Diligence Reports of Sample Islands: Summary

Table of Contents

1 METHODOLOGY AND CASE STUDIES

1.1. METHODOLOGY FOR THE MINIGRID ISLANDS DESIGN

1. For the purpose of this analysis, the islands outside the greater Male' region are referred to as the outer islands. Electricity services for islands in the Greater Male' region are provided by STELCO while FENAKA covers the remaining islands. Out of a total of the 194 inhabited islands in the Maldives, power systems on 162 FENAKA and STELCO islands[1] were analysed on an island-by-island basis, regarding their electricity production and consumption, installed generation capacities, and associated costs. For A two-step approach was followed with the first step the selection of 5 sample islands in 2013 that were considered generally representative of the islands in the Maldives. Detailed technical analysis including resource mapping, power system analysis and system modelling and due diligence of the site was carried out. In the second step, the systems designed for the 5 islands were extrapolated to cover the remaining 157 islands. For the technical design, three conceptual models with different modes of operation based on the proportion of renewable energy penetration (RE %) were developed for the project. These three models are given in Table 1.

Table 1: Three models with different levels of renewable energy penetration

Type A: Moderate renewable energy penetration (RE penetration up to 10 % in energy terms)	For Type A islands, the proportion of renewable energy is up to about 10% in energy terms on an annual basis. The power systems on these islands absorb and utilize renewable energy as available. While renewable energy contributes during periods of high solar or wind availability, the share of diesel based power remains significant even at those times. This moderate level of renewable energy penetration level does not require the installation of battery storage systems. However, these systems would need to be backed up with automatic generator controllers and take advantage of any flexible loads that can be re-scheduled. The islands chosen for Type A usually correspond to large electricity consuming islands with efficient levels of operation. Type A is an intermediary step to transitioning 100% diesel dependent islands to Type B islands.
Type B: High renewable energy penetration (10% RE penetration to 80% in energy terms)	For Type B islands, the proportion of renewable energy is between 10% and 80% on energy terms on an annual basis. For these islands, a battery storage system is designed to provide grid support and can be used as a backup system to overcome cloud-shading effects in the PV panels and other intermittency issues associated with renewable energy systems. Existing generators may not supply enough inertia to the system when outages or abrupt changes in the output of renewable energy occur leading to instantaneous fluctuations in frequency and causing system instability. The existing control devices in the system are usually unable to follow abrupt changes and countermeasures including demand side management and batteries (such as lithium ion batteries) are proposed as grid support for these islands.

[1] Electricity services on the remaining islands are provided by individual island development councils with significant support in forms of capital investment from the Government. Lack of professionally qualified operators and spares has over time resulted in a decline in service quality and the electricity systems on these islands are gradually being absorbed by the utility companies e.g. FENAKA.

	The islands chosen for Type B correspond to medium levels of population and electricity consumption.
Type C: Full RE penetration (RE penetration higher than 80%):	For Type C islands with full RE energy penetration, practically all energy consumed by energy customers would be sourced from renewable energy generation plants on an annual basis. The energy storage is designed and sized in this case for power stability support as well as energy support in case of long periods of lack of solar or wind energy. This type of micro-grids is dominated by battery inverter/charger although, sometimes, diesel backup is installed for security reasons for supply security in case of failure or maintenance. The islands chosen for Type C correspond to low population, low volumes of electricity consumption and very high cost of electricity and very high levels of subsidies.

2. The methodology, used in this study to recommend the least cost approach for integrating the required contribution of renewable energy into the grid system, is as follows:

- A reference scenario for projected diesel use, under a business as usual scenario, is established, taking into account the projected load forecast including future increases in demand. Different load forecasts are defined for each of the proposed Types.
- The estimated reduction in diesel use with the proposed RE interventions against the reference scenario, is established.
- Land and roof-top availability constraints are considered for maximum RE penetration.
- Renewable energy options (solar energy and wind energy) considered potentially viable on an island by island solution, are explored in detail with regards to their resource potential, technical feasibility and cost. Several simulations are also prepared for optimal penetration over an atoll-wise approach. The Software Homer is used at this stage to arrive at the optimal solution.
- A simulation model is run to calculate the limits of intermittent renewable energy penetration and to determine grid compatibility. The size of the battery storage system is pre-designed when necessary (For Type B and C).
- According to each island classification (A, B, C), the generation mix in order to achieve the optimal RE system penetration is calculated.
- Different financing arrangements are modelled to determine the financial sustainability of the project.

3. This methodology has enabled an understanding of:

- the renewable energy options which are available to Maldives, given both the country's resource potential and particular grid characteristics;
- the amount of renewable energy required to be generated according to Type A, B and C classification, and
- the cost and financial implications the selected renewable energy scenarios.

4. Given an understanding of the above, a least cost approach for integrating the required contribution of renewable energy into the grid is recommended and presented. The modelling outputs for the 5 sample islands are provided below.

1.2. Case Study 1: S. Addu

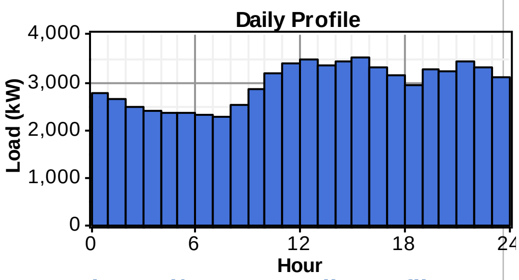
Atoll. Island:S. Addu

Current situation:

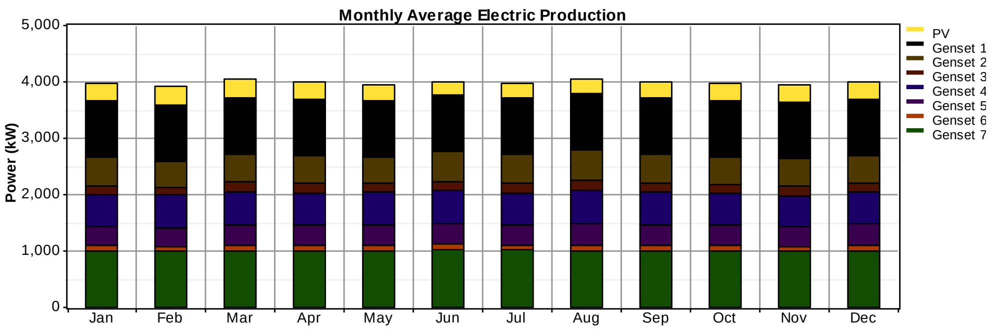
Installed generation capacity (kW)	**6850**
Population	**32,062**
Measured peak (kW)	**6500**
Energy consumption (MWh/day)	**96**
Specific fuel consumption (L/kWh)	**0.290**
Estimated CO_2 emissions (kg/year)[2]	**26,744,095**

Proposed Hybrid System

Photovoltaic (kWp)	**1600**
Total diesel (kW)	**6850**
- Generator 1 (kW)	**1000**
- Generator 2 (kW)	**1000**
- Generator 3 (kW)	**1000**
- Generator 4 (kW)	**750**
- Generator 5 (kW)	**750**
- Generator 6 (kW)	**750**
- Generator 7 (kW)	**1600**
Batteries (kWh)	**0**
Battery inverters (kW)	**0**
RES penetration (%)	**7.3**
Estimated CO_2 emissions (kg/year)[1]	**22,342,208**



Estimated/Current Daily Profile



Comments

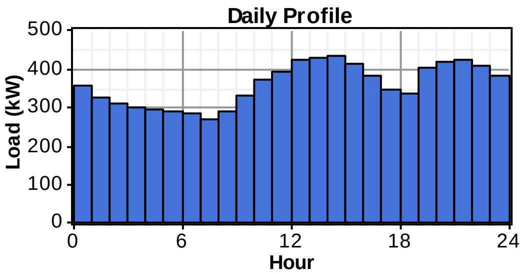
All currently installed generators may continue in operation since their specific fuel consumption is acceptable. A Type A configuration is initially proposed and a transition to Type B can be considered at a subsequent stage.

