in a difficult situation (15). The textile industry has problems competing with Chinese labour, while the sugar industry experiences lower sugar prices, a liberalisation of the global sugar market and the phase out of guaranteed trade agreements with the EU (15). In addition, the island has become more aware of the risks of environmental degradation, climate change and the increasing costs of fuel imports (36). To answer these multiple challenges, the Mauritian government has launched a sustainability strategy, *Maurice Ile Durable* (MID) - Mauritius Sustainable Island (4) (15). The strategy defines four areas for sustainable development: Economic, environmental, social and governmental (4). The strategy acknowledges the links between financial sustainability and a diversification of the economy, industry and energy supply (4). The *MID* especially emphasises a diversification of electricity generation, towards more renewable energy sources (38) (19). With a goal of increasing energy self-sufficiency to 35 % within 2025 (38) (19), investments in renewable energy and energy efficiency is crucial. In this regard, the planned coal power plant could reduce the changes of achieving these goals.

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Appendix

Conversion factors

From/To (3)	TJ	toe	TWh	Barrels of crude oil
TJ	1	23.88	0.000278	175
toe	0.0419	1	0.0000116	7.33
TWh	3600	85985	1	630385
Barrels of crude oil	0.00571	0.1364	0.0000016	1

1 tonne of (18)	toe	GJ
Bagasse	0.16	6.70
Charcoal	0.74	30.98
Coal	0.62	25.96
Diesel oil	1.01	42.29
Dual Purpose Kerosene	1.04	43.54
Fuel oil	0.96	40.19
Fuelwood	0.38	15.91
Gasolene	1.08	45.22
Liquefied Petroleum Gas (LPG)	1.08	45.22

Global energy data (3)

2010 fuel shares of TPES (Total Primary Energy Supply)

Fuel	Mtoe	EJ
Natural gas	2721	114
Nuclear	725	30
Hydro	292	12
Biofuels and waste	1272	53
Coal/peat	3472	145
Oil	4120	173
Other	114	5
Total	12717	532

2010 Electricity generation by fuel

Fuel	TWh	EJ
Natural gas	4758	17
Nuclear	2765	10
Hydro	3429	12
Coal/peat	8701	31
Oil	986	4
Other	793	3
Total	21431	77

2010 Energy consumption

Fuel	Mtoe	EJ
Natural gas	1319	55
Biofuels and waste	1102	46
Coal/peat	850	36
Oil	3575	150
Other	295	12
Electricity	1536	64
Total	8677	363

Natural gas prices (USD/GJ) (5)