[2] The CO_2 emissions have been estimated taking into account the expected demand growth.

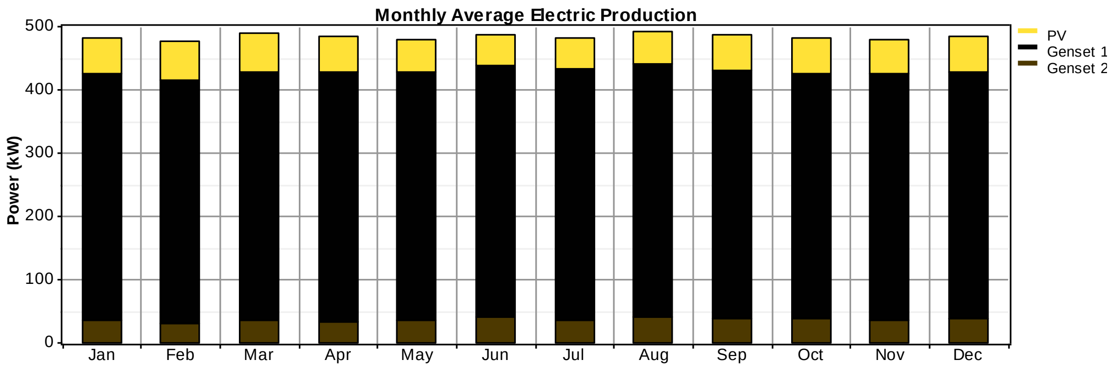
1.3. CASE STUDY 2: GA. VILINGILI

Atoll. Island: Gaaf Alif. Vilingili	
Current situation:	
Installed generation capacity (kW)	**800**
Population	**4264**
Measured peak (kW)	**768**
Energy consumption (MWh/day)	**12**
Specific fuel consumption (L/kWh)	**0.324**
Estimated CO_2 emissions (kg/year)[3]	**3,623,312**

Proposed Hybrid System	
Photovoltaic (kWp)	**300**
Total diesel (kW)	**800**
- Generator 1 (kW)	**500**
- Generator 2 (kW)	**300**
Lithium-ion batteries (kWh)	**78.0**
Battery inverters (kW)	**200**
RES penetration (%)	**11.2**
Estimated CO_2 emissions (kg/year)[1]	**2,882,627**



Estimated/Current Daily Profile



Comments

It is proposed that all currently installed generators be replaced by new ones because the island's specific fuel consumption is excessive. A Type B configuration is proposed.

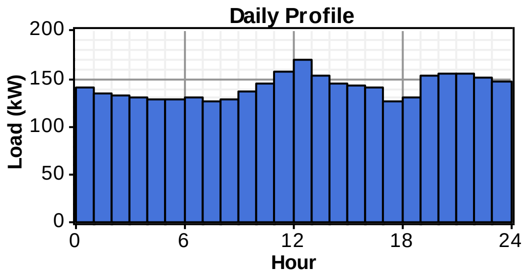
[3] The CO_2 emissions have been estimated taking into account the expected demand growth.

1.4. CASE STUDY 3: LH. KURENDHOO

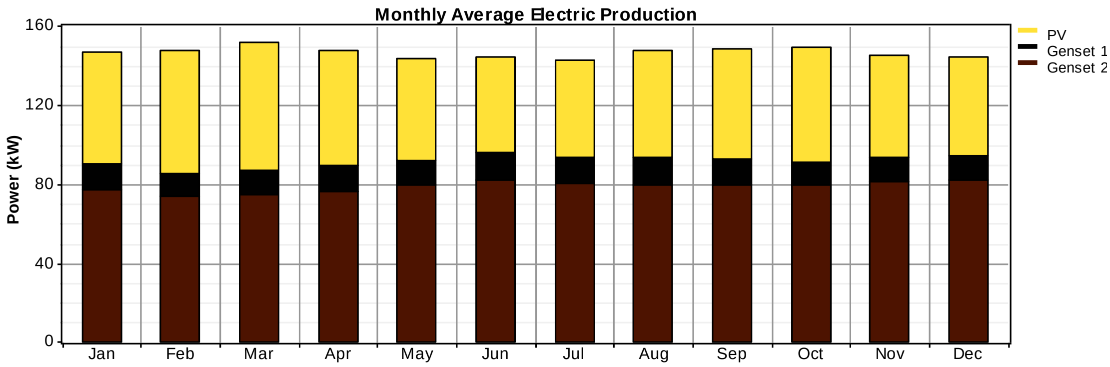
Atoll. Island: Lhaviyani. Kurendhoo	
Current situation:	
Installed generation capacity (kW)	**258**
Population	**1965**
Measured peak (kW)	**210**
Energy consumption (MWh/day)	**3.4**
Specific fuel consumption (L/kWh)	**0.400**
Estimated CO_2 emissions (kg/year)[4]	**1,300,472**

Proposed Hybrid System

Photovoltaic (kWp)	**300**
Total diesel (kW)	**254**
- Generator 1 (kW)	**104**
- Generator 2 (kW)	**150**
Lead-acid batteries (kWh)	**78.0**
Battery inverters (kW)	**300**
RES penetration (%)	**34.9**
Estimated CO_2 emissions (kg/year)[1]	**633,030**



Estimated/Current Daily Profile



Comments

It is proposed that the currently installed generators be replaced by new generators, because their specific fuel consumption is excessive. A Type B configuration is proposed.

1.5. CASE STUDY 4: B. GOIDHOO

[4] The CO_2 emissions have been estimated taking into account the expected demand growth.

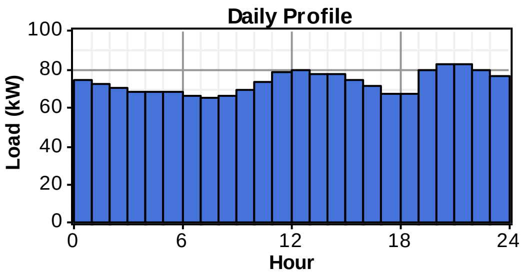
Atoll. Island: Baa. Goidhoo

Current situation:

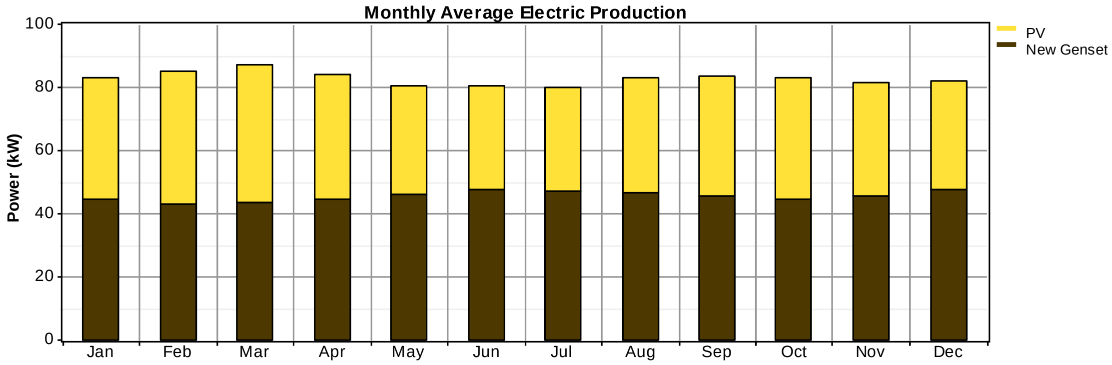
Installed generation capacity (kW)	**128**
Population	**738**
Measured peak (kW)	**109**
Energy consumption (MWh/day)	**1.8**
Specific fuel consumption (L/kWh)	**0.400**
Estimated CO_2 emissions (kg/year)[5]	**674,904**

Proposed Hybrid System

Photovoltaic (kWp)	**200**
Total diesel (kW)	**160**
- Generator 1 (kW)	**160**
- Generator 2 (kW)	
- Generator 3 (kW)	
Lead-acid batteries (kWh)	**78.0**
Battery inverters (kW)	**200**
RES penetration (%)	**37.5**
Estimated CO_2 emissions (kg/year)[1]	**423,175**



Estimated/Current Daily Profile



Comments

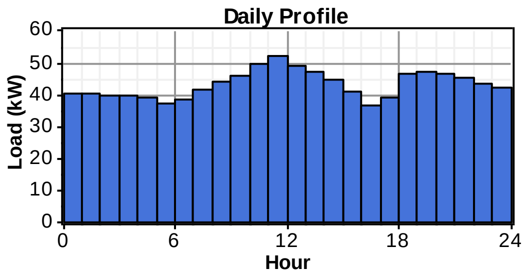
It is proposed that the currently installed generators be replaced by a new 160kW generators, because their specific fuel consumption is excessive. Type B and Type C configuration were considered and a Type B is proposed.

[5] The CO_2 emissions have been estimated taking into account the expected demand growth.

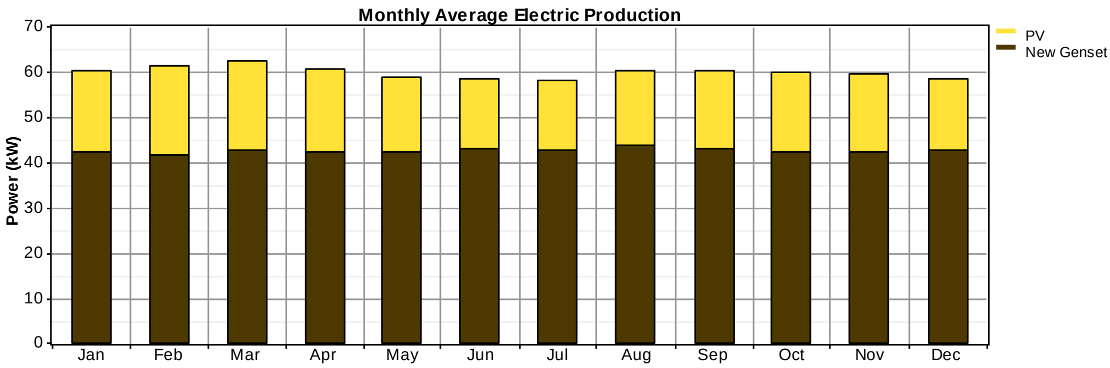
1.6. Case Study 5: Th. Buruni

Atoll. Island:Thaa. Buruni	
Current situation:	
Installed generation capacity (kW)	**228**
Population	**599**
Measured peak (kW)	**69**
Energy consumption (MWh/day)	**1.0**
Specific fuel consumption (L/kWh)	**0.520**
Estimated CO_2 emissions (kg/year)[6]	**646,885**

Proposed Hybrid System	
Photovoltaic (kWp)	**100**
Total diesel (kW)	**100**
- Generator 1 (kW)	**100**
- Generator 2 (kW)	
- Generator 3 (kW)	
Lithium-ion batteries (kWh)	**39.0**
Battery inverters (kW)	**100**
RES penetration (%)	**20.7**
Estimated CO_2 emissions (kg/year)[1]	**346,481**



Estimated/Current Daily Profile



Comments

It is proposed that the currently installed generators be replaced by a new 100kW generators, because their specific fuel consumption is excessive. Type B and Type C configuration were considered and a Type B is proposed.

[6] The CO_2emissions have been estimated taking into account the expected demand growth.

2 SUMMARY OF THE ROADMAP

2.1. MAIN RESULTS FROM THE ROADMAP

1. Of a total of the 194 inhabited islands, power systems on 162 islands were analyzed based their electricity production and consumption, installed capacities, and associated costs. Several different scenarios were taken up based on rolling out of the different configurations for the islands, savings in fuel and availability of financing for capital expenditure.

2. A base case roadmap is developed with the following configuration of solar diesel hybrid projects (type A: 4 islands, type B: 148 and type C: 10). This includes a configuration of solar PV power generation units (on ground and roof-top) with a total capacity of about 25 MWp and 44 MW of diesel generation (including existing diesel generation sets) for a total capacity of 69 MW. The hybrid systems range from less than 10 kWp for a small individual island to about 1.6 MWp for solar PV and 35 kW to 1600kW (existing) for diesel generators. Further, the roadmap considered various storage options and has been developed considering Li-Ion based battery storage systems.

3. Other key options for the roadmap include (i) configuring all 162 islands as Type B islands and (ii) configuring the 10 smallest islands as Type C islands and the remaining 152 islands as Type B islands. The requirement for solar PV and storage would accordingly vary with the largest installation on S. Addu reaching 4 MWp of solar PV and over 1000 kWh of energy storage.

4. Based on a request received from the Government in August 2014, the roadmap is being updated to include solar PV and related energy efficiency investments for some of the Greater Male islands that could be considered under the sector project.

3 REPLACEMENT OF BATTERIES

5. The dismantlement of Li-ion batteries installations after their operation life is a concern for customers and for environmental authorities. The main lithium ion battery manufacturers have taken this issue into account and offer alternative plans for bringing the batteries back to the factory and recycling the main components. Potential bidders providing energy storage solutions would need to indicate methodologies for routine checks and disposal of batteries at the end of life in the Maldives. The following paragraphs include an example of the procedure proposed to end customers by manufacturers to perform the dismantlement and recycling of their batteries.

3.1. EXAMPLE OF LI-ION BATTERY RECYCLING PROCESS[7]

6. It is important to note that back to factory programs have been already implemented by grid scale Li-ion batteries manufacturers. The containers and boards need to be handled properly at the end of its life. The manufacturer can provide a complete solution to customer assuming customer will bring back (at own cost) the containers to a dismantling point located in factories. Usually, they have multiple points of collection to store and dismantle batteries. The complete solution will include the following steps, dismantling, grouping, and selection of adequate recyclers and the recycling of the battery modules.

3.2. GROUPING

7. After dismantling, sub-assemblies and components are to be grouped along several categories:

- Metallic fractions: including the container itself with roofing and flooring, the electrical wiring, the battery racking system,
- Electrical systems: including BMM modules, the converters and inverters, the electrical part of the fire suppressant systems and air conditioning systems, but excluding gas canisters and cooling fluids,
- Gas canisters:
- Battery modules: special care against electrical risks needs to be taken when dismantling and handling.

3.3. SELECTING THE RIGHT RECYCLERS

8. After receiving the used batteries, the manufacturer usually can select the proper recyclers for the different grouped fractions; metallic fraction, electrical systems, and gas canisters.