	Japan	Europe	USA
01/01/2003	4.52	3.55	5.15
01/02/2003	4.58	3.44	7.30
01/03/2003	4.54	2.71	5.62
01/04/2003	4.56	2.66	4.99
01/05/2003	4.57	2.87	5.51
01/06/2003	4.53	2.51	5.52
01/07/2003	4.53	2.63	4.76
01/08/2003	4.49	2.02	4.73
01/09/2003	4.59	2.23	4.38
01/10/2003	4.49	3.83	4.38
01/11/2003	4.50	4.42	4.24
01/12/2003	4.58	5.00	5.81
01/01/2004	4.56	4.97	5.82
01/02/2004	4.56	4.05	5.09
01/03/2004	4.68	3.80	5.11
01/04/2004	4.63	3.62	5.41
01/05/2004	4.62	3.55	6.00
01/06/2004	4.89	3.42	5.94
01/07/2004	4.81	3.42	5.62
01/08/2004	4.95	4.10	5.12
01/09/2004	5.17	4.75	4.88
01/10/2004	5.35	4.35	6.01
01/11/2004	5.34	5.07	5.84
01/12/2004	5.42	5.69	6.24
01/01/2005	5.19	5.32	5.86
01/02/2005	5.28	7.23	5.82
01/03/2005	5.32	7.71	6.60
01/04/2005	5.41	5.67	6.79
01/05/2005	5.45	5.38	6.13
01/06/2005	5.39	4.96	6.81
01/07/2005	5.69	4.82	7.23
01/08/2005	5.97	5.25	9.02
01/09/2005	6.04	4.71	11.31
01/10/2005	6.11	5.47	12.72
01/11/2005	6.31	13.25	9.77
01/12/2005	6.25	13.71	12.50
01/01/2006	6.25	11.08	8.23
01/02/2006	6.65	10.82	7.14
01/03/2006	6.81	12.56	6.53
01/04/2006	6.43	6.87	6.79
01/05/2006	6.70	6.19	5.91
01/06/2006	6.66	5.06	5.89
01/07/2006	6.51	6.98	5.85
01/08/2006	6.91	6.16	6.79
01/09/2006	7.26	4.81	4.64
01/10/2006	6.84	3.73	5.54
01/11/2006	6.93	6.86	7.02
01/12/2006	6.98	5.79	6.43
01/01/2007	6.71	4.98	6.20
01/02/2007	6.61	3.65	7.58
01/03/2007	6.62	3.73	6.74
01/04/2007	6.73	3.04	7.20
01/05/2007	6.83	4.25	7.24
01/06/2007	6.74	4.06	6.96
01/07/2007	7.02	5.77	5.89
01/08/2007	7.50	5.42	5.93
01/09/2007	7.56	6.45	5.76
01/10/2007	8.17	8.00	6.39
01/11/2007	8.93	9.55	6.75
01/12/2007	8.61	9.74	6.75
01/01/2008	9.73	10.02	7.58
01/02/2008	9.98	9.45	8.10
01/03/2008	10.85	10.36	8.95
01/04/2008	10.69	11.57	9.58
01/05/2008	11.06	10.84	10.74
01/06/2008	11.34	11.56	12.02
01/07/2008	11.81	11.31	10.51
01/08/2008	12.52	9.63	7.86
01/09/2008	13.98	11.90	7.23
01/10/2008	14.44	9.21	6.38
01/11/2008	14.53	8.23	6.35
01/12/2008	13.13	8.10	5.53
01/01/2009	12.17	8.37	4.97
01/02/2009	10.04	6.44	4.28
01/03/2009	9.04	4.36	3.75
01/04/2009	7.76	4.05	3.31
01/05/2009	7.16	3.96	3.63
01/06/2009	6.87	4.09	3.60
01/07/2009	7.22	3.54	3.21
01/08/2009	7.42	3.43	2.98
01/09/2009	8.05	3.00	2.83
01/10/2009	8.70	3.87	3.80

	Japan	Europe	USA
01/11/2009	9.01	4.25	3.49
01/12/2009	9.34	4.84	5.07
01/01/2010	9.60	6.09	5.53
01/02/2010	9.70	5.30	5.04
01/03/2010	9.96	4.57	4.07
01/04/2010	10.19	4.77	3.82
01/05/2010	10.86	5.49	3.92
01/06/2010	10.05	5.89	4.55
01/07/2010	10.82	6.64	4.39
01/08/2010	10.81	6.32	4.11
01/09/2010	10.54	6.01	3.69
01/10/2010	10.63	6.88	3.25
01/11/2010	10.37	7.52	3.52
01/12/2010	10.47	9.18	4.05
01/01/2011	10.93	8.37	4.26
01/02/2011	11.47	8.21	3.88
01/03/2011	11.94	9.29	3.78
01/04/2011	12.41	8.85	3.99
01/05/2011	13.00	8.83	4.07
01/06/2011	13.87	8.94	4.30
01/07/2011	15.49	8.42	4.19
01/08/2011	15.83	8.33	3.85
01/09/2011	15.62	8.04	3.69
01/10/2011	15.76	8.33	3.38
01/11/2011	16.02	8.71	3.09
01/12/2011	15.75	8.29	3.01
01/01/2012	15.95	8.00	2.53
01/02/2012	15.34	9.79	2.37
01/03/2012	15.62	8.76	2.06
01/04/2012	16.13	9.10	1.84
01/05/2012	16.35	8.61	2.31
01/06/2012	16.43	8.13	2.34
01/07/2012	17.17	8.21	2.80
01/08/2012	16.96	8.12	2.69
01/09/2012	16.09	9.23	2.69
01/10/2012	14.62	9.81	3.14
01/11/2012		9.92	
01/12/2012		10.11	

Solar energy calculations

Solar irradiation on a horizontal surface

Parameters	
Latitude (ϕ)	-20.28°
Longitude (ψ)	57.55°
Time zone	4
Slope (β)	0°
Surface azimuth angle (γ)	180°
Local Standard Time Meridian (ψ_{zone})	60°