3.4. RECYCLING THE BATTERY MODULES

9. The battery modules need to be properly packaged for shipment to an authorized battery collection organization. From this collection point forward, the battery will be transported to a fully permitted recycler. An example provided was UMICORE that is Saft recycler for Li-Ion and guarantees that recycling rate is above 50% in terms of mass as required by the European directive for batteries and accumulators 2006/66/CE.

10. The battery modules recycling process is given in described below.

11. The modules are placed in a furnace and melted with adequate control of the temperature (above1450 ° C) and pressure of oxygen (oxidation) so that:

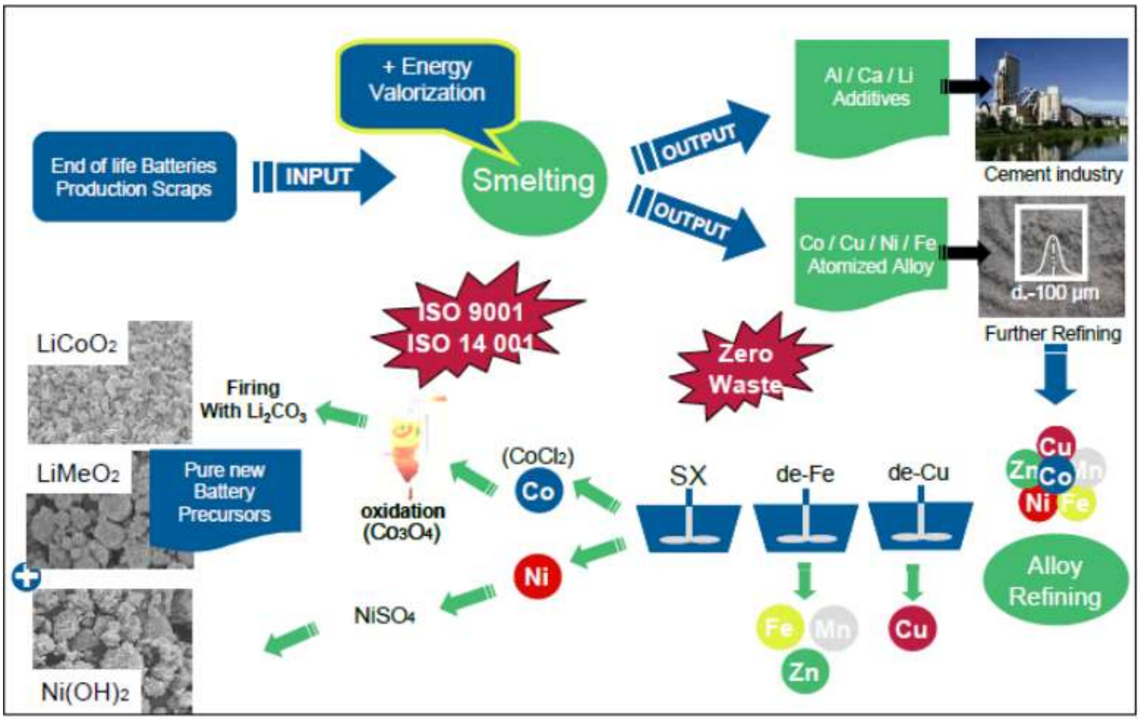
- The electrolyte is burned and no dioxins cannot be formed through a gas treatment installation with a plasma torch,

[7] Source: Based on industry discussions

- an inert slag (Ca, Al, Li) is formed and used as a construction material,
- All metals (Ni, Co, Cu, Fe) are melted and reduced in an alloy.

12. The metal alloy is granulated and then refined. Then the pure compounds of cobalt and nickel are converted to new positive active materials used in new and rechargeable batteries (recycling in a closed loop).

Figure 1: Recycling of Batteries



4 GRID INTEGRATION ISSUES

13. There are two major challenges to be overcome to integrate significant quantities of intermittent energies into small grids like those in Maldives; (i) grid stability, and (ii) load dumping.

14. To maintain system steady state stability for all power systems implemented in Maldives, the respective generation capacities of the groups, along with RES and power storage should exceeds the energy demand and meet the loads. Furthermore, the droop control implemented in the control systems must perform this operation efficiently to reduce fuel consumption.

15. Maintaining stability in dynamic and transient states is a complex issue that should be taken into account. The diesel generators will have to absorb the small variances occurred in the network (to minimize the impact on the batteries) due to changes in demand or renewable power generation. However, the high penetration rate of RE will lead to situations in which the diesel units would not be capable of maintaining the system stability as they would not have enough inertia for large changes. In these cases, the control devices implemented in the PV inverters and batteries would need to smooth out the ramps to help maintain grid stability.

16. For the final project design being implemented, it will be necessary to perform detailed voltage and frequency stability studies. This report includes in an annex a frequency stability analysis motivating the need for battery storage elements to maintain system frequency under security margins.

17. A second problem stems from the need to reject renewable energy (load dump) due an oversupply. If high penetration figures above approximately 10% renewable energy are to be achieved, the installed capacity of renewable energy must be large in relation to the minimum loads of the systems. In addition, there are minimum requirements with respect to diesel generator output. Two main criteria are considered when determining minimum settings of diesel generators.

- The need for sufficient spinning reserve capacity to compensate for sudden changes in renewable energy output; and
- The lower limits a specific generator should be loaded in order to avoid a deterioration of the fuel efficiency and reduced lifetime of the engines.

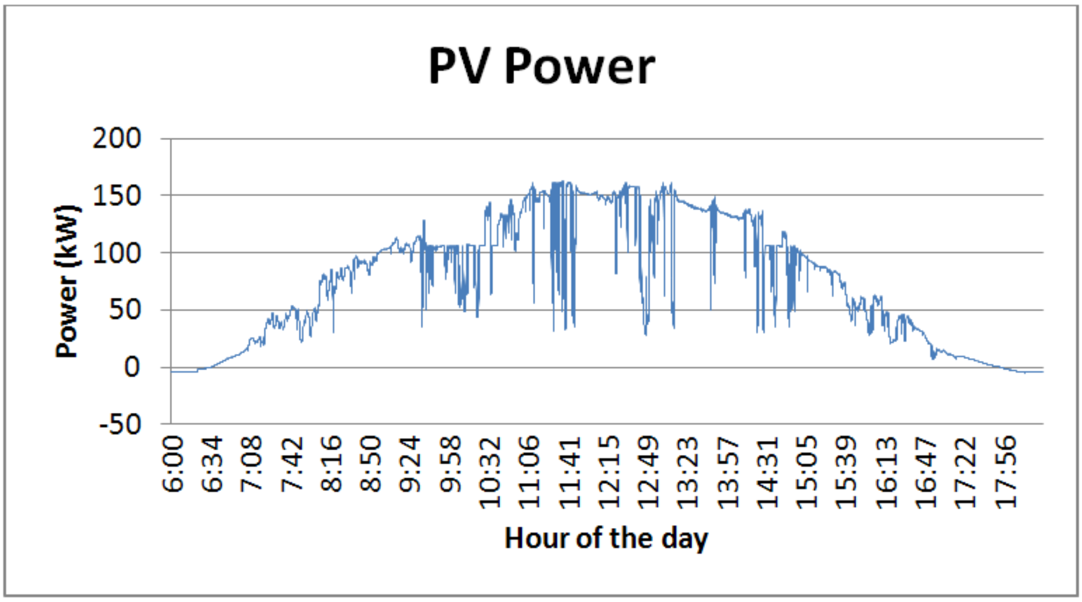
18. These criteria may cause a rejection of renewable energy contribution, especially in low load situations. There is a tradeoff between high renewable energy penetration and fuel efficiency of the diesel generators in the system.

19. Both problems described above have technical solutions. The easiest way is to (manually or automatically) disconnect individual renewable energy facilities from the grid during times of low demand. This incurs losses in renewable energy contribution but does not require any significant additional investment. The second option is the integration of non-time critical consumers such as water pumps or ice making plants into the system. Such consumers can be connected to the grid with priority during times of high renewable energy availability. Switching can be manual or automatic by an integrated supervisory control system (SCADA). The third option is the introduction of storage.

20. Using storage systems for power smoothing in micro-grids with RES and highly variable loads is one of the alternatives to help control frequency and voltage. However, storage is expensive over the lifetime of micro-grids. That is why many micro-grids use storage systems to enhance short term power balancing capabilities and use operating and control strategies that do not rely on storage. They also utilize active control of RES and demand side management.

21. In small systems, PV systems are unable to assist with the inertial response and the effect of clouds shading in PV plants can compromise grid stability. These fluctuations can be observed from a PV power plant located in Male, Figure 2, where power productions ramps over 70% of nominal power occur in seconds. Besides PV inverters are usually operated at maximum power point, they cannot assist in the primary frequency control by providing extra power to compensate for a loss of generation or a load increase.

Figure 2. Measurement for PV output located at Male



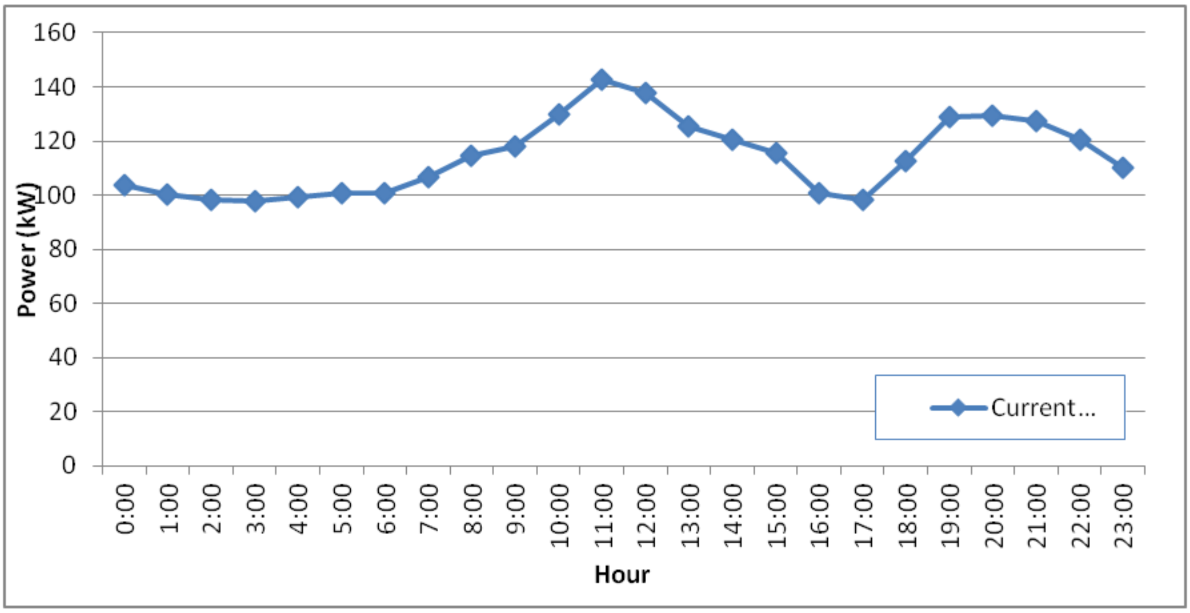
22. In a small system with significant penetration of RES, such as those under study, the initial rate of frequency change is typically greater and a lower value of frequency can be reached in a shorter time than in conventional systems with all generation supplied by rotating machines, possibly resulting in under-frequency load shedding and disconnecting PV and wind generators. In such cases, adequate spinning reserve should be available and provided by rotating machines with a sufficient governor response and a high inertia. Diesel generators can typically provide fast spinning reserve with a consequent reduction in the transient frequency drop. The required increase in spinning reserve to compensate for the lack of frequency control support of RES is an important matter even in relatively large isolated grids.

23. An alternative to generation based spinning reserve is the use of energy storage. This is one of the most technologically advanced and long term solutions for frequency stability. Another option for isolated systems is load shedding but its “cost” to system users, in terms of perceived loss of power quality and reliability, has to be balanced with the cost of providing adequate spinning reserves. It should be noted that in many cases, autonomous diesel-hybrid systems present secondary loads with intrinsic energy storage characteristics, such as water heaters, water pumping, water desalination plants and ice making plants that can be disconnected for some time without major issues for the consumers. Even space heaters and coolers can be disconnected for short periods without noticeable impact.

24. In sunny regions, like Maldives, the peak demand can be expected during the mid-afternoon of summer months as a result of air conditioning use during the day[8].

[8] C. S. Chen, M. S. Kang, J. C. Hwang, and C. W. Huang, “Synthesis of power system load profiles by class load study,” International Journal of Electrical Power and Energy Systems, Vol. 22, No. 5, pp. 325-330, June 2000.

Figure 3: Real daily Load Curve, measured for day 17/08/2013 in Kurendhoo



25. A solution that is gaining more prominence, as a result of government incentives and advances in technology is the use of PV microgrids as peaker plants[9]. Photovoltaic power plants are suitable for use as peak power plants, especially in sunny regions, since the peak power output of the PV coincides with the peak load demand during summer. The challenge is to mitigate the impact of the fluctuating nature of the PV source on the power system stability and utilize the potential of distributed resources to enhance the overall system reliability. However, an excess grade of penetration of renewable energy in the network can cause instability, mainly due to the large variations that occur in the amount of energy generated by the photovoltaic plant, due to stochastic nature of solar radiation and wind. Thus, it is necessary to control devices capable of maintaining stability of the mains.

[9] A. Domijan, F. Torres, and C. Alvarez, "Microgrids: a look into the power delivery system of the future," Proc. of the International Conference on Power and Energy Systems, Jan 2007.

5 STABILITY ANALYSIS

5.1. MAIN CONSIDERATIONS AND SCOPE

26. The models used in this analysis are generic, so the actual behavior of the system when operating will depend specifically on the equipment to be used. Moreover, the distribution system is not being considered because there will be no decentralized PV system and the distribution grid will be a passive element in power distribution, thus the stability of the distribution grid and the voltage at the different points thereof were not analyzed. The system's frequency will be the same throughout the system and will be controlled by the hybrid power system as a whole.

27. The load disturbances analyzed do not consider inrush currents resulting from the reconnection of sections of the distribution grid after a failure or during system startup.

28. Protection devices are not modeled in this analysis.

29. The scenarios simulated are the worst cases for the different system operating modes that are possible, such as diesel-off operation, and parallel operation with solar and thermal plant. The resolution of the simulations used is 10 microsecond (0.00001 sec) and the type of simulation is EMT (electromagnetic transients). It is important to note that extreme cases were considered in each case by using step-like changes in the load and PV generation that rarely occur under normal conditions but are the worst possible cases. Thus, if the system supports the abrupt changes simulated in this analysis, it will also support the most common disturbances. In those cases where the stability of the grid is not acceptable an storage system will be added and the results will be analyzed.

30. The five grids considered are the sample islands that were studied in 2013 and 2014.

5.1.1. Frequency Stability

31. An important characteristic of frequency is that it is the same throughout the system. Frequency is controlled by the Voltage Source Converter controls. In this study simulations will be based on international standards about under and overfrequency limits.