Local time (LT)	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Fall equinox											
Declination (δ)	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8
Hour angle (ω)	-75.0	-60.0	-45.0	-30.0	-15.0	0.0	15.0	30.0	45.0	60.0	75.0
cos θ (angle of incidence)	0.2	0.5	0.7	0.8	0.9	0.9	0.9	0.8	0.7	0.5	0.2
Angle of incidence (θ)	75.7	61.7	48.1	35.2	24.4	19.5	24.4	35.2	48.0	61.7	75.6
Maximum irradiation	247.1	473.3	667.7	816.9	910.7	942.8	911.0	817.4	668.5	474.3	248.2
Minimum irradiation	24.7	47.3	66.8	81.7	91.1	94.3	91.1	81.7	66.8	47.4	24.8
Winter solstice											
Declination (δ)	23.4	23.4	23.4	23.4	23.4	23.4	23.4	23.4	23.4	23.4	23.4
Hour angle (ω)	-75.0	-60.0	-45.0	-30.0	-15.0	0.0	15.0	30.0	45.0	60.0	75.0
cos θ (angle of incidence)	0.1	0.3	0.5	0.6	0.7	0.7	0.7	0.6	0.5	0.3	0.1
Angle of incidence (θ)	85.1	73.0	61.9	52.6	46.1	43.7	46.1	52.6	61.9	73.0	85.1
Maximum irradiation	84.7	292.3	470.5	607.3	693.3	722.6	693.3	607.4	470.6	292.4	84.9
Minimum irradiation	8.5	29.2	47.0	60.7	69.3	72.3	69.3	60.7	47.1	29.2	8.5
Spring equinox											
Declination (δ)	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
Hour angle (ω)	-75.0	-60.0	-45.0	-30.0	-15.0	0.0	15.0	30.0	45.0	60.0	75.0
cos θ (angle of incidence)	0.2	0.5	0.7	0.8	0.9	0.9	0.9	0.8	0.7	0.5	0.2
Angle of incidence (θ)	75.7	61.8	48.1	35.3	24.5	19.7	24.6	35.3	48.2	61.8	75.8
Maximum irradiation	246.9	473.1	667.3	816.2	909.8	941.6	909.5	815.7	666.5	472.2	245.9
Minimum irradiation	24.7	47.3	66.7	81.6	91.0	94.2	91.0	81.6	66.7	47.2	24.6
Summer solstice											
Declination (δ)	-23.4	-23.4	-23.4	-23.4	-23.4	-23.4	-23.4	-23.4	-23.4	-23.4	-23.4
Hour angle (ω)	-75.0	-60.0	-45.0	-30.0	-15.0	0.0	15.0	30.0	45.0	60.0	75.0
cos θ (angle of incidence)	0.4	0.6	0.7	0.9	1.0	1.0	1.0	0.9	0.7	0.6	0.4
Angle of incidence (θ)	68.9	55.4	41.7	28.0	14.3	3.2	14.3	28.0	41.7	55.4	68.9
Maximum irradiation	360.7	568.3	746.5	883.2	969.2	998.5	969.1	883.1	746.4	568.1	360.6
Minimum irradiation	36.1	56.8	74.6	88.3	96.9	99.8	96.9	88.3	74.6	56.8	36.1

Solar irradiation on a tilted surface

Parameters	
Latitude (ϕ)	-20.28°
Longitude (ψ)	57.55°
Time zone	4
Slope (β)	20.28°
Surface azimuth angle (γ)	180°
Local Standard Time Meridian (ψ_{zone})	60°