Table 3: International standards for under and over frequency

	Max limit	Recommended value	Time delay
Over-frequency limit	52.4 Hz	51.5 Hz	≤100 ms
Under-frequency limit	47.5 Hz	47.5 Hz	≤100 ms

5.1.2. Methodology Used

32. The stability analysis of the hybrid power system was performed with the PSCAD/EMTDC software of the Manitoba HVDC Research Centre This software is a computational tool for electric power system analysis for transmission, distribution, generation and smart grid applications.

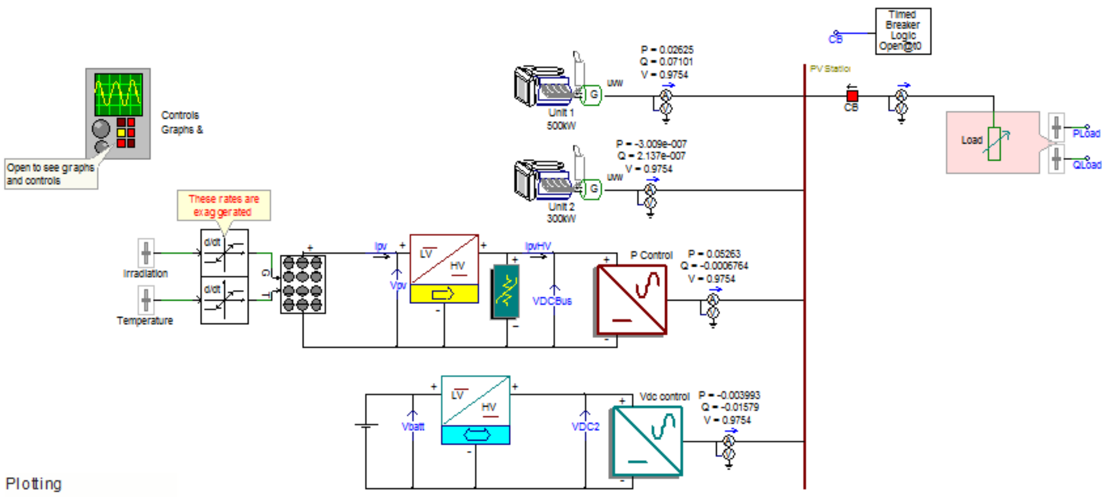
33. The thermal plant set, inverter and PV power plant models were all run on PSCAD with the characteristics specified in the final design document. Since the power generation system will be centralized, the analysis does not take into consideration the detailed model of the distribution grid and simply examines a number of low-voltage loads. Once the model was set up, a series of scenarios were defined to test the stability of the proposed design. The scenarios cover fluctuations in PV generation, fluctuations in the power load and the effect of a cloud on the PV generation. Simulations of the different scenarios verify that the

system operates under the established limits. The models employed involve generic components that only approximately represent the actual behavior of the specific components to be used.

5.2. DESCRIPTION OF THE MODELS USED

34. This section describes the models used for system simulation with the PSCAD/EMTDC software. Figure 2 shows the schematic of the entire hybrid power system. It includes a PV plant, its inverter and its controls, 2 diesel generators and the load connected to the power system. The 2 considered minigrids have the same structure but the power and some controls may differ.

Figure 4: Schematic of the system



35. It is worth mentioning that a detailed model of the distribution network was not taken into account for this model.

5.2.1. DIESEL GENERATOR SET MODEL

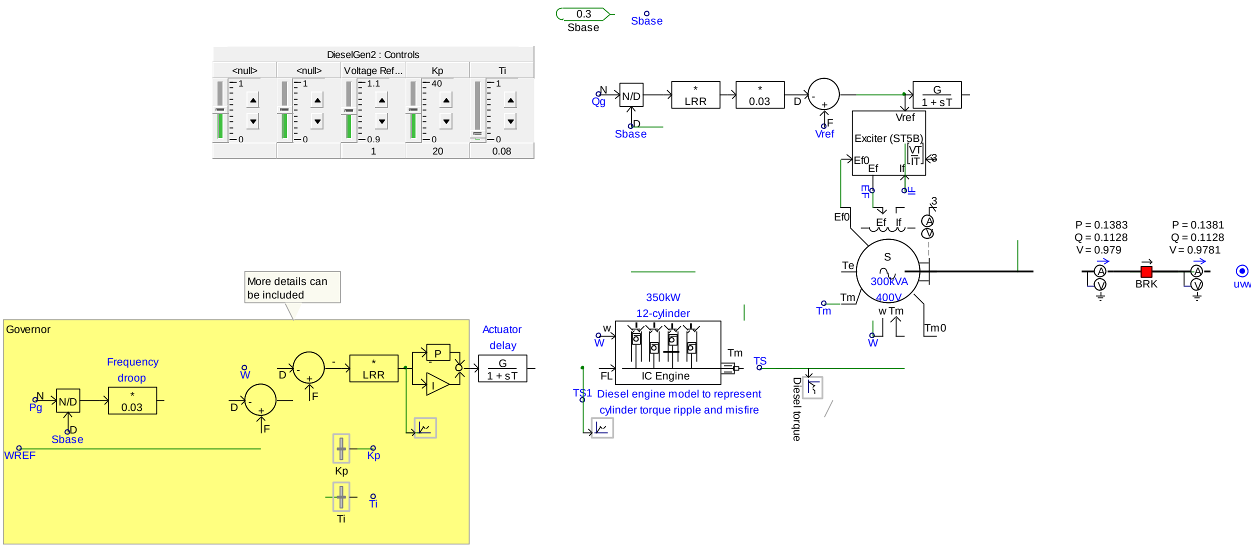
36. Three models were considered for modeling the thermal power plant sets: a standard self-excited synchronous generator model, a diesel engine model and a standard Automatic Voltage Regulator (AVR) model.

37. The diesel engine model is consistent with the mechanical drive (prime mover) of the synchronous generators used. This model consists of three parts integrated into the same model and represented by their corresponding transfer function: the mechanical governor, the diesel engine itself and the electronic controller.

38. This model comprises an electronic control (PID controller), an actuator for controlling fuel flow to the engine and, finally, a model of the engine. The model also features the frequency droop functions and active power specified in the final design. Frequency droop has been limited to 3%.

39. The model's parameters depend on the physical characteristics of each of the elements and on the characteristics of the entire system as a whole. The parameters were adjusted so that the system would operate stably under the expected conditions and in conjunction with the other elements (voltage regulator and synchronous generator). The gain and time constant parameters are specific for each system and depend largely on the load conditions of the grid impedance, power and inertia constant of the generator set.

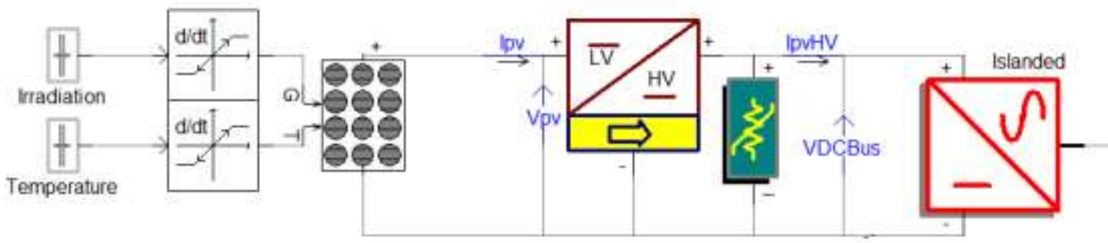
Figure 5: Schematic of the diesel generator set



5.2.2. PV PLANT MODEL

40. The PV model consist on a PV panel, a boost converter, a chopper and a Voltage Source Converter (VSC).

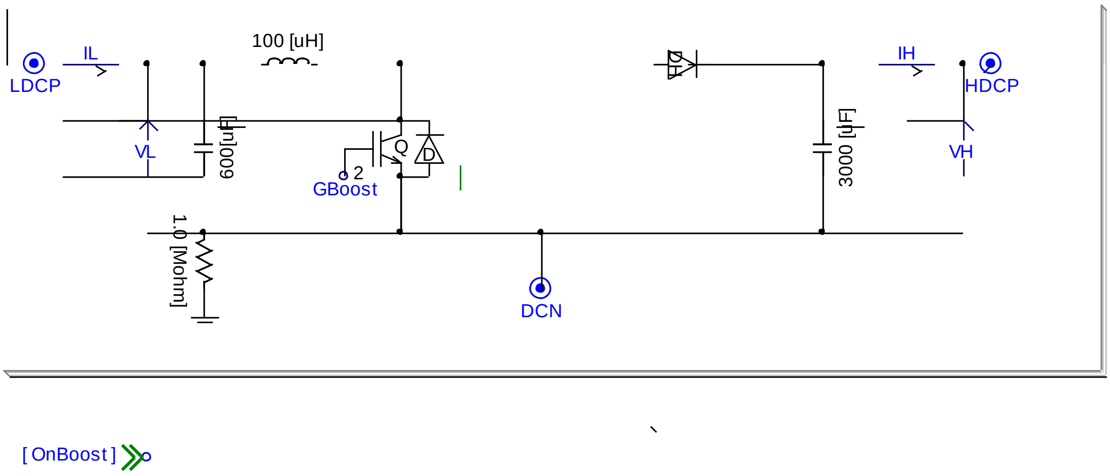
Figure 6: Schematic of the PV Plant



5.2.2.1. PV BOOST

41. This element a step-up power converter that takes in a low voltage input and provide an output at a much higher voltage.

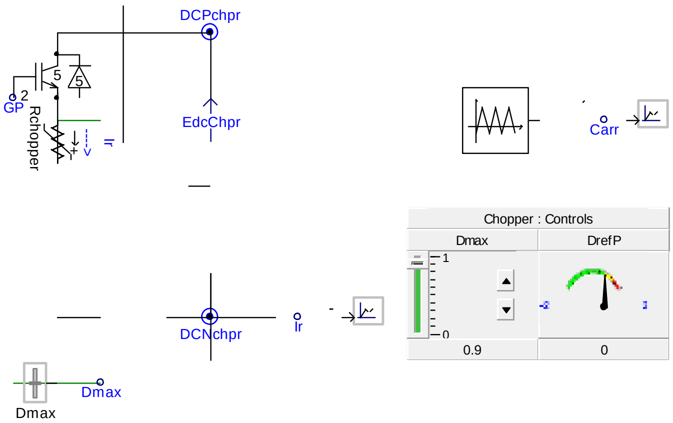
Figure 7.Schematic of the PV Boost



5.2.2.2. CHOPPER

42. A chopper is a static device which is used to obtain a variable DC voltage from a constant dc voltage source. A chopper is also known as DC-DC converter. The thyristor converter offers greater efficiency, faster response, lower maintenance, smaller size and smooth control. Choppers are widely used in trolley cars, battery operated vehicles, traction motor control, control of large number of dc motors, etc. They are also used in regenerative braking of DC motors to return energy back to supply and also as DC voltage regulators. In this case, the chopper is used.

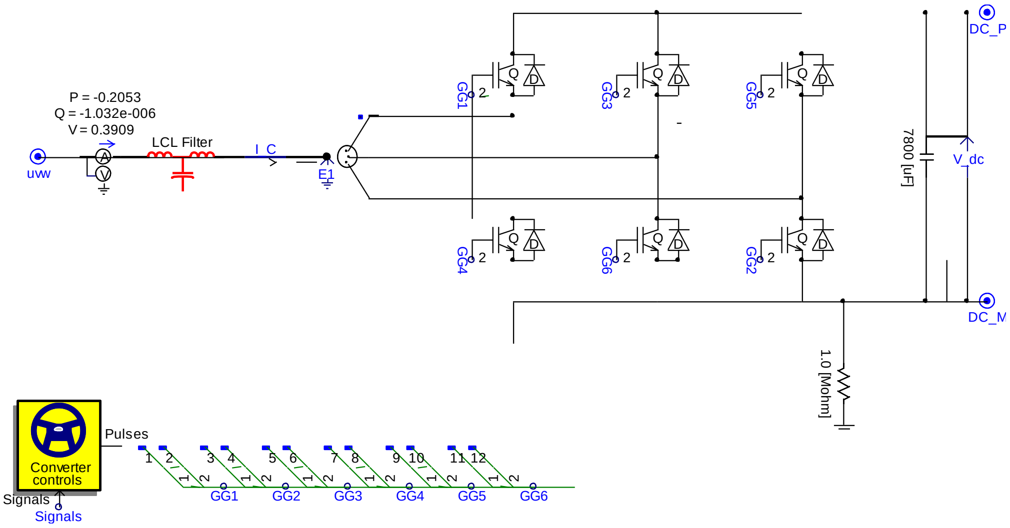
Figure 8.Schematic of the PV Boost



5.2.2.3. VOLTAGE SOURCE CONVERTER (VSC)

43. In order to be able to connect the PV system to the minigrid, the DC output power of the DC-DC converter should be converted into a three phase AC power using a three phase voltage source converter. It is part of inverters' task to keep the DC voltage across its input (DC-DC converter's output) at a constant value.

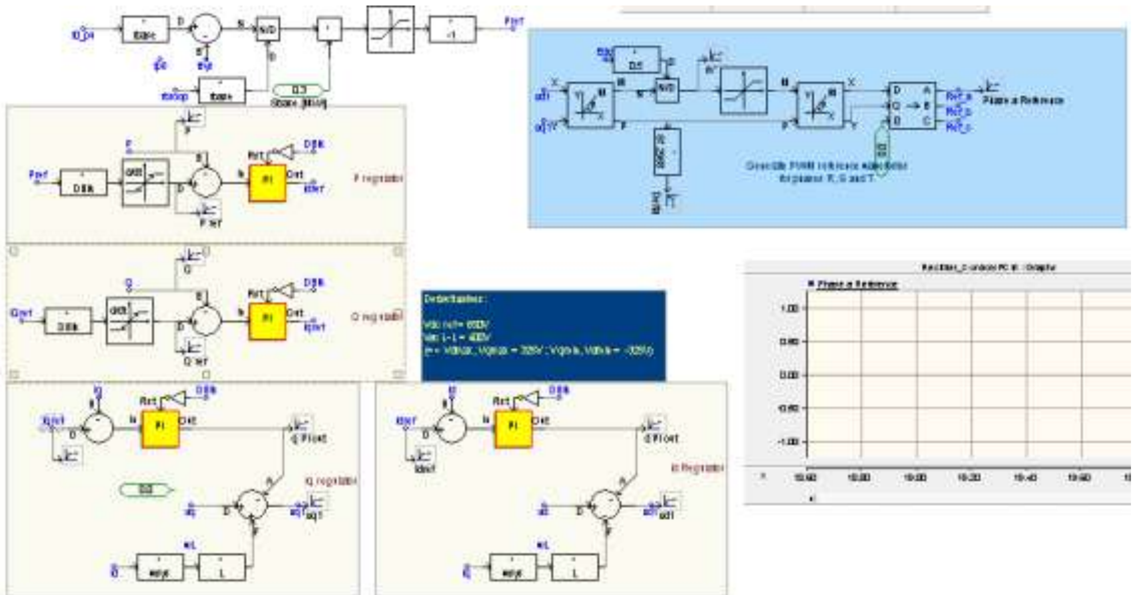
Figure 9.Schematic of the VSC of the PV plant



- **VSC CONTROLS**

44. The control strategy applied for inverter consists of two control loops. Usually there is a fast inner control loop which controls output current and an external power loop which control dc link power flow. The current control loop is responsible for power quality issues like low THD and good power factor, whereas power control loop balances the power flow in the system. Synchronous reference frame control also called d-q control uses a reference frame transformation abc to dq which transforms the grid current and voltages into d-q frame. The transformed power detects phase and frequency of AC side, whereas transformed current controls the AC side current. Thus the control variables becomes dc values, hence filtering and controlling becomes easier.