Local time (LT)	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Fall equinox											
Declination (δ)	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8	-0.8
Hour angle (ω)	-75.0	-60.0	-45.0	-30.0	-15.0	0.0	15.0	30.0	45.0	60.0	75.0
cos θ (angle of incidence)	0.3	0.5	0.7	0.9	1.0	1.0	1.0	0.9	0.7	0.5	0.3
Angle of incidence (θ)	75.0	60.0	45.0	30.0	15.1	0.8	15.0	30.0	45.0	60.0	75.0
Maximum irradiation	258.2	499.4	706.6	865.6	965.7	999.9	966.0	866.2	707.5	500.5	259.4
Minimum irradiation	25.8	49.9	70.7	86.6	96.6	100.0	96.6	86.6	70.7	50.0	25.9
Winter solstice											
Declination (δ)	23.4	23.4	23.4	23.4	23.4	23.4	23.4	23.4	23.4	23.4	23.4
Hour angle (ω)	-75.0	-60.0	-45.0	-30.0	-15.0	0.0	15.0	30.0	45.0	60.0	75.0
cos θ (angle of incidence)	0.2	0.5	0.6	0.8	0.9	0.9	0.9	0.8	0.6	0.5	0.2
Angle of incidence (θ)	76.3	62.7	49.6	37.4	27.6	23.4	27.6	37.4	49.6	62.7	76.3
Maximum irradiation	237.3	458.6	648.6	794.4	886.1	917.4	886.2	794.6	648.8	458.8	237.5
Minimum irradiation	23.7	45.9	64.9	79.4	88.6	91.7	88.6	79.5	64.9	45.9	23.8
Spring equinox											
Declination (δ)	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
Hour angle (ω)	-75.0	-60.0	-45.0	-30.0	-15.0	0.0	15.0	30.0	45.0	60.0	75.0
cos θ (angle of incidence)	0.3	0.5	0.7	0.9	1.0	1.0	1.0	0.9	0.7	0.5	0.3
Angle of incidence (θ)	75.0	60.0	45.0	30.0	15.0	0.6	15.0	30.0	45.0	60.0	75.0
Maximum irradiation	259.4	500.5	707.5	866.3	966.0	999.9	965.7	865.7	706.7	499.5	258.2
Minimum irradiation	25.9	50.0	70.7	86.6	96.6	100.0	96.6	86.6	70.7	49.9	25.8
Summer solstice											
Declination (δ)	-23.4	-23.4	-23.4	-23.4	-23.4	-23.4	-23.4	-23.4	-23.4	-23.4	-23.4
Hour angle (ω)	-75.0	-60.0	-45.0	-30.0	-15.0	0.0	15.0	30.0	45.0	60.0	75.0
cos θ (angle of incidence)	0.2	0.5	0.6	0.8	0.9	0.9	0.9	0.8	0.6	0.5	0.2
Angle of incidence (θ)	76.3	62.7	49.6	37.4	27.6	23.4	27.6	37.4	49.6	62.7	76.3
Maximum irradiation	237.5	458.8	648.8	794.5	886.2	917.4	886.1	794.5	648.6	458.6	237.4
Minimum irradiation	23.8	45.9	64.9	79.5	88.6	91.7	88.6	79.4	64.9	45.9	23.7

Summer solstice, 45 degrees east

Parameters	
Latitude (ϕ)	-20.28°
Longitude (ψ)	57.55°
Time zone	4
Slope (β)	20.28°
Surface azimuth angle (γ)	-45°
Local Standard Time Meridian (ψ_{zone})	60°

Local time (LT)	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Summer solstice, 45 degrees east											
Hour angle (ω)	-75.0	-60.0	-45.0	-30.0	-15.0	0.0	15.0	30.0	45.0	60.0	75.0
cos θ (angle of incidence)	0.6	0.8	0.9	1.0	1.0	1.0	0.9	0.7	0.6	0.4	0.2
Angle of incidence (θ)	51.4	38.9	26.6	15.3	10.2	17.9	29.6	42.0	54.5	66.8	78.8
Maximum irradiation	623.6	777.9	894.2	964.5	984.1	951.6	869.2	742.6	580.4	393.5	194.9
Minimum irradiation	62.4	77.8	89.4	96.5	98.4	95.2	86.9	74.3	58.0	39.4	19.5

Summer solstice, 45 degrees west

Parameters	
Latitude (ϕ)	-20.28°
Longitude (ψ)	57.55°
Time zone	4
Slope (β)	20.28°
Surface azimuth angle (γ)	135°
Local Standard Time Meridian (ψ_{zone})	60°

Local time (LT)	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Summer solstice, 45 degrees west											
Hour angle (ω)	-75.0	-60.0	-45.0	-30.0	-15.0	0.0	15.0	30.0	45.0	60.0	75.0
cos θ (angle of incidence)	0.1	0.3	0.5	0.7	0.8	0.9	1.0	0.9	0.8	0.7	0.5
Angle of incidence (θ)	86.9	73.1	59.4	45.9	33.1	22.3	17.8	23.5	34.7	47.6	61.1
Maximum irradiation	54.3	290.0	508.7	695.4	837.3	924.9	952.1	917.2	822.4	674.2	482.8
Minimum irradiation	5.4	29.0	50.9	69.5	83.7	92.5	95.2	91.7	82.2	67.4	48.3