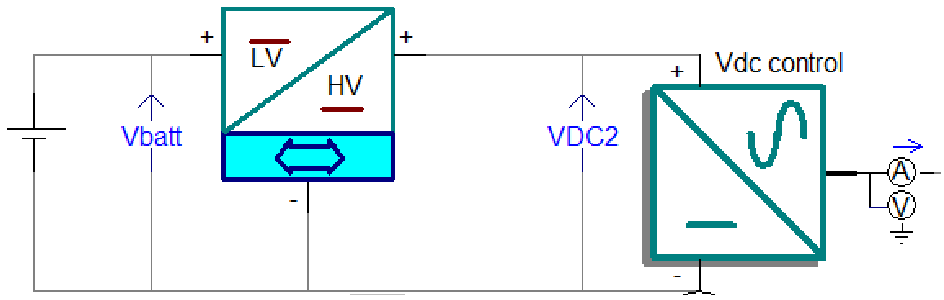
Figure 10.Schematic of the VSC control



5.2.3. STORAGE SYSTEM

45. The storage consist on the model of the voltage source, the bidirectional converter and the VSC.

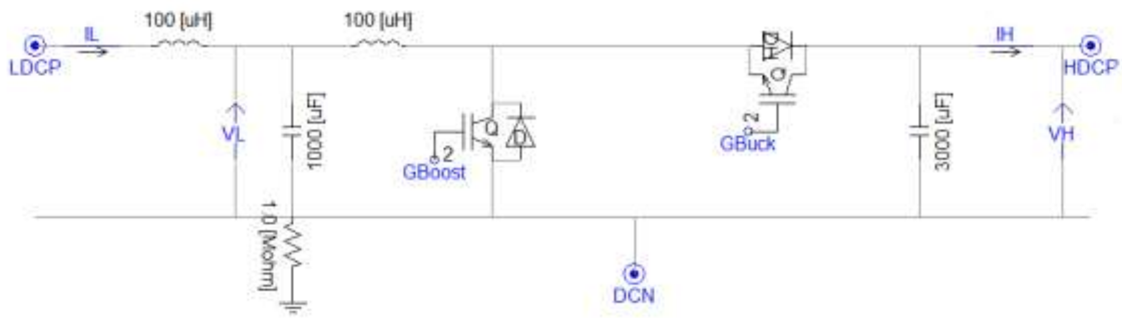
Figure 11.Schematic of the Storage system



5.2.3.1. STORAGE CONVERTER

46. This element will raise (Boost) or decrease (Buck) the voltage depending if the battery is being discharged or charged.

Figure 12.Schematic of the Boost-Buck converter



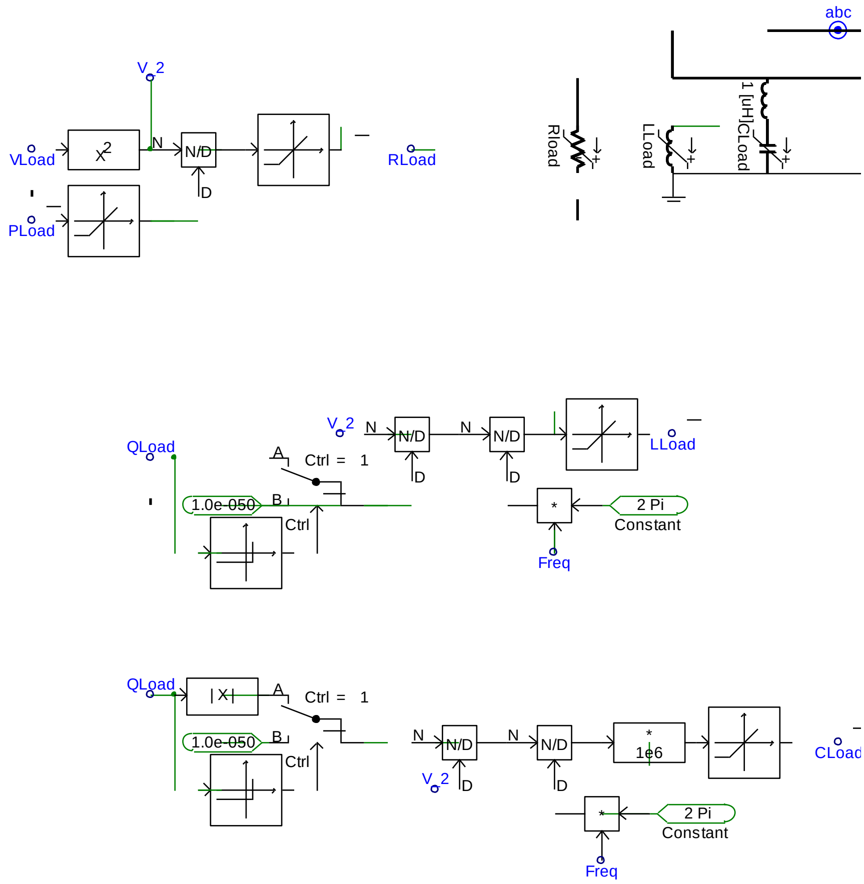
5.2.4. VOLTAGE SOURCE CONVERTER

47. The Voltage Source and its control is the same as the PV plant described before.

5.2.5. LOAD

48. The load is modeled as an adjustable RLC circuit. With this circuit, the user can modify the real and reactive power demanded by the load, and the values of the passive components are automatically set to consider these levels of power.

Figure 1.Load Model



5.3. SUMMARY OF THE RESULTS

49. Table 4 provides the summary of the results of each simulation.

Table 4.Summary of the results

Island	Conditions	Critical frequency without storage (Hz)	Critical frequency with storage (Hz)
S. Addu	100% PV power loss	47.93	-
	Sudden load power loss of 40%	51.65	-
	Power load increase and PV power loss with two generators	48.08	-
Ga. Vilingili	100% PV power loss	49.18	-
	Sudden load power loss of 30%	50.8	-
	50% PV power loss due to clouds	49.77	-
	50% PV loss and load increase	47.46	49.28
Lh. Kurendhoo	100% PV power loss	48.79	-
	Sudden load power loss of 30%	50.56	-
	50% PV power loss due to clouds	49.73	-
	PV loss and load increase	47.09	49.38
Th. Buruni	80% PV power loss	49.47	-
	100% PV power loss	48.7	-
	Sudden load power loss of 30%	50.49	-
	PV power loss and load increase	47.41	48.49
B. Goidhoo	80% PV power loss	48.8	-
	100% PV power loss	48.22	-
	Sudden load power loss of 30%	50.60	-
	PV power loss and load increase	47.5	49.